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Project Title: Low Temperature SO_2 Removal with Solid Sorbents in a Circulating Fluidized Bed Absorber

by

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A	cross-sectional area of bed reactor, m^2
A_b	cross-sectional area of bed, m^2
Ar	Archimedes number (dimensionless)
C_D	drag coefficient (dimensionless)
C_s	weight of solids in a bed, kg/m^3
$C_{s,crit}$	critical weight of solids in Figure 3.3
D_b	diameter of bed reactor, m
$d_{p,min}$	minimum size of parent solids, μm
d_s	diameter of solid, μm
d_{pi}	discrete size of solids, μm
$d_{p,min}$	minimum size of solids, μm
$d_{p,MMD}$	mass mean diameter of the parent solids, μm
E_a	attrition activation energy, kJ/kg
E_{exc}	excess energy by the gas velocity above minimum fluidization velocity, m/s
F	fluid-dynamic induced forces.
$F_e(t)$	elutriation rate of solids, kg/s
$F_r(t)$	recirculating rate, kg/s
$F_o(t)$	feeding rate of solids, kg/s
g	gravitational constant, m/s^2
h_i	inflection point in the voidage profile.
h	height, m
H	height of dense zone in a bed, m
H_b	height of bed reactor, m
H_{mf}	height of dense zone at minimum fluidization velocity, m
k_a	attrition rate constant, s^{-1}
k_o	frequency factor in an Arrhenius form
k_w	attrition rate constant under wet condition, s^{-1}
M_g	mass flow rate of fluidizing gas, kg/s
M_s	mass of solids, kg
M_w	molecular weight of gas, kg/kg-mole
n	total number.
P	absolute pressure of gas, $kg/m{\cdot}s^2$
Q	volumetric flow rate of gas, m^3/s
R	gas constant, kJ/kg-mole·°K
Re_{mf}	The Reynolds number.
t	time, s
T	temperature, °K
U	superficial gas velocity, m/s
Ua	air velocity, m/s
U_g	gas velocity, m/s
U_{mf}	minimum fluidization velocity, m/s

CHAPTER 1. INTRODUCTION

1.1 Background

Levels of SO_2 gas concentration in the air have been documented to cause serious health and environmental problems. For example, excessive levels of SO_2 in the ambient air are associated with a significant increase in acute and chronic respiratory diseases. Also, SO_2 gas emissions combine with water vapor in the atmosphere to form sulfuric acid, one of the major contributors to acid rain. When SO_2 bonds to airborne particulates such as dust, smoke and aerosols in the atmosphere, these sulfates can be transported by the prevailing winds long distances, for example from the northeastern portion of the United States up into Canada.

SO_2 is released into the air primarily through the burning of coal and fuel oils. Up until the 1950s, the burning of coal by railroad locomotives was a major source of sulfur dioxide pollution. Emissions from industrial sources [1] such as nonferrous smelters and sulfuric acid plants grew sharply between 1940 and 1970, as a result of increased production. But since 1970, industrial emissions have decreased because of the introduction of control systems. In the U.S. today, two-thirds of the total SO_2 emissions come from electric power plants, 95% of which are coal-fired as illustrated in Figure 1.1. Besides coal-fired electric power plants, other sources of SO_2 emissions include refineries, pulp and paper mills, steel smelters, chemical plants, and other types of energy facilities such as shale oil,

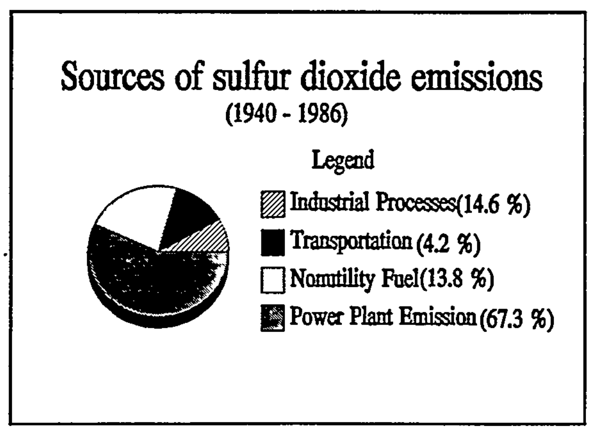


Figure 1.1 Sources of SO_2 Emissions. (Source; National Air Pollutant Emissions Estimates, 1940-1986, USEPA, 1988)

synfuel processing, and petroleum processing. In addition, home furnaces and coal burning stoves are sources that more directly affect residential neighborhoods.

Therefore, strategically, today's major effort is to reduce SO_2 emissions from coal-fired power plants, while continuing to lower emissions from other major sources. A considerable number of flue gas desulfurization (FGD) processes have been developed and are expected to play an important role in lowering SO_2 emissions from power plants. One of the recent advances in FGD is the dry scrubbing process, which includes furnace injection scrubbers, in-duct scrubbers, and post-furnace scrubbers.

Furnace injection scrubber During the late 1960's and early 1970's, the USEPA and its predecessor organizations [2] were the first to conduct research on dry sorbent injection for coal-fired utility boilers. The Tennessee Valley Authority (TVA) was the forerunner of dry limestone injection into the boiler, demonstrating the dry boiler injection process at Shawnee Station in Paducah, Kentucky [3]. The flow diagram for this process is illustrated in Figure 1.2. In this furnace injection scrubber, the fine, 10 μm limestone is uniformly injected in the 2200 °F-2300 °F temperature zone. The gas temperature in the reaction zone is selected between 1200° F and 2300° F to maximize limestone calcination, but to minimize high temperature sintering. The concentration of SO_2 in the boiler is about 3000 ppm, and the residence time is from 1 to 2 seconds. During this time the limestone must be calcined, the SO_2 oxidized to SO_3^-, and the SO_3^- reacted with the calcined limestone. The sulfate products, unreacted lime, and fly ash are then removed by a cyclone or electrostatic precipitator (ESP). The highest SO_2 removal efficiency obtained

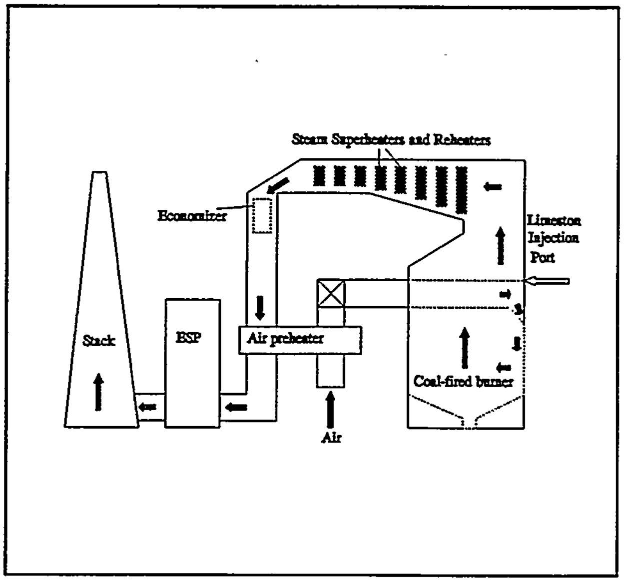


Figure 1.2 TVA furnace injection scrubber process.

was 36% with the boiler running at half load. However at higher boiler loadings, SO_2 removal efficiency was in the range of 17% to 20%.

In the late 1970's, following the TVA efforts, the US EPA initiated research on a limestone injection multistage burner (LIMB) process. In the LIMB process dry sorbent is injected along with the coal directly through the multistage burners. The process was demonstrated in 1987 at Ohio Edison's Edgewater plant [4]. A process flow diagram of the complete LIMB/humidifier system is provided in Figure 1.3. LIMB is easily retrofitted to existing boilers and its capital investment is relatively low. Although it achieves removal efficiencies lower than other flue gas scrubbers, the cost per unit of sulfur removed is much lower than that for other flue gas scrubbers. At a Ca/S ratio of 2, SO_2 removal between 55% and 72% is achievable. The specific sorbent type and the degree of humidification were the two primary factors affecting removal efficiency. Sorbent types include commercial calcitic hydrated lime, dolomitic hydroxide and commercial calcitic hydrated lime with a small amount of calcium lignosulfonate additive. The additive and humidification improved the sorbent's reactivity.

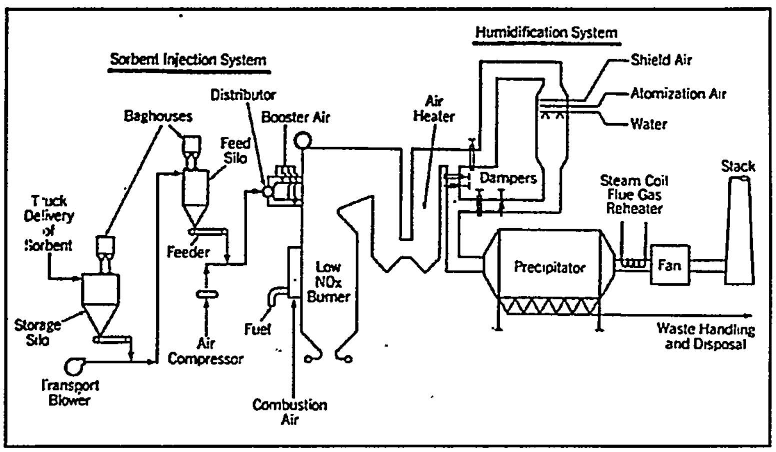


Figure 1.3 LIMB process flow diagram.

In-duct scrubber The sorbent injection port of entry is different for in-duct injection scrubbing compared to the port of entry for furnace injection scrubbing. Specifically, for in-duct injection the sorbent is injected into the existing duct work downstream of the boiler, between the air heater and the duct control equipment (i.e., the electrostatic precipitator, ESP, or the bag house). The reaction zone of the sorbent is restricted to existing duct work connecting the air heater to the ESP. The key factor to success for in-duct injection is matching gas residence time to sufficient sorbent drying time and the desired removal efficiency. Three in-duct injection technologies developed by Bechtel Nation, Dravo Engineering, and General Electric Environmental Services, respectively, will be briefly described below [5].

Bechtel's process injects a finely atomized slurry of lime and water into the ductwork through dual-fluid atomizing nozzles. The slurry flow rate is controlled to maintain the desired exit gas temperature. For most runs, an outlet temperature of 160°F is maintained with an approach to saturation of 35°F.

Dravo's process involves a two-step in-duct process; first injection of water vapor and second injection of dry sorbent. For this process the first stage humidification is used to maintain a constant temperature at the entrance of the test section and the second stage to cool the flue gas to the desired exit gas temperature. For Ca/S ratios near 2, 50% SO_2 removal is achieved for an approach to saturation temperature between 20°-30°F.

GE's process injects lime slurry with a rotary atomizer directly into existing ductwork without utilizing a separate reaction vessel [6]. The in-duct scrubbing process flow of GE's process is illustrated in Figure 1.4. Collection of reaction products along with the fly ash is accomplished in existing control devices, ESP or fabric filter. GE constructed a 50,000 acfm pilot plant burning high sulfur coal to demonstrate the scrubbing technology. For a Ca/S ratio of 1.5, GE achieved 50% SO_2 removal.

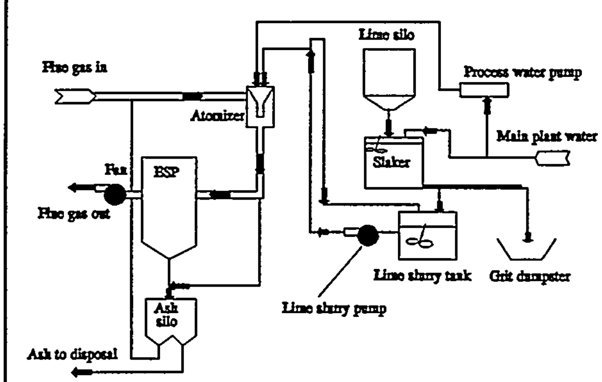


Figure 1.4 GE's in-duct scrubbing process flow diagram.

Post-furnace scrubber The post-furnace scrubbing technology is very similar to in-duct scrubbing; the fundamental difference is that the post-furnace scrubbing employs a specific reactor vessel placed in series, downstream of the boiler instead of injecting sorbent directly into the existing ductway. The post-furnace scrubbers can achieve higher SO_2 removal efficiency and higher sorbent utilization, depending upon reactor design factors such as reactor residence time, mixing pattern, and recycle.

One well established post-furnace scrubber is a spray dryer. The spray dryer reactor injects wet sorbent (lime slurry) through a rotary or pneumatic nozzle into the reactor vessel with flue gas flow. The atomized lime slurry dries by evaporation and simultaneously reacts with the flue gas as it flows through the length of the spray dryer. The dry reacted lime/sulfate product is then captured in a downstream fabric filter. The flue gas SO_2 is removed in the reactor by the sorbent and in the fabric filter by the unreacted dust-cake sorbent. The SO_2 removal efficiency of the spray dryer is much higher than that of dry sorbent injection scrubbers, but its capital and operating cost are more expensive.

Numerous studies have been conducted at the full scale and at the pilot scale demonstrating the SO_2 removal efficiency in a spray dryer/fabric filter system [7,8,9]. In general, the studies have shown that the SO_2 removal efficiency increases with increased stoichiometric ratio and with near approaches to saturation at the spray dryer outlet. Keener and Davis [9] developed a more cost effective modification to conventional $Ca(OH)_2$-based spray dryer technology. The improved system is comprised of a conventional spray dryer system for the initial SO_2 removal, plus a supplemental injection zone for gaseous NH_3. The combined $Ca(OH)_2/NH_3$ system is shown in Figure 1.5. Removal efficiency of the modified system surpasses the conventional $Ca(OH)_2$-based spray dryer. SO_2 removal efficiency of 90% can be realized using high-sulfur coal.

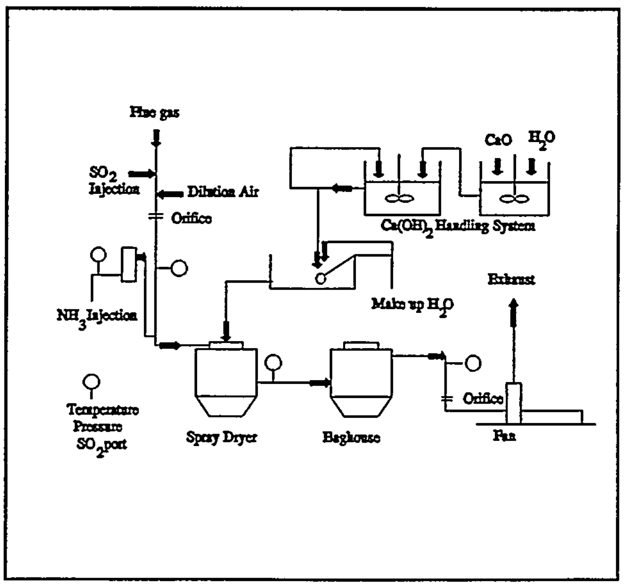


Figure 1.5 Schematic diagram of the spray dryer/fabric filter pilot plant.

Earlier, Babcock and Wilcox [10] developed a dry injection FGD process, which is illustrated in Figure 1.6. In this post-furnace scrubber process, a fixed bed reactor is employed to absorb SO_2. The reacted sorbents are recovered to a marketable sulfuric acid. This process offers no stack gas buoyancy problems and eliminates the waste disposal problems by regenerating the sorbents.

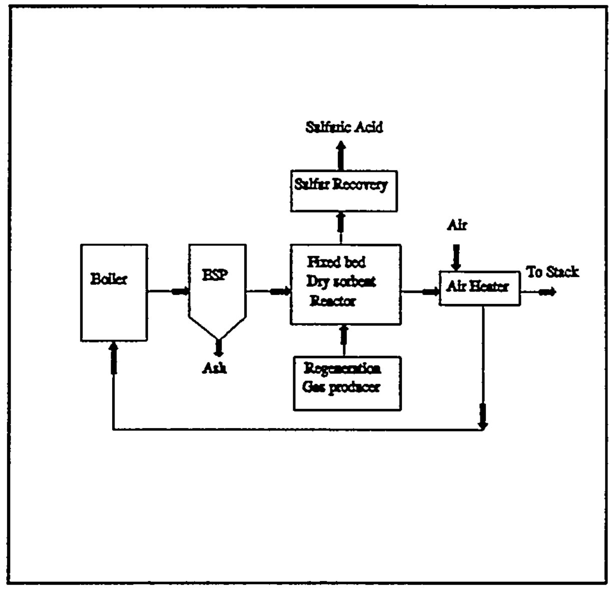


Figure 1.6 Babcock and Wilcox-Esso Process.

Hokkaido Electric in Japan [11] developed a post-furnace SO_2 scrubber employing a moving-bed reactor placed downstream of ESP. The process is shown in Figure 1.7. An active sorbent is used, composed of a mixture of slaked lime, calcium sulfate, and combusted coal fly ash. The sorbent mixture is pelletized with water, and treated at 100°C using steam to produce porous pellets ranging from 3 to 10 mm in particle size. SO_2 removal efficiency of 90% is achieved at a temperature of 140°C.

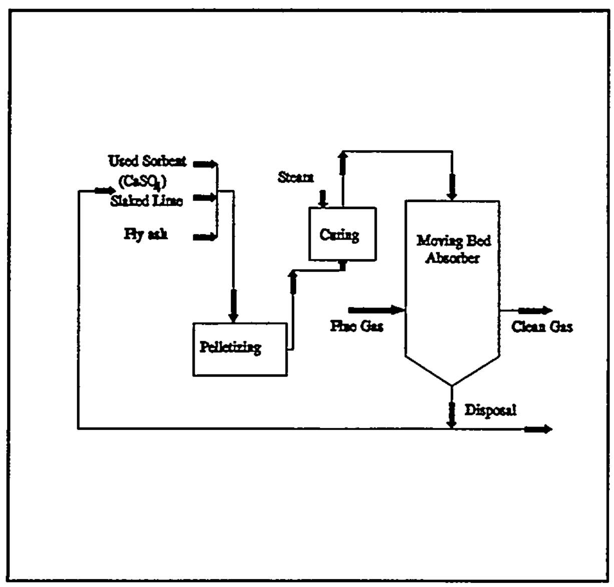


Figure 1.7 Dry lime fly ash sorbent process by Hokkaido Electric.

Keener and Jiang [12] developed and constructed a Circulating Fluidized Bed Absorber (CFBA). The CFBA is a low capital cost, post-furnace FGD process that offers high sorbent utilization and operational simplicity. A CFBA basically consists of a fluidized bed reactor utilizing the flue gas for vigorous high velocity fluidization. Under the vigorous action, the solid sorbent is attritted by particle to particle contact. The gas/solid separator following the reactor captures the entrained sorbents and recirculates the sorbents back into the fluidized bed reactor. Several different sorbent types have been investigated in the CFBA. SO_2 removal efficiency and sorbent utilization was over 90% with sodium bicarbonate sorbents. Another bench-scale dry CaO injection CFBA has been constructed and is under operation in the University of Cincinnati [13] for research on low temperature SO_2 removal.

1.2 Objective

As reviewed in the above section, dry scrubbing flue gas desulfurization, (FGD) processes have received considerable attention as a low-cost SO_2 control technology option. Over the past several years extensive studies have been ongoing in the area of process optimization. A novel FGD technology has been developed at the University of Cincinnati incorporating a circulating fluidized bed absorber (CFBA) reactor with dry sorbent [12,14]. The main features of CFBA are high sorbent/gas mixing ratios, excellent heat and mass transfer characteristics, and the ability to recycle partially utilized sorbent. Subsequently, higher SO_2 removal efficiencies with higher overall sorbent utilization can be realized compared with other dry sorbent injection scrubber systems.

Higher sorbent utilization is achieved in the CFBA compared to other dry injection processes through attrition mechanisms that occur under the vigorous action of the high bed gas velocity. This offers a significant economic advantage. Utilization of the other dry injection processes are limited by pore plugging from the large molar volume of the product sorbent sulfate. Plugged pores prohibit SO_2 diffusion into the particle interior [15,16]. Measurements of the rate of reaction between SO_2 and $Ca(OH)_2$ at 1000°F by EPA indicate that 25% of the particle is converted in milliseconds, at which point the reaction essentially stops. For a spherical sorbent particle, this represents a penetration of the product of only 9% of the initial radius of the particle. This thin layer of impervious material prevents the remaining portion of the particle from being exposed to SO_2. However the CFBA process is unique because it provides an aggressive mechanical means of attriting the product layer from the particle exterior, allowing further reaction with unreacted sorbent.

While lime attrition occurs to some degree in some of the other FGD processes, the underlying attrition mechanisms have rarely been studied in a systematic fashion because of the difficulties in identifying a large number of variables affecting the attrition. Therefore, the objective of this investigation is to find the predominant mechanisms in lime attrition during fluidization. Also, it is of interest to establish a relationship between extent of lime attrition and CFBA operating conditions. The earlier part of Chapter 3 represents the experimental findings obtained from the lime attrition tests in a fluidized bed, and a comprehensive attrition model applicable for the fluidized bed FGD processes. In the latter part of Chapter 3, an unsteady state population model is presented to predict the changes in size distribution of bed materials. The unsteady state population model, verified with the experimental data, may be applicable for the batch and continuous operations of fluidized beds in which the solid size reduction predominantly results from attrition and elutriation. Such significance of the mechanical attrition and elutriation is frequently seen in a fast fluidized bed as well as in a circulating fluidized bed.

Although the original investigations of sorbent injection for SO_2 removal were primarily done at high temperatures and under dry conditions, recently, water injection and cooling of flue gas has been investigated and found to enhance the utilization of dry calcium-based sorbents [17]. Water injection has been found to be extremely important for increase of sorbent reactivity in the dry calcium-based sorbent injection FGD processes. It was suggested that a spray of pure water without additives will be sufficient for sulfur dioxide removal if the wetting efficiency between sorbent particles and water droplets could be increased with newly developed humidification techniques. The water injection not only activates the sorbent reactivity enhancing SO_2 removal, but also conditions the flue gas for improved ESP performance by lowering the gas resistivity.

From a review of the literature and experimental results of CFBA operations, there is an apparent impetus to develop a suitable water injection technique to enhance the reaction of dry sorbents with SO_2 in flue gas at relatively low gas temperatures. Therefore, Chapter 4 includes a discussion and experimental results for a novel toroidal ring nozzle water injection technique designed and installed in the CFBA to increase the degree of particle wetting. In addition, Chapter 4 includes a developmental discussion of the important operating conditions affecting the toroidal ring nozzle water injection. Of primary interest is to a report of nozzle's effectiveness to enhance wetting efficiency and sorbent activity, as measurable by flue gas SO_2 removal and sorbent utilization.

CHAPTER 2. CIRCULATING FLUIDIZED BED ABSORBER (CFBA)

2.1 Circulating Fluidized Bed (CFB) Process

Circulating fluidized bed (CFB) technology has become more and more attractive during the last two decades as a promising core technology for the future within the field of solid processing and reactions. This is because a CFB provides good gas-solid contact, flexibility in gas-solid slip velocity, and the ability to fluidize the coarse solids. However, the relatively late emergence of a scientific approach to CFB technology can be seen, and as a result, its commercial application has been limited to catalytic cracking units for a long time. Only in the late 1960s was a successful CFB version of aluminum calcination developed, and not before the late 1970s did CFB technology become really widespread [18].

LURGI in Germany [19] developed a semi-dry process for FGD using a circulating fluidized bed, and demonstrated it at the Schwandorf power station, Munich, Germany. Their major conclusions were as follows :

. Excellent mass transfer from gaseous pollutant to solid sorbents and intensive gas/solid mixing occur in a CFB.

. Extremely high mass transfer rates occur within the lime particles of a CFB.

. Long residence time is achieved by recirculation of lime.

The schematic diagram of LURGI's CFB is shown in Figure 2.1. The core system of LURGI's CFB process is a venturi reactor with a dust separator and solid recirculation system. In the venturi reactor, flue gases are intimately mixed with a fine-grained lime and carried to the top of the reactor by the relatively high gas velocity of 2 to 8 m/s. After dust separation in a downstream ESP, the solids captured by a cyclone or ESP are recirculated to the venturi reactor, leading to extremely long residence times of up to about 20 minutes. Modifications to LURGI's CFB process include using hydrated lime and water injection to further activate the sorbents. The performance of LURGI's CFB is summarized in Table 2.1.

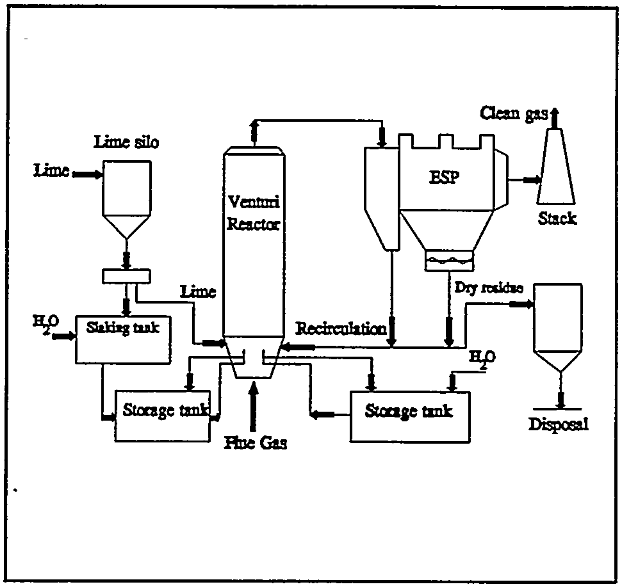


Figure 2.1 **LURGI's CFB [19].**

Table 2.1 Performance* of LURGI's CFB Reactor.

SO_2 removal efficiency	> 88 - 92 %
Hydrated lime injection as Ca/S ratio	< 3
Pressure drop including ESP and duct	< 24.5 mbar
Power consumption	< 760 kw
Steam injection rate	< 3 ton/hr

* The CFB was operated under the approach to saturation temperature of 15-20°C

The Tennessee Valley Authority (TVA) tested an innovative dry flue gas desulfurization clean coal technology at Paducah, Kentucky in 1993 [61]. The technology, called "gas suspension absorption" (GSA), combines the economic benefits of spray dryers with SO_2 removal levels close to those of wet scrubbing processes in a circulating fluidized bed. It was the first application on U.S. coals and the first large scale unit to treat flue gas from a coal-fired boiler application. The demonstration is being conducted on a 10 MWe slip stream from a 150 MWe boiler fired with high sulfur coal.

As shown in Figure 2.2, the heart of the process is a vertical reactor where flue gases from the air preheater are intimately contacted with lime sorbent, flyash and recycled reaction products. The lime slurry is injected through a spray nozzle located at the bottom of the reactor. The flow of lime slurry is regulated by a variable speed pump controlled by measurement of the acid gas concentration in the outlet flue gas stream. Cooling water added to the reactor is controlled by continuous measurement of the reactor/cyclone flue gas exit temperature. After the SO_2 reaction, the solids are separated from the flue gas in a cyclone and most of these solids are recycled to the inlet of the vertical reactor. The gas stream then passes through an electrostatic precipitator where remaining particulates are collected.

Results from the tests show that incremental changes in SO_2 removal efficiency become more significant as the flue gas temperature in the reactor approaches the adiabatic saturation temperature of the flue gas. The overall system SO_2 removal efficiency increased from 65% to 99% as the approach to saturation temperature decreased from 40°F to 5°F.

One important aspect of the process is the ability to use recycled sorbent products. Typically, a solid particle will pass through the system about 100 times before leaving as a waste product. This circulation affords a high level of sorbent utilization and reduces operating costs. Their estimation was that a commercial GSA system would cost about 40% less than wet scrubber systems and 20% less than spray drying systems.

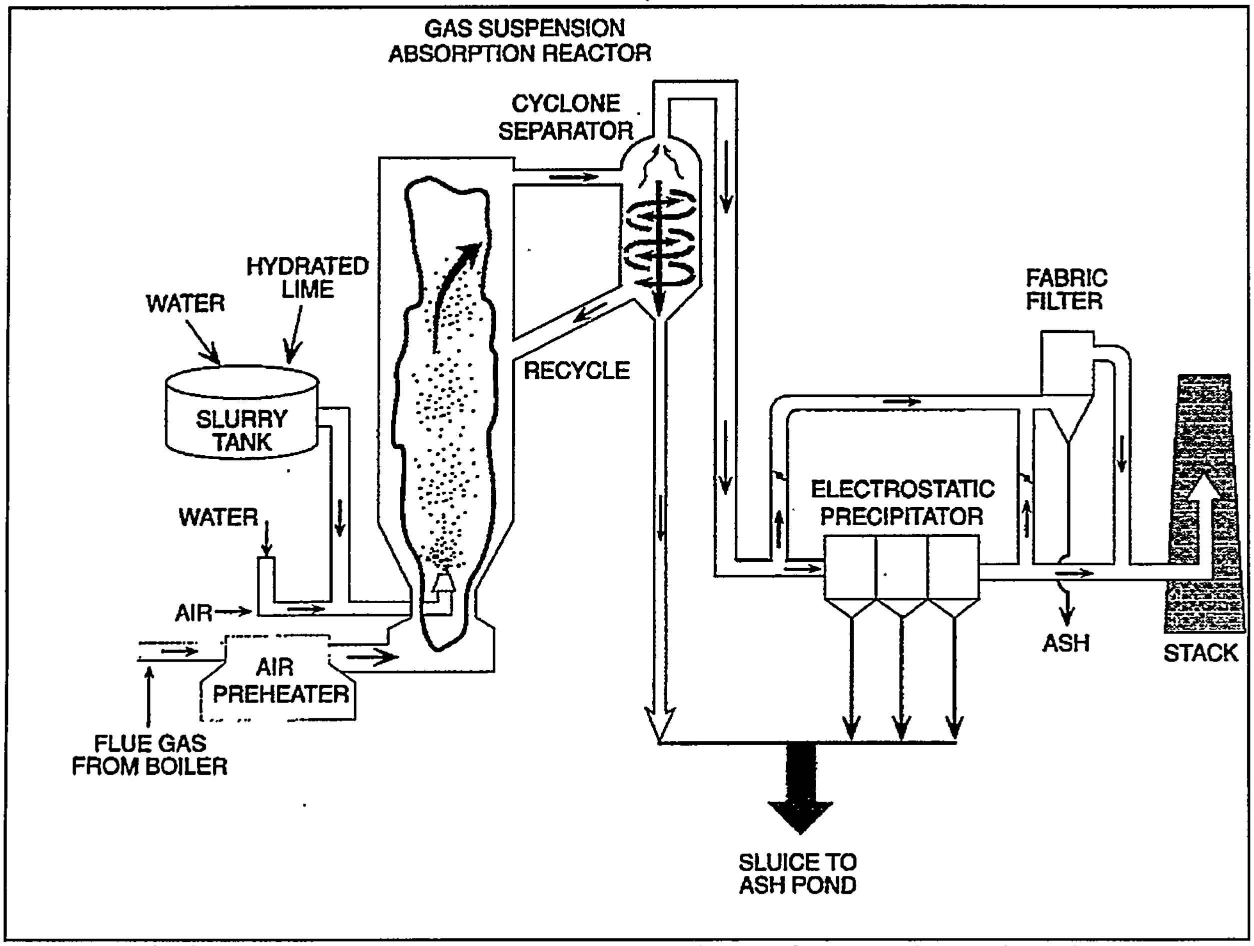


Figure 2.2 Simplified gas suspension absorption (GSA) process schematic [61].

Currently there are many new industrial processes that use the circulating fluidized bed as a key element. Table 2.2 lists the industrial applications of CFB [20]. Clearly, most applications are high temperature non-catalytic processes.

Table 2.2 Industrial Applications of Circulating Fluidized Beds.

HIGH TEMPERATURE APPLICATIONS (°C)	LOW TEMPERATURE APPLICATIONS (°C)
. Calcination of $Al(OH)_3$ (650-1450)	. Dry scrubbing of HF from Aluminum electrolysis (70)
. Pre-calcination of cement raw meal (850)	
. Calcination of phosphate rock (650-850)	. Dry scrubbing of HCl, HF, SO_2 from incinerator waste gases (150-250)
. Calcination of clay (650)	
. Synthesis of $SiCl_4$ (400)	. Desulfurization of flue gases (100)
. Low-pollution combustion of coal (850)	
. Gasification of wood and biomass (800-900)	
. Synthesis of AlF_3 (530)	

2.2 Hydrodynamics in CFB

The hydrodynamic phenomena in the CFB are still not understood, and the definition and mapping of flow regimes are not completely established. Under the current program, a number of controversial points have been raised while establishing quantitative descriptions of the flow regime, minimum fluidization velocity, and the voidage distribution.

Flow regime Although bubbling fluidization is the most published fluidization flow regime, high-velocity fluidization has been well developed in recent years, including both turbulent and fast fluidization [21,22]. Since turbulent and fast beds are fluidized at high gas velocities, they have some advantages over conventional bubbling beds. Higher gas velocity promises higher processing capacities as well as more efficient contact between gas and solid particles. In addition, it allows both coarse-sized particle systems and cohesive particles to be fluidized.

Today, many industrial CFB reactors, including catalytic cracking reactors and regenerators, are operated in the turbulent flow regimes. As gas velocity increases above minimum fluidization velocity, bubbling fluidization begins with bubbles rising and growing larger. When the gas velocity of the bed is further raised, larger bubbles and slugs break down and the motion of gas and solid particles becomes more vigorous than in bubbling fluidization. The surface of the bed is indistinguishable and the carry-over of solid particles from the top of bed increases. This is referred to as turbulent fluidization and this turbulent bed can exist until gas velocity reaches transport velocity. Beyond transport velocity, solid particles rapidly become entrained and the bed density is dependent on the feed rate of the solid particles. If the feed rate is sufficiently high, the bed will operate as a typical fast bed, having a relatively high density with considerable backmixing of solids particles. If the feed rate is too low, dilute-phase flow without backmixing of particles occurs. Figure 2.3 illustrates these fluidization flow regimes [21].

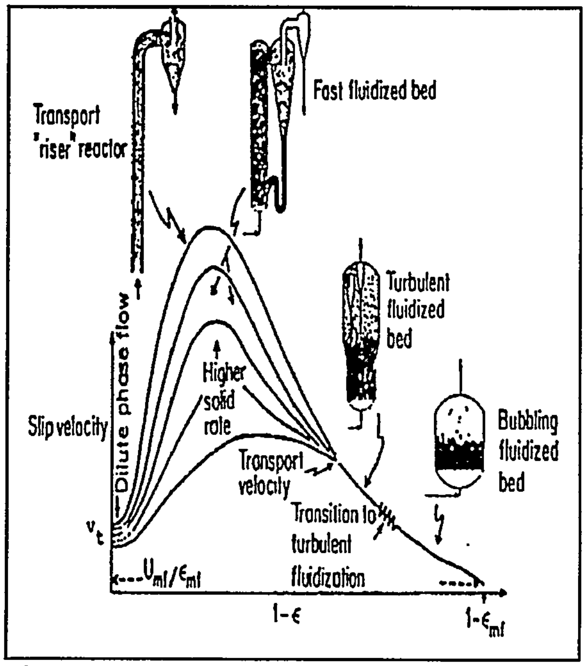


Figure 2.3 Fluidization flow regimes [21].

Lanneau [23] examined the fluidization characteristics by measuring bed density fluctuations in a bed of 0.72 m (D) x 4.6 m (H). He observed periodic fluctuations caused by bubbles passing through the tip of the probe at gas velocities between 0.15 and 0.43 m/s - a regime of bubbling fluidization. At 1.01 m/s, these periodic fluctuations disappeared and gradually changed to an "almost uniform" condition. He suggested that the change resulted from the breakdown of slugs into smaller bubbles containing a higher proportion of solid particles, and the more uniform regime beyond a bubbling fluidization promised a greater degree of interaction between gas and solid, and thus a higher mixing effect.

Turbulent fluidizations of coarse particles with sizes of 650 and 2500 μm were observed in two beds of square cross-section with dimension of 0.305m x 0.305m and 0.61m x 0.61m by Canada [24]. The turbulent bed in this case had no large bubbles and slugs but had smaller voids. Also, the bed had more extensive lateral mixing than the slugging bed. Kehoe and Davidson [25] also observed a breakdown of the slugging regime into a continuous coalescence - turbulent state. They reported that the transition to a turbulent regime occurred at a gas velocity (U_g) three times greater than the terminal velocity (U_t) of the smallest particle.

Minimum fluidization velocity, U_{mf} Several correlations derived from the Ergun equation have been used for the determination of minimum fluidization velocity, U_{mf}, as follows [26,27,28] ;

$$\text{Ergun (1952)}, \quad \frac{1.75}{\epsilon_{mf}^3 \phi_s^2} Re_{mf}^2 + \frac{150 (1 - \epsilon_{mf})}{\epsilon_{mf}^3 \phi_s^2} Re_{mf} = Ar$$

$$\text{Wen and Yu (1966)}, \quad U_{mf} = \frac{\mu}{\rho_a d_s} \sqrt{33.7^2 + 0.0408 Ar} - 33.7$$

$$\text{Babu et al. (1978)}, \quad U_{mf} = \frac{\mu}{\rho_a d_s} \sqrt{25.25^2 + 0.0651 Ar} - 25.25$$

where ε_{mf} is the minimum fluidization voidage, ϕ_s, shape factor, ρ_a, gas density (g/cm^3), ρ_s, solid density (g/cm^3), d_s, diameter of solid (cm), and μ, viscosity (g/cm/s). The Reynolds number, Re_{mf}, and Archimedes number, Ar, are defined as :

$$Re_{mf} = \frac{d_s \rho_a U_{mf}}{\mu}$$

$$Ar = \frac{d_s^3 \rho_a (\rho_a - \rho_a) g}{\mu^2}$$

Voidage distribution, ε_h ; A CFB under the turbulent flow regime has a dense region in the lower section and a dilute region in the upper section. Correlations for the vertical voidage distribution, ε_h, are given as follows [29,30];

$$\text{Li and Kwauk (1985)}, \quad \frac{\epsilon_h - \epsilon_h^*}{\epsilon_d - \epsilon_h} = \exp\left[- \frac{h - h_i}{h_o} \right]$$

$$h_o = 500 \exp [- 69 (\epsilon_d - \epsilon_h^*)]$$

$$\text{Rhodes and Geldart (1987)}, \quad U_t \epsilon_h^2 - \epsilon_h \left(U_a + U_t + \frac{E_h}{\rho_s} \right) + U_a = 0$$

where ε_d is the voidage of the dilute phase, ε_h*, voidage of the dense phase, h, height (m), h_i, inflection point in the voidage profile, ε_h, voidage at h, U_t, terminal velocity (m/s), and E_h, entrainment flux at height, h (kg/m^2/s).

2.3 CFBA Construction and Operation

For the purpose of identifying the comprehensive attrition mechanism and its effect on sorbent utilization, and investigating low temperature SO_2 removal with dry sorbent injection, a bench-scale fluidized bed unit was designed and constructed. The bench scale CFBA unit was designed similar to the pilot scale unit built earlier [9,14]. The CFBA unit is schematically shown in Figure 2.4 and is illustrated in Figure 2.5-2.8. The CFBA used for experiments consisted of a tubular reactor with a gas heating system, a sorbent injection system, a water injection system, and a gas-solid separation/recycle system. In addition, the reactor was equipped with gas sampling ports for data acquisition and monitoring of gas flow, concentration, temperature and pressure.

The diameter of the tubular bed reactor used was 0.0762 meters. It extended a total of 3 meters. It was made from two separate sections. One section was steel extending 1.83 m, and the other section was constructed from pyrex glass (1.22 m) for visual observation of the fluidization of the sorbent and the gas during experimentation. The steel and the pyrex sections were butted up against one another. At the base of the bed a woven stainless steel mesh (mesh # 70) served to distribute gas flow uniformly and also to support the sorbent in the reactor when the bed was not fluidized. At the inlet of the reactor, a heater was used to maintain a simulated flue gas temperature of 177 °C. A fluidizing gas mixture of SO_2 and air was injected at the reactor bottom before the heater. Vigorous fluidization was achieved by a high superficial gas velocity (2 - 5 m/s). The experiments were conducted using a gas mixture of 3000 ppm of SO_2 in air to simulate flue gas emissions from the combustion of Ohio high sulfur coal.

A transparent sorbent injection port was used to assure a continuous feed without clogging. Sorbent was injected through a pneumatic L-valve. A high velocity carrier gas (1~2 acfm of air) was used to carry the particles through the L-valve.

The water injection system, located just below the sorbent injection point at the bottom of bed, consisted of a specially designed pressurized spray nozzle. Its design and installation are explained in Chapter 4.

A gas/solid separation system was used to capture attritted sorbent chips elutriated out

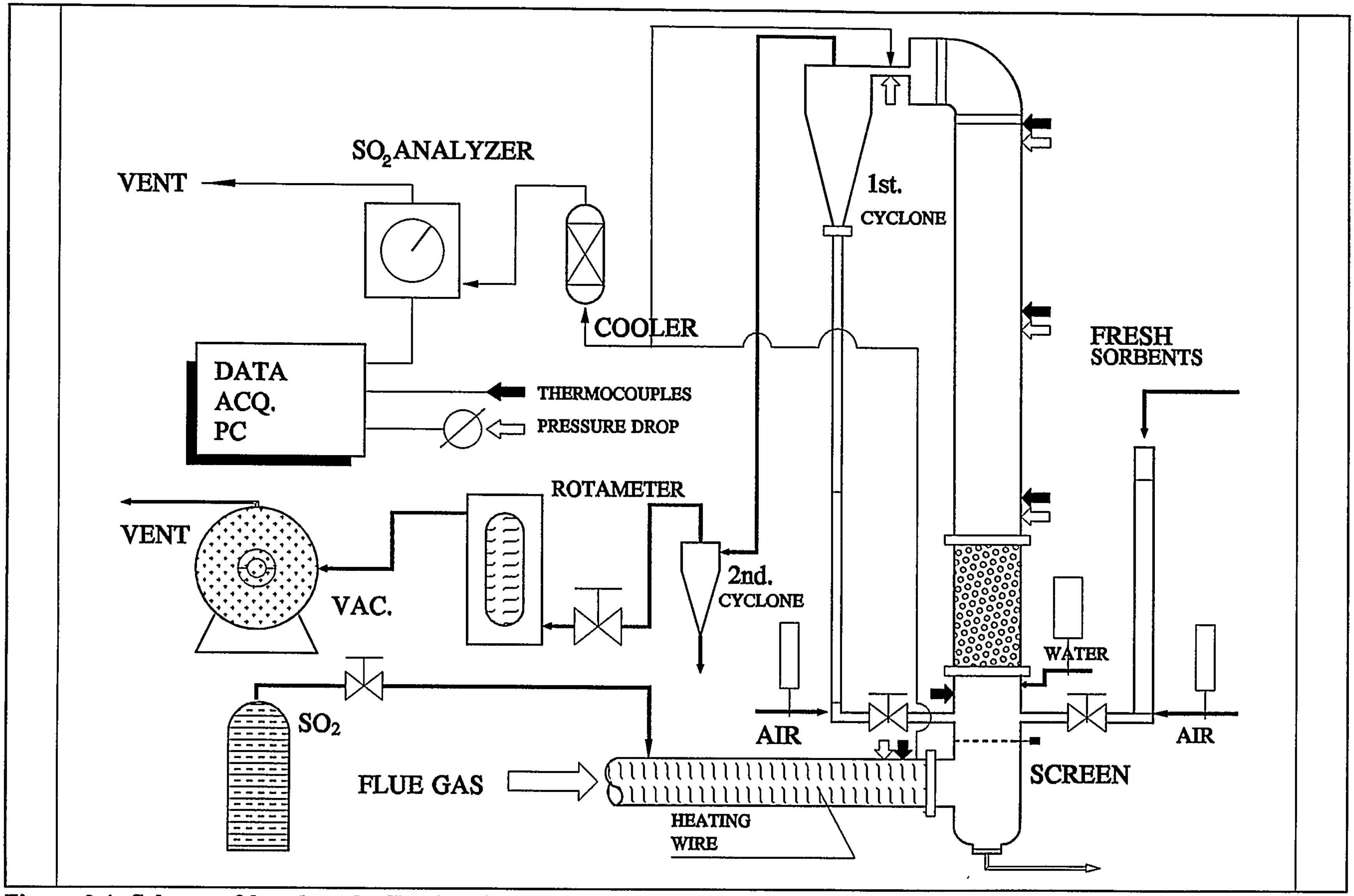


Figure 2.4 Scheme of bench scale CFBA unit.

of the reactor. The attritted pieces were entrained by the fluidizing gas flow due to their reduced terminal velocity compared to the MMD of the bed particles. The separation system consisted of two high efficiency cyclones. One cyclone was used to collect sorbent particles greater than 32 μm (cyclone diameter = 0.061 m, 99.9% efficiency), while the other cyclone was used to collect particles between 10 and 32 μm (cyclone diameter = 0.038 m, 97.9% efficiency). The collected sorbents were recirculated into the bed at the base of reactor through another L-valve port. This port was transparent to serve as a visual check to assure continuous sorbent recycle without clogging.

Sampling ports to measure SO_2 concentration were positioned at the top and bottom of the reactor. SO_2 gas concentrations were determined by monodispersive infrared analysis (Horiba SO_2 analyzer Model 2000). Pressure taps and thermocouples for the measurement of bed pressure drop and temperature were installed at equal distances throughout the height of the fluidized bed. Continuous data recording was made with a data acquisition system. The data acquisition system recorded the measured gas concentrations, temperatures, and pressures. After the CFBA unit was turned off, sorbent from the bed and the two cyclone collectors was collected and weighed to monitor attrition. Also, small samples from the bed and the two cyclone collectors were measured for total sulfur (LECO sulfur analyzer) , particle size, and degree of hydration (thermogravimetric analyzer 951 TGA, Du Pont Co.)

After its complete construction, the CFBA unit was calibrated for gas flow, sorbent injection and recirculation valves, water injection, pressure drop, etc. All the calibration results are attached in Appendix A.

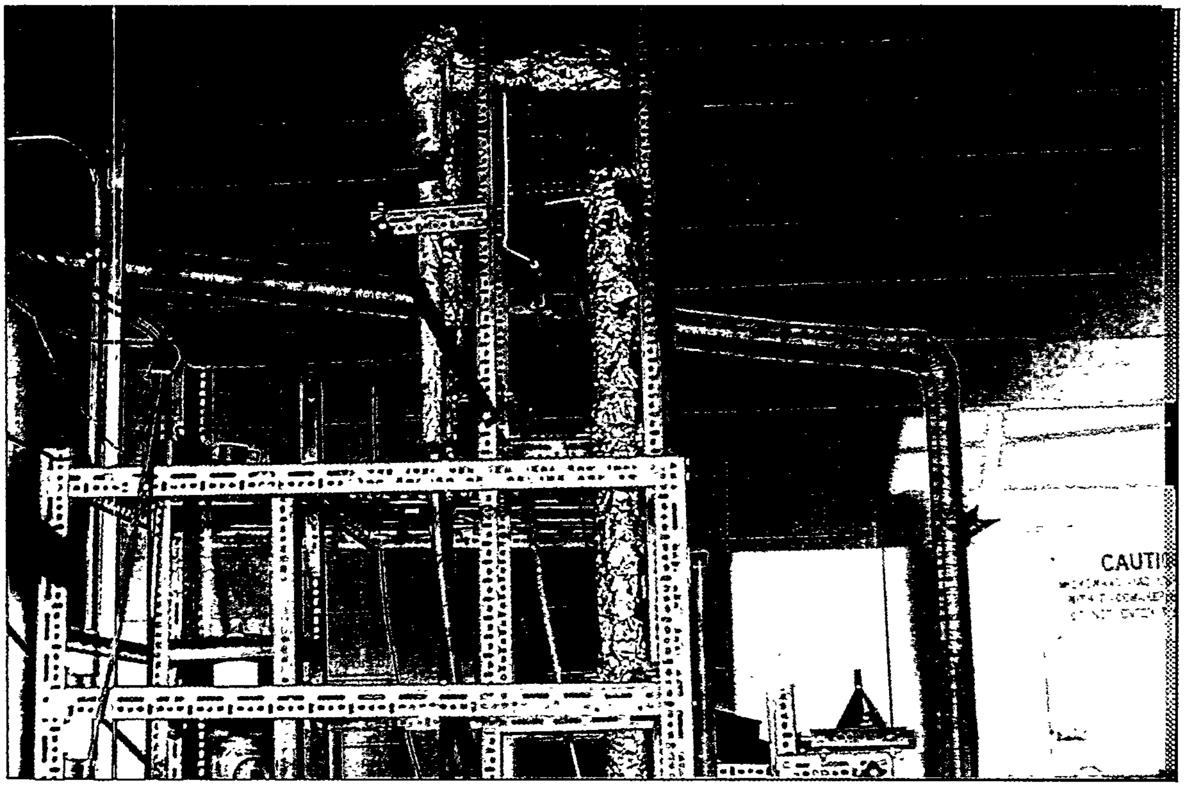


Figure 2.5 Upper part of CFBA unit.

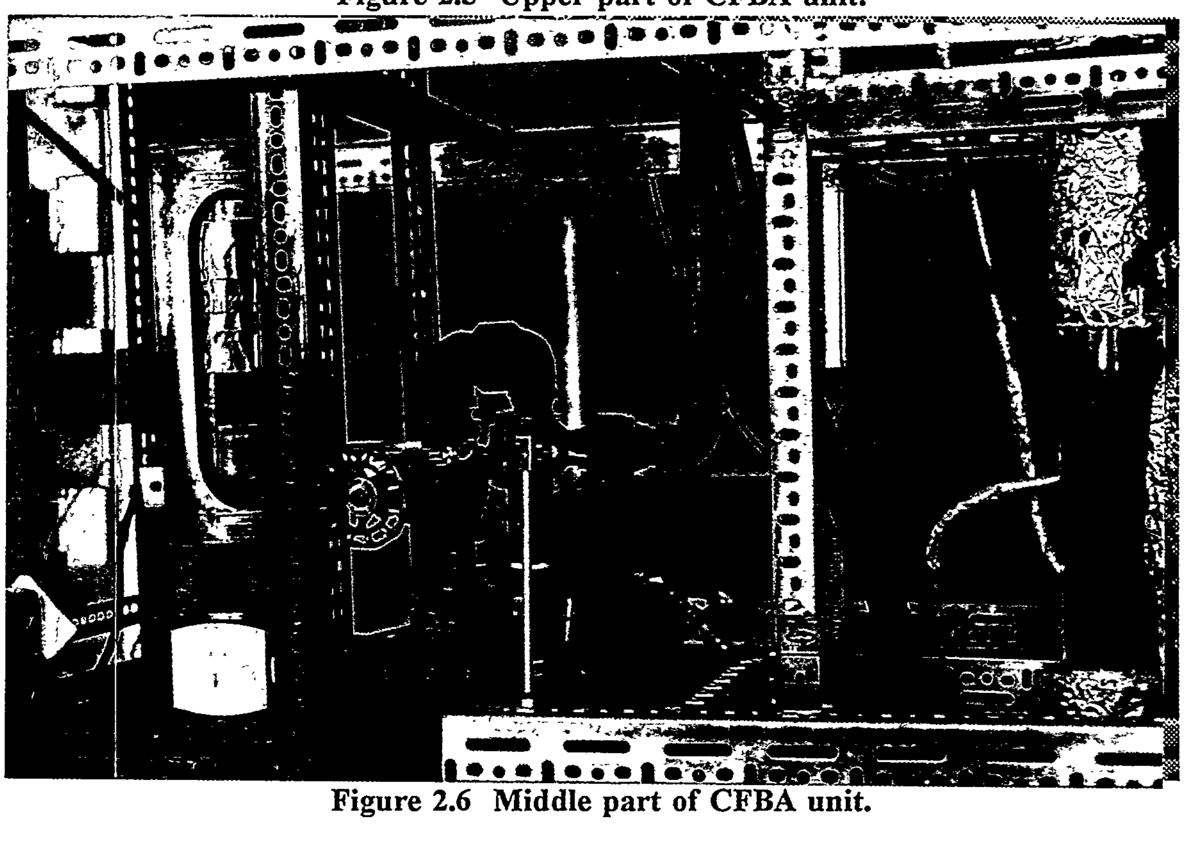


Figure 2.6 Middle part of CFBA unit.

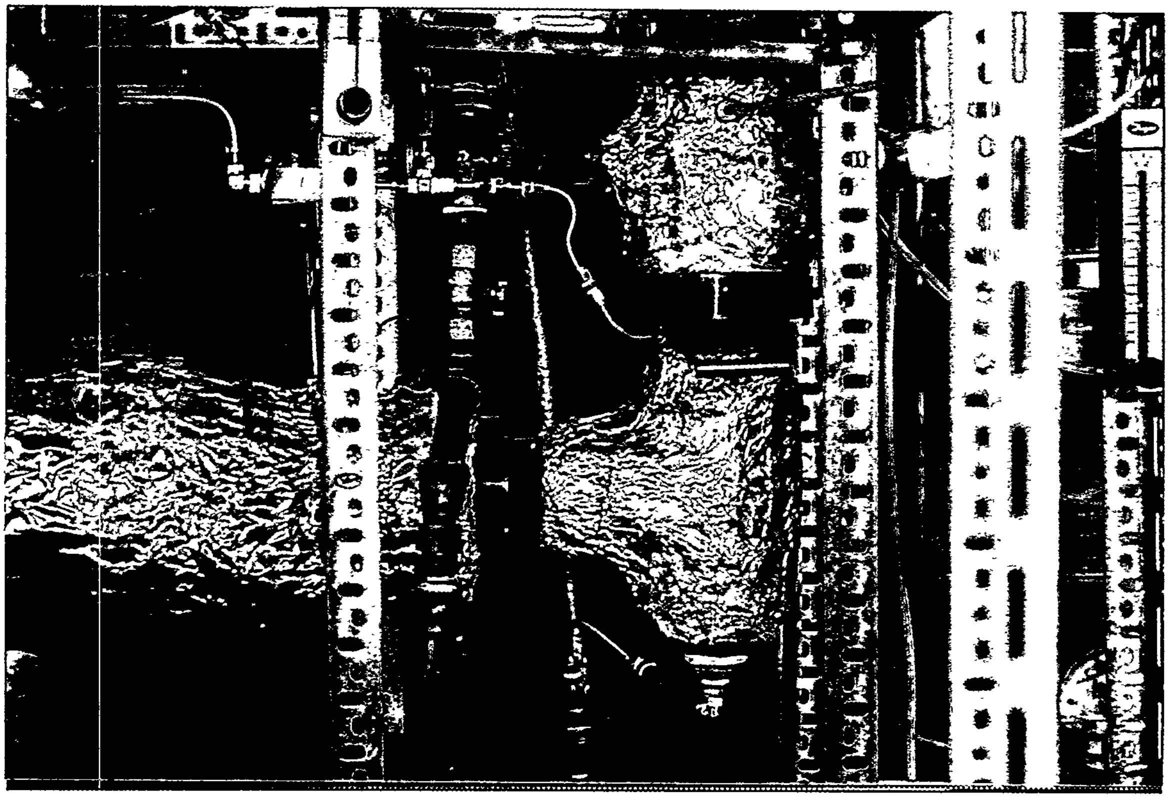


Figure 2.7 Lower part of CFBA unit.

Figure 2.8 Illustration of lime fluidization in a CFBA.

CHAPTER 3. ATTRITION OF LIME IN A CFBA

3.1 Literature Review

3.1.1 Attrition in a fluidized bed

For dry sorbent injection processes for flue gas desulfurization (FGD), a number of investigators [2,6] concluded that a primary mechanism involved in poor sorbent utilization is pore plugging. These investigators believe that pore plugging is due to the product layer formation from the gas-solid reactions between the SO_2 gas and the solid hydrated lime sorbent. Specifically, complete utilization is limited due to the product layer that plugs the pores making it impossible for SO_2 to diffuse to unreacted, unutilized sorbent beneath. The product sulfate layer formed during gas-solid reactions quickly plugs the hydroxide sorbent pores due its larger molar volume. The thin product layer of impervious material prevents the fresh portion of the solid sorbent from being exposed to SO_2.

Greater utilization of the sorbent is realized when the impervious reaction products are removed, allowing the unutilized sorbent beneath to be exposed for further reaction. A circulating fluidized bed absorber (CFBA) provides this mechanism. The CFBA is operated at relatively high fluidization velocities imposing strong fluid-induced mechanical forces sufficient to attrit the solid sorbents. Increased sorbent utilization results due to the vigorous action inside the CFB. The vigorous action continuously attrits the product layer on the exterior of the sorbent, continuously exposing fresh sorbent surface to the yet unremoved SO_2 from the flue gas.

Identifying and understanding attrition mechanisms involved in the CFBA process is of key importance in increasing sorbent utilization. For instance, during operation of the CFBA significant sorbent particle size reduction occurs due to attrition during fluidization.

Moreover, finding a means of quantifying the extent of attrition would allow for the proper design of the cyclones necessary for product recycle and wastage.

The factors which affect attrition dynamics include the properties of the sorbents (particles), the influence of the reactor environment and the types of breakage mechanics which dominate for the particle-reactor system [31]. The properties of particles such as size, surface, porosity, hardness, cracks, density, and shape strongly affect the attrition rate. Attrition rate is also dependent upon time, velocity, pressure, shear, temperature, viscosity, and turbulence in the CFBA system. In addition, the extent of attrition varies depending upon the breakage mechanism. Typically, for abrasion, the attrition rate is moderate compared to the abrasion rate from such mechanisms as shattering, fracture, and grinding.

The shape of the particle influences the behavior of the particle when subjected to external forces through the distribution of the stresses within the solid. Spherical particles are less likely to attrit than irregularly shaped particles. The size of the particle and the size distribution of the entire particle population also influence attrition. In general, larger particles are more easily attritted than smaller ones because the smaller particles possess fewer faults, flaws and discontinuities. However, there is no systematic relationship between particle size, size distribution and friability. The porosity of the particle influences its friability. In general, porous particles are more resilient than nonporous particles of similar size and thus attrit less. Decrepitation (breakdown in particle size due to internal forces, generally induced by heating) may be responsible for particle attrition of porous solids subjected to sudden extreme changes in temperature. Also, pores filled with liquids are more likely to rupture due to changes in state of the liquid caused by temperature or pressure changes. The surface roughness of the particle also affects the rate of production of fines. These fines, the characteristic product of abrasion processes, are formed from the wearing away of the surface peaks of the larger particles. The particle hardness provides a general measure of the particle's ability to resist wear and to its susceptibility to fracture [31,32].

The influence of the reactor environment [31] along with the properties of the solids, as discussed above determine the extent of attrition. The variables which have been shown to influence attrition within the reactor include reactor wall material (i.e. hard surface or soft), the time of exposure in the reactor, the particle velocity, and the system temperature and pressure. Examples of how the reactor environment influences the attrition include: in a screw conveyer used to transport powder, attrition results from the *shear* of the particles moving past one another; while in duct injection such as boiler duct injection, thermal shock may cause attrition of the sorbent due to the large temperature gradients experienced upon injection.

The mechanics which govern attrition are complex [32]. The systems of stresses and strains which act on a particle are difficult to measure quantitatively or assess qualitatively. In terms of uniaxial compression and pure shear, some methods are available for determining relative measures of strength or resistance. A number of quantitative expressions have been developed to measure such properties as the particle strength (Hooke's Law), the particle tendency to fracture through crack propagation, and the energy required to break particles (e.g. Rittinger's Law). Two areas which have not been studied as extensively are decrepitation by thermal shock and breakage by gas-solid reactions [13].

In a fluidized bed, attrition of particles has been considered as the result of disruptive stresses acting on the particles [33,34,35]. The disruptive stresses acting on the particles include the particle to particle impacting induced by the high velocity fluid dynamic stresses, chemical stresses due to chemical reactions, thermal stresses from thermal expansion and internal pressure changes. Attrition behavior in a CFBA is complicated by the simultaneous action and interactions of these combined stresses. Up to this point, no comprehensive quantitative model for assessing the attrition phenomena is available. Literature reviews [13,31] showed attrition studies have mostly been limited to special processes. Generally, the attrition studies to date have been conducted on carbon or limestone materials that do not fracture or abrade readily. In addition, the attrition models to date simply relate the size or weight reduction of particles to the energy input of the specific system.

In the literature, attrition has been studied for the application of coal in a fluidized bed combustor (FBC). Merrick and Highley [36] found that the size distribution of fines produced was approximately constant for a particular bed material. They found the final particle size distribution of fines produced by fluidization was independent of the initial particle size distribution in the bed. They also found that the final particle size distribution was independent of most of the operating conditions. Based on Rittinger's law, they developed an attrition model where the attrition of ash is proportional to the excess gas velocity, $(U-U_{mf})$, and the weight of bed material, W.

Arena et al. [37] studied bituminous coal attrition using a 140 mm ID fluidized bed combustor. The attrition effects due to excess air, bed temperature, fluidizing gas velocity and sand and coal particle size were investigated. Their results indicated that attrition of carbon in a fluidized bed combustor (FBC) is directly proportional to the product of the excess of gas velocity (above the minimum fluidization velocity) and the overall carbon surface area exposed to attrition inside the bed. They found that the attrition rate constant, particularly for the finer coal, is dependant upon the bed temperature and to a lesser extent dependant upon the sand particle size.

Chirone et al. [38] similarly investigated the generation of fines due to the abrasion of bed solids on the surface of burning particles in a 40 mm ID fluidized bed combustor (for petroleum coke batches). They found that combustion enhances attrition. From attrition curves, they found that peak attrition rate occurs between the beginning of combustion to burn-out. They related the peak of attrition rate to the opposite effects of surface activation, which leads to an increased concentration of asperities, and particle shrinkage resulting in the reduction of the surface. The attrition rate of char particles in a char/sand fluidized bed was obtained experimentally by Lin et al. [39]. They correlated the attrition rate to an exponential function as ; $k_a = 2.81x\ 10^{-3} \exp [0.162(U-U_{mf})]$.

Ulerich et al. [33] studied the attrition of limestone in the bubbling upper zone of a fluidized bed combustor. They found that the attrition rate decreases monotonically to a steady state value. They developed an equation describing the rate decrease. Also, they found that the attrition rate is proportional to the excess bubble velocity.

Shamlou et al. [35] investigated the hydrodynamic influences on particle breakage in fluidized beds and described the rate of generation of fines. They observed the continuous decrease of the agglomerates with 5 % binder concentration during fluidization at a velocity of 1.2 U_{mf}. For the bulk of the fluidized bed under low energy impact conditions, the attrition rate constant, k_a, was interpreted as a first-order dependency with respect to the excess gas velocity above the minimum fluidization velocity. But their experimental data failed to describe the high impact model developed for the distributor region.

Flamant et al. [40] experimentally correlated the kinetic, thermal and chemical attrition rate constants of $MnCl_2$ in a fluidized bed as functions of gas velocity and minimum fluidization velocity, and temperature. The results showed a smooth increase of attrition below 300 °C and a rapid increase in attrition above 300 °C. They also reported that a similar trend was observed for other materials for which the rate constants may differ. Their experiments revealed that thermal attrition was an order of magnitude larger than kinetic attrition or chemical attrition. Jiang [14] also examined the chemical attrition of limes in a CFBA with water injection. His results suggested that extremely rapid attrition, measured by bed weight loss, occurs when the bed material moisture content exceeds a certain critical level. Jiang found that the attrition resulted from wetting of the hydrated lime particles and subsequent shattering. He concluded that the lime wetting and shattering mechanism causes much more attrition than the abrasion mechanism dominant under dry conditions, and hence the attrition rate is strongly dependent upon the approach to saturation temperature under wet conditions. The correlation between the attrition rate constant, k_w under wet conditions and approach to saturation temperature, Δt, were obtained as ; $k_w = 0.021 - 0.00017\Delta t$.

3.1.2 Population models

Current industrial applications of circulating fluidized bed absorbers (CFBA) run with relatively high velocity fluidization, where strong fluid-induced mechanical forces attrit the fluidized bed particles. The attrition phenomenon are oftenly seen in many industrial applications [31]. Particle size in a reactor is significantly reduced due to attrition. The particle size reduction strongly affects on reactor performance as well as fluidizing properties of CFB.

Sorbent attrition in flue gas desulfurization (FGD) processes is beneficial because it serves to remove the reacted product layer from the sorbent. The composition of the fines generated by attrition is primarily reacted sorbent product sulfate, and these fines are then carried out of the bed by elutriation. As a result, sorbents left in the bed can have fresh unreacted surfaces continuously in contact with the surrounding SO_2.

The changes in particle size distributions of bed materials, as well as the attrition mechanism, should be identified and characterized in order to operate a fluidized bed optimally. Most fluidized bed performance variables, such as minimum fluidization velocity, terminal velocity, elutriation rate, chemical reaction rate, etc., are strongly dependent upon the size of the bed solids [41,42].

The size changes during fluidization may be predicted by a population balance model, which has been developed and applied by others [43,44,45,46,47,48]. Levenspiel et al. [43] developed a population model based upon a mass balance. This model relates the bed particle size distribution, as a function of time, to the feed rate and the outflow. The model takes into account the size distribution of feed solids, arbitrary particle growth or shrinkage within the bed, and the effect of elutriation on the properties of both outflow and carryover under steady state continuous fluidization. It is applicable for continuous operation of circulation systems where solids grow in one unit and shrink in the other.

Grimmett [44] suggested that the rate of attrition as a function of particle size and the various operating parameters should be developed for the more accurate prediction of the particle size distribution in a fluidized bed process. He particularly emphasized that study of attrition would yield valuable information to the field of fluidized bed technology. He presented a general mathematical model which describes particle dynamics in fluidized bed processes. The model developed for fluidized bed calcination processes includes the various rates of particle growth, particle attrition, elutriation of particles from the surface of the bed, and particle feed to the bed. The model uses a partial differential equation to express the particle size distribution in the fluidized bed as a function of size and time. His numerical solutions of this elutriation model were consistent with his actual observations.

Chen and Saxena [45] developed a mechanistic model applicable for noncatalytic gas-solid reactions in bubbling fluidized beds. The model describes a general steady state population balance. While the other models consider only the particle size changes, this model incorporates both particle size and particle density (due to chemical reaction) changes. Unfortunately, this model does not consider the particle size decrease due to attrition ; however, particle size decrease due to a shrinking chemical reaction is considered.

Stecconi [46] modified Chen and Saxena's model to incorporate particle size decrease by attrition. His model considers chemical reaction together with attrition by superficial abrasion. The assumption that the attritted solids are fine and immediately elutriated is used for this model. The solid feed is considered in terms of a distribution as a function of size and fractional conversion. The model may be extended to reactor-generator systems which are typical of many catalytic reactions.

Overturf and Reklaitis [47] also developed a particle balance model which accommodated the particle distributions dependent on both size and density. However, their model included populations consisting of multiple solids. The particle balance is imbedded within a nonisothermal Davidson-Harrision bubbling bed model which includes both grid and freeboard region compartments. Comparison of the model to experimental results obtained from the fluidized bed combustor of Babcock and Wilcox was made, and its results suggested that satisfactory modelling of the combustors required a more reliable prediction of singleparticle elutriation rates.

Ray and Jiang [48] represented a steady state population model, considering the effect of the fines generated in the fluidized bed particle mixtures, while Stecconi [46] assumed the fines are immediately blown out. In the model, the evolution of the attritted fines was more realistically assessed so that the possible effects of fines on the attrition and reaction were considered. They introduced a surface-reaction model under many assumptions in order to assess the effect of fines on attrition rates of a multicomponent mixtures, and stated that the attrition rate for each component is proportional to its surface area, and is also a function of the interactions between different materials. The population model combined with the surface reaction model which describes the effect of fines on the attrition and reaction, however, was not verified experimentally.

3.2 Experimental Approach

3.2.1 Preparation of lime samples

High calcium quicklime, CaO, supplied by Dravo Lime Company was the fluidized sorbent studied. Two particle size ranges were used in the experimental studies. A pulverizer (BICO Co.) was used to crush the as received lime (1.3 cm particles) into two particle size ranges, Lime 1 and Lime 2. Lime 1 was pulverized to a mass mean diameter (MMD) of 903 μm. Lime 2 was pulverized to a MMD of 1764 μm. Figure 3.1 shows the resulting narrow particle size distributions after pulverization for Lime 1 and Lime 2. Tables 3.1 and 3.2 summarize the measured physical and chemical properties of the lime used. The lime was processed by Dravo, the manufacturer from limestone, $CaCO_3$, by calcination. The available lime was measured as 90%, and a slaking test confirmed the high reactivity of the lime. Pore size distribution of the Dravo Lime was also measured with Micrometrics Poresizer 9310 and the results are illustrated in Figure 3.2. Other information obtained from the porosimeter is given in Appendix B.

Table 3.1 *Physical Properties of Lime Samples.

SAMPLE NUMBER	MASS MEAN DIAMETER (MICRONS)	SURFACE MEAN DIAMETER	SPECIFIC BET SURFACE AREA (M^2/KG)	BULK DENSITY (KG/M^3)
Lime 1	**903**	**820**	**1.36×10^3**	**1.28×10^3**
Lime 2	**1764**	**1682**	**1.27×10^3**	**1.45×10^3**

* Measured

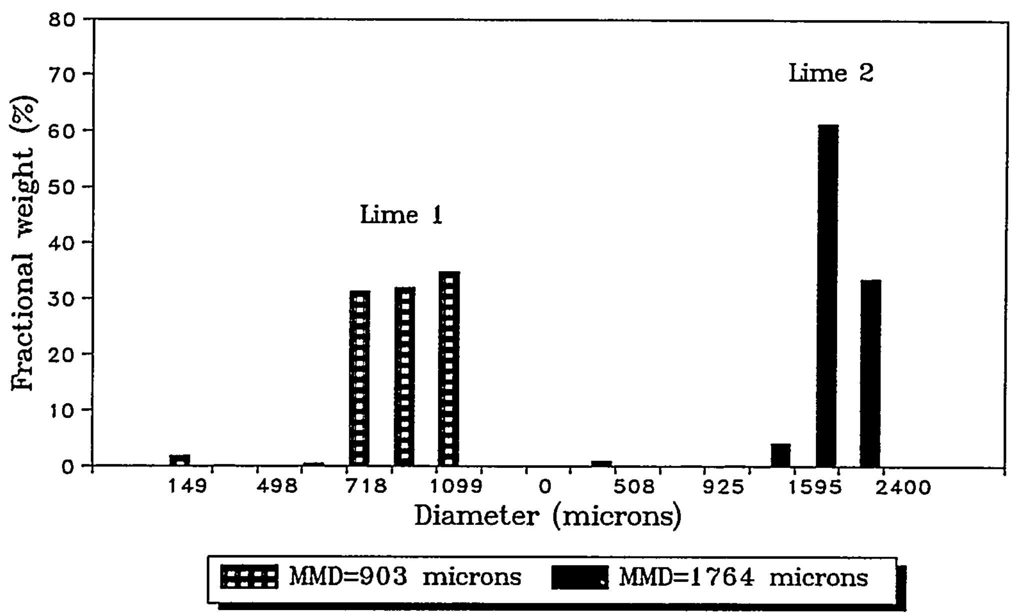


Figure 3.1 Size distributions of lime samples.

Table 3.2 **Chemical Properties of Lime Samples.

CHEMICAL COMPONENTS	WEIGHT %
Total CaO	93
Available CaO	87.5-88.5 (95*)
MgO	2.65-2.75
Sulfur	0.045-0.050
$CaCO_3$	1.1-1.2
H_2O	0.4
SiO_2	1.95-2.05

* Measured

** Obtained from Dravo Lime Co.

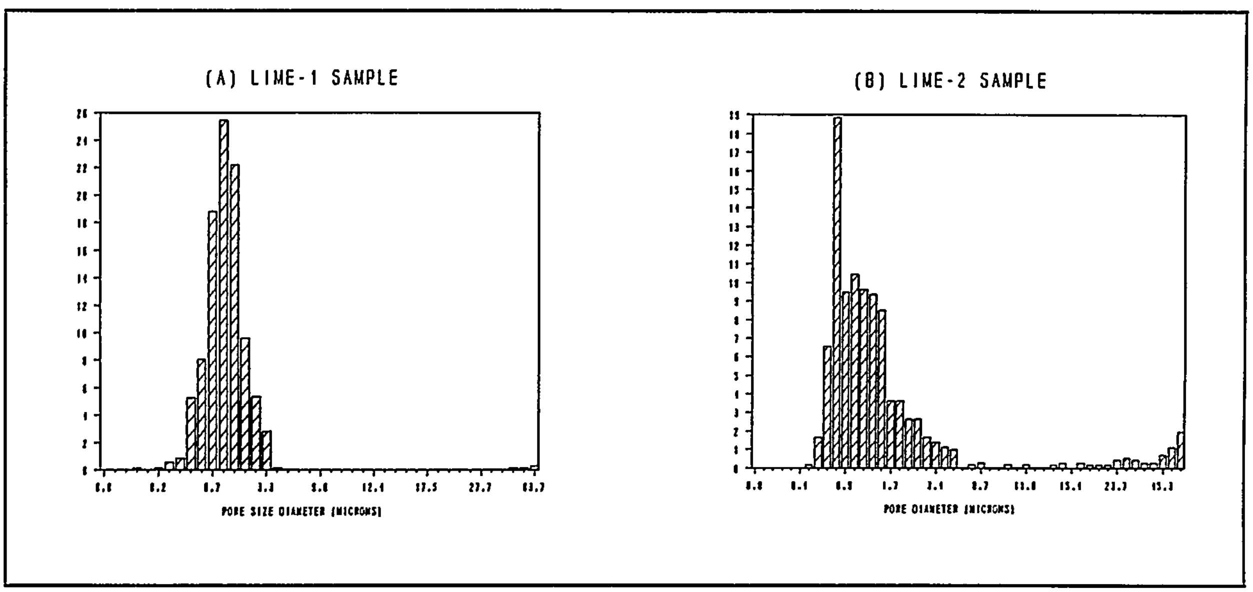


Figure 3.2 Pore size distributions of lime sample

3.2.2 Experimental Procedures

Attrition tests were carried out in a bench-scale CFBA unit as shown in Figure 2.3. Dravo limes of 1764 μm (lime 1) and 903 μm (lime 2) in mass mean diameter (MMD) were injected into the CFBA. Air was used as the fluidizing gas at superficial gas velocity of 2 m/s for lime 2 and 3 - 5 m/s for lime 1, respectively. Since the gas velocities were much less than the lime terminal velocities (10 m/s for lime 1 and 8 m/s for lime 2), no elutriation of the parent solids was expected during fluidization. All bed weight reduction was attributed to attrition. The gas temperature was kept constant at 20 °C for the mechanical attrition studies. Thermal attrition was studied by running individual runs at different temperatures ranging from 65 °C-177 °C. During all of the runs, the gas velocity and temperature was held constant .

For an attrition test, 0.5 kg of lime was injected so that the initial pressure drop in the bed reactor reached about 15.24 cm H_2O. During the test, the recirculating valve was closed to prevent the attritted fines from reentering the bed. The attritted fines were captured by the first cyclone. At regular time intervals (30 min.- 20 hours), the fluidization was turned off, and all the samples were taken immediately from the bed and the first and second cyclone. And then another attrition test was repeated for a longer time period. The collected samples were weighed and used as a measure of the extent of attrition. The size distributions of bed materials and fines attritted were also measured by a sieving method and a Coulter counter (Model TA II, Coulter Electronics, Inc.), respectively. In addition, the samples taken were visually observed through a microscope. An image analysis system was used to enhance and assess the particle shapes. Detailed explanations for analytical methods are given in Appendix B.

3.3 Results and Discussion

3.3.1 Experimental results

Attrition tests at room temperature were carried out with lime samples in a CFBA in a batch mode to see the fluid-induced attrition tendency. The fluidizing gas was air with superficial velocities from 2 to 5 m/sec. Figure 3.3 shows the typical bed weight reductions of the parent solids with a MMD of 1764 μm due to attrition during fluidization in CFBA. The weight reduction occurs rapidly at the beginning of fluidization, continues, and finally levels off to reach a minimum weight, W_{min}, after 15 hours. A similar trend was also noted by Shamlou et. al. [35] and Chraibi and Flamant [40] for the attrition of agglomerates prepared from narrowly classified soda glass beads, and manganese chloride particles,

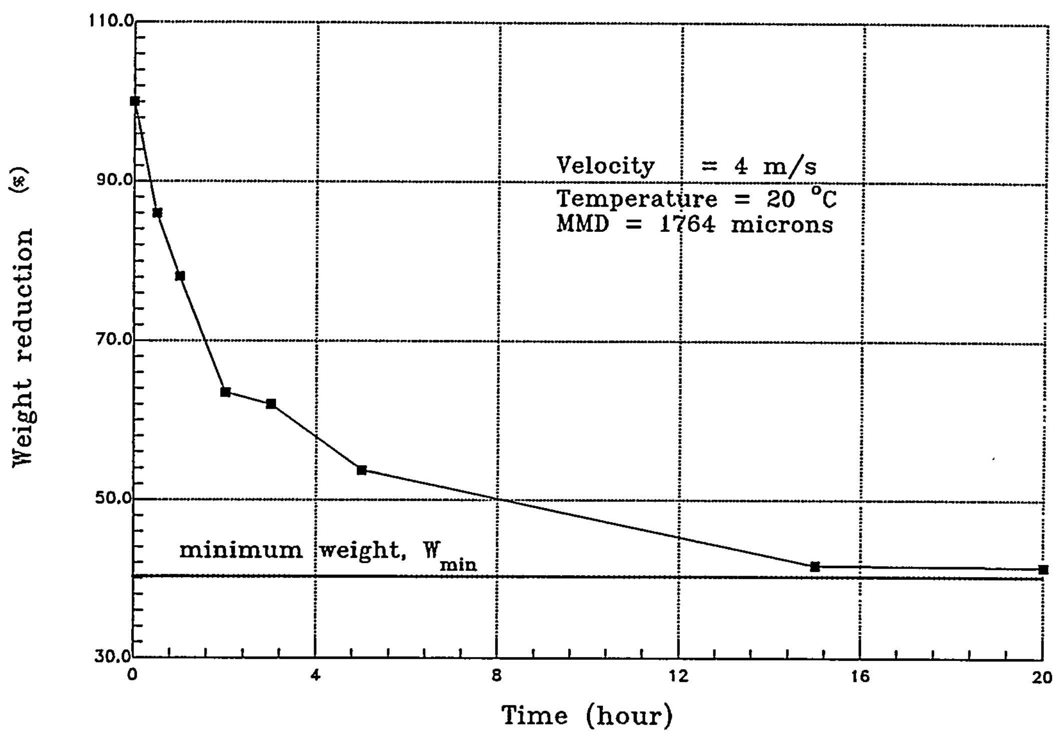


Figure 3.3 Typical attrition tendency of lime in a CFBA.

respectively. All other attrition tendencies obtained from attrition tests in CFBA closely follow the trends as shown in Figure 3.3. The results clearly imply a rounding off of the sharp edges and corners of the particles during initial fluidization, and a surface abrasion process at later fluidization.

The sharp edges gradually disappear, maintaining the same sphericity, and the surface becomes rougher and rougher due to collisions with time. The BET surface area of the parent solids, as shown in Figure 3.4, appeared to increase slightly due to collisions as the fluidization continue, and thus indicates that the surface of the parent solids became rougher while the appearance seemed to be smoother.

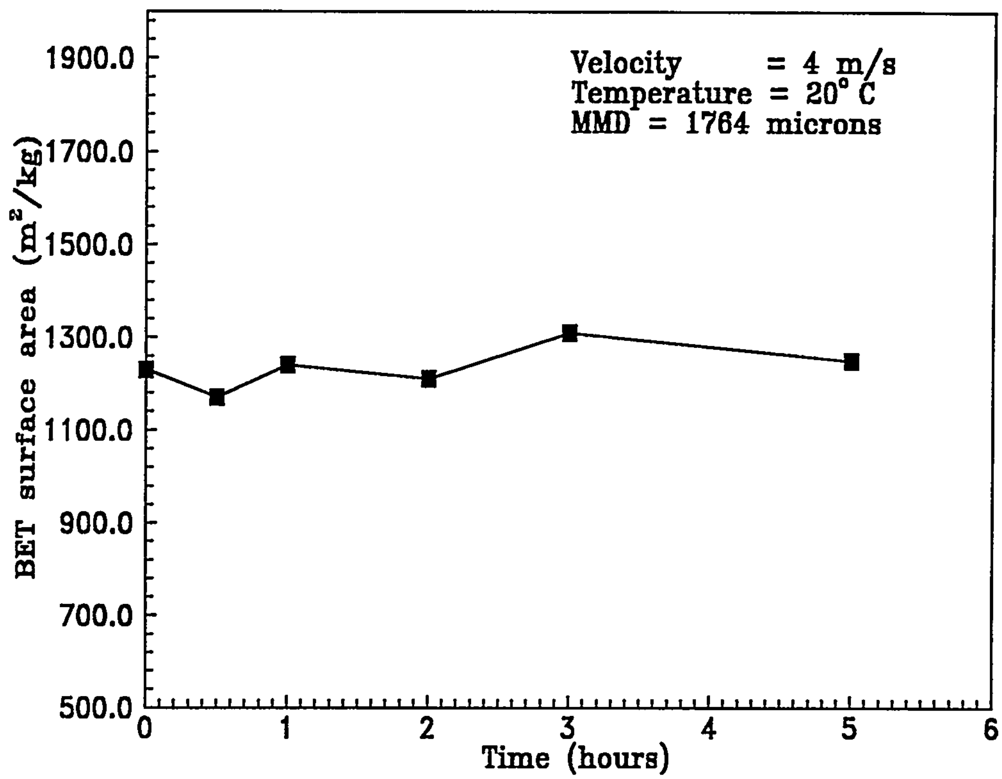
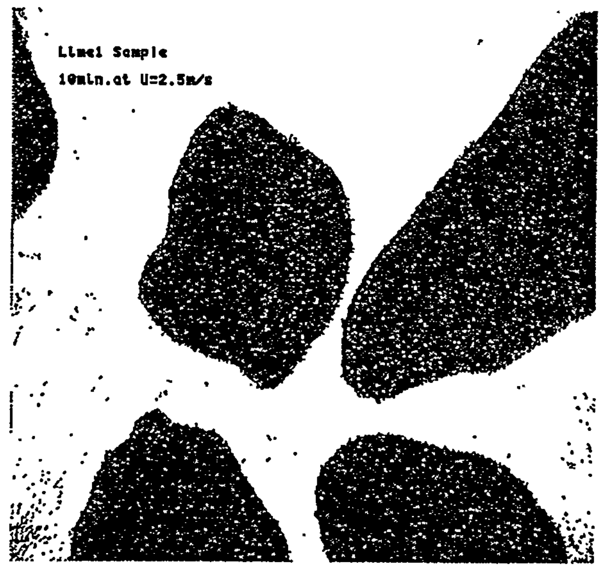


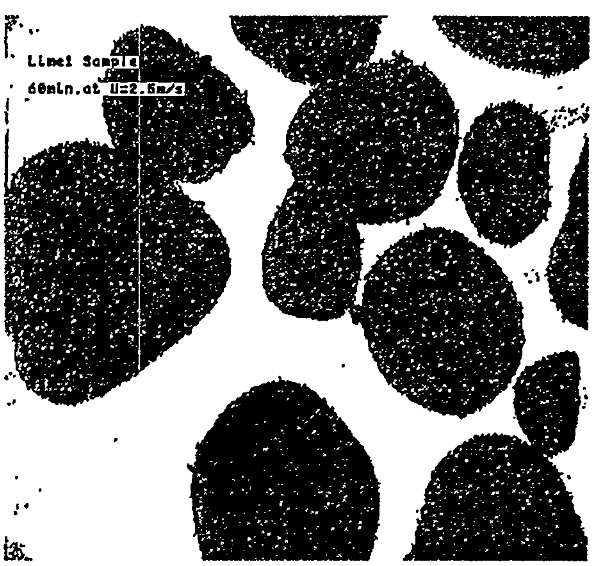
Figure 3.4 Effect of attrition on BET surface area of lime.

(a) Raw lime samples

(b) Limes after 10 minutes attrition



(c) Limes after 60 minutes attrition



(d) Limes after 300 minutes attrition

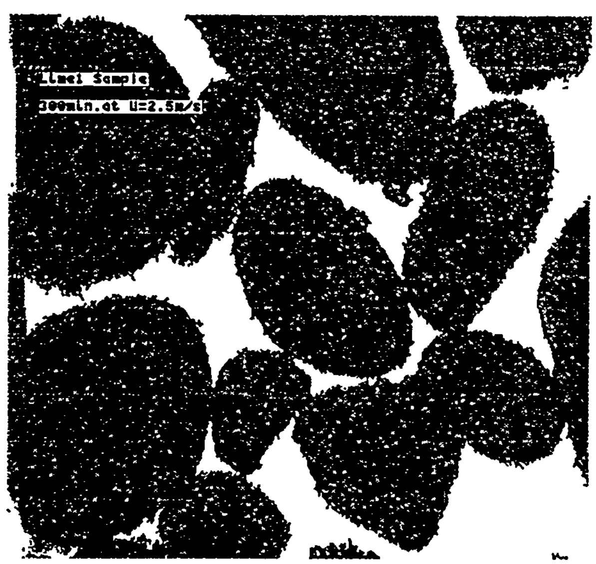


Figure 3.5 Microscopic observations of parent solids after fluidization in CFBA.

The rounding off and surface abrasion of bed materials were also observed with a microscope as illustrated in Figure 3.5. Figure 3.5 shows the rough and irregular surface of the raw samples and the abraded surface of the parent solids after 10 minutes, 30 minutes, 1 hour, and 5 hours of fluidizations with a superficial gas velocity of 2.5 m/sec.

The measurements of size distribution of fines attritted and sphericity of the parent solids are shown in Figures 3.6 and 3.7. The size of fines abraded and captured by cyclones and filter during fluidization ranged between the least MMD of 6.5 µm at the filter and the largest MMD of 11.3 µm at the second cyclone, and the sphericity of the parent solids appeared to remain constant with time. The results, as well as the visual observations clearly indicate that the predominant mechanism of lime attrition is surface abrasion resulting from collisions of the parent solids in the bed during fluidization.

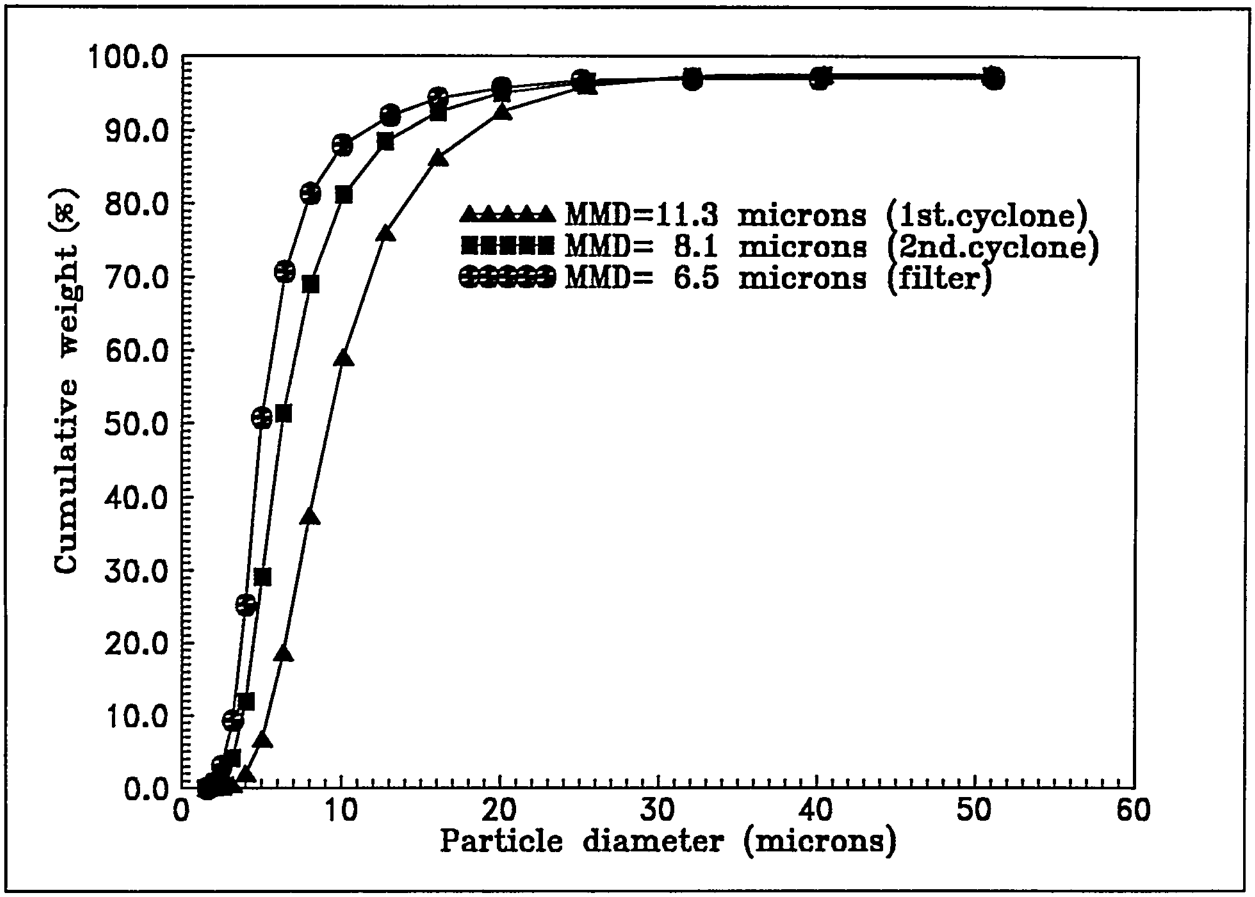


Figure 3.6 Size distributions of fines collected by cyclones and filter.

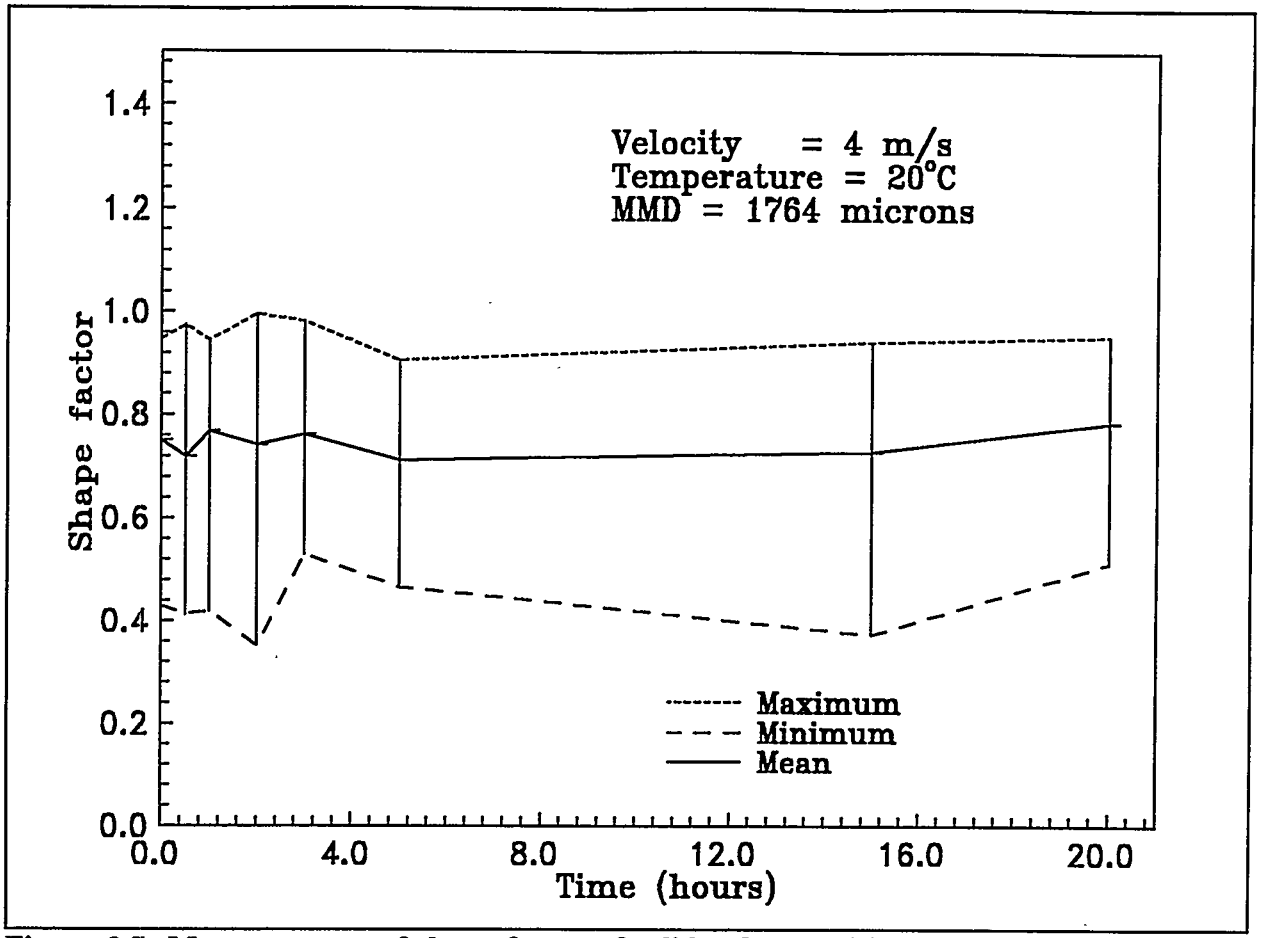


Figure 3.7 Measurements of shape factor of solids after attrition.

The effect of initial solid concentrations on the attrition is shown in Figure 3.8. The measurements were obtained with a gas velocity of 4 m/s for lime 1 and 2 m/s for lime 2. Evidently, the attrition increases proportionally due to collisions of the parent solids until the initial solids concentrations reaches a critical point. After the critical point, $C_{s,crit}$, attrition appeared to be constant with regard to solids concentrations in the bed. Therefore, the following conditions exist;

at $C_s < C_{s,crit}$ k_a is a function of the mass of bed materials

at $C_s \geq C_{s,crit}$ k_a is independent of the mass of bed materials

where C_s is solid weight (kg/m^3), and k_a is the attrition rate constant (sec^{-1}) but may be a function of the type of solids and fluidizing parameters.

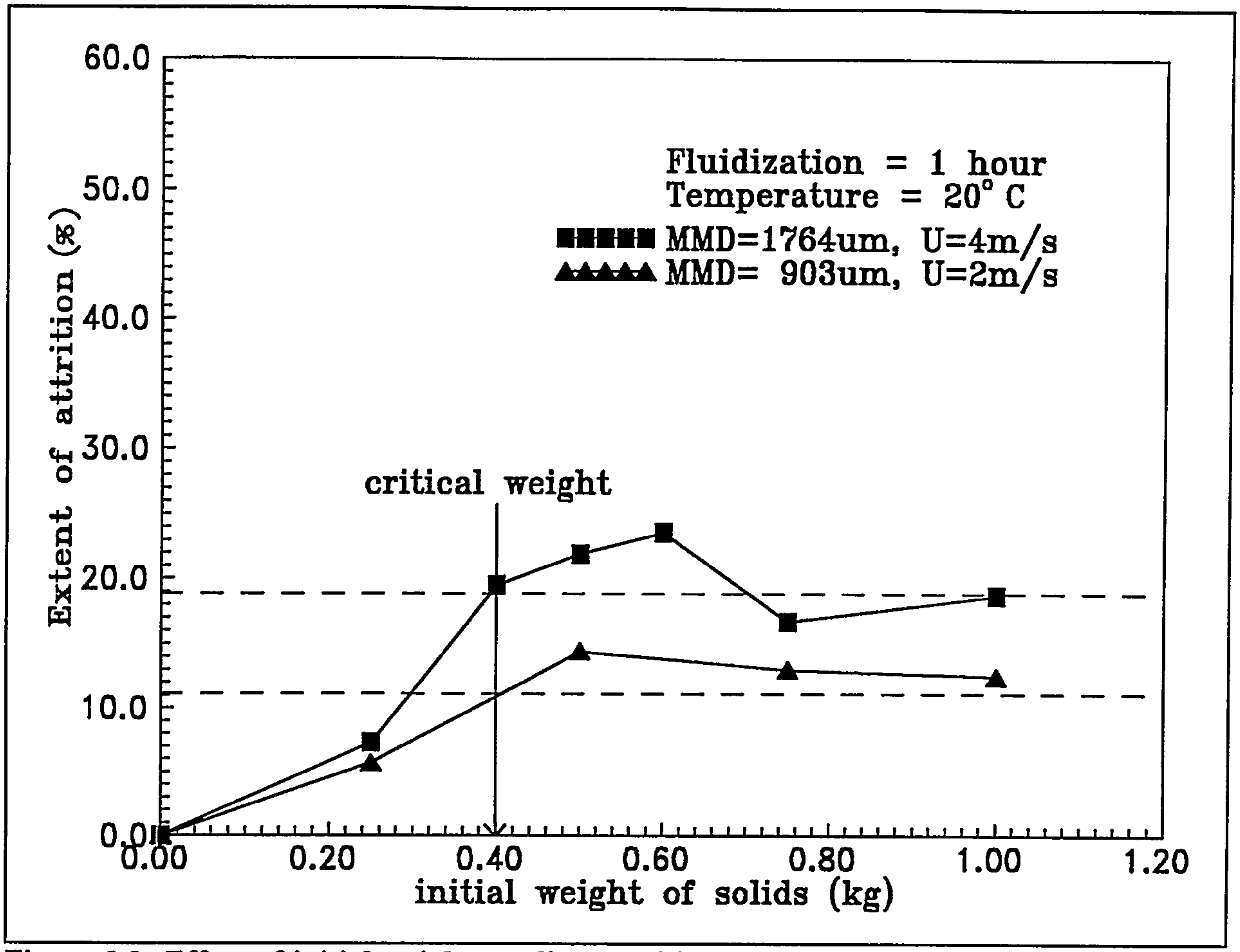


Figure 3.8 Effect of initial weights on lime attrition.

The effect of gas velocity on attrition during fluidization is illustrated in Figure 3.9. Figure 3.9 shows that as the gas velocity increases, the extent of attrition significantly increases. The extent of attrition is defined as ;

$$X_a = \left(1 - \frac{W}{W_o}\right) \times 100 \tag{7}$$

where x_a is the extent of attrition of lime (%), W is the weight (kg) of parent solids in a bed measured at time t (sec), and W_o is the initial weight (kg).

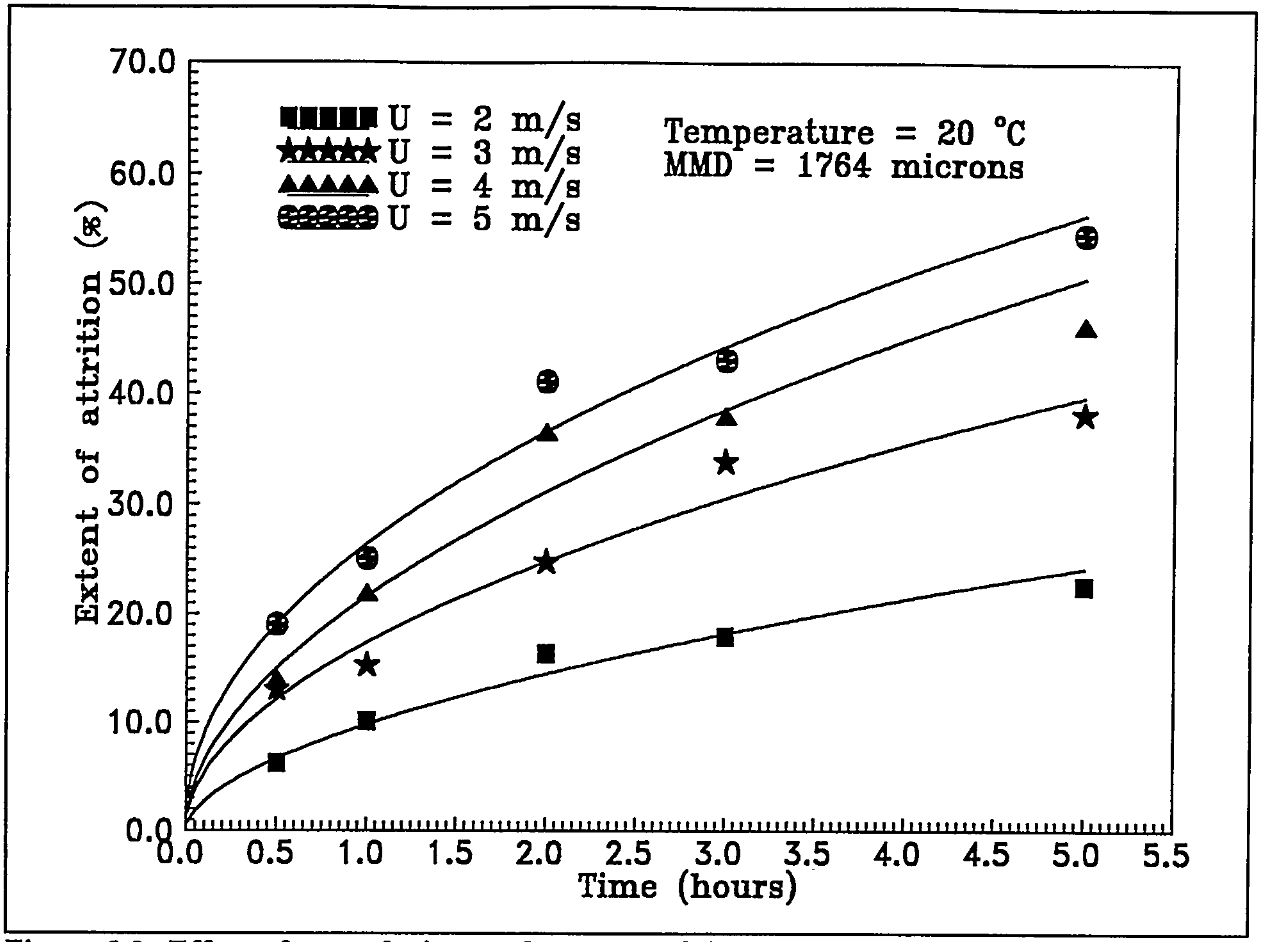


Figure 3.9 Effect of gas velocity on the extent of lime attrition.

Since temperature affects the properties of solid sorbents, such as hardness and density, as well as those of the fluidizing gas, some solids may be easily attritted at low temperature, or others may soften or become brittle at high temperature. Flamant and Chraibi [40] observed a slightly increasing attrition rate of manganese chloride particles with rising temperatures to 300 °C. Ulerich et al. [33] also found that as temperature increased to 815 °C with a heating rate of 400 °C/min, the rate of limestone attrition increased. They suggested that the strength of limestone decreases at higher temperatures and leads to the higher rate of limestone attrition during calcination of the limestone. But lime is extremely hygroscopic and absorbs moisture from the air to become hydrated lime, which has a hardness that is less than that of lime. As the temperature increases, hydration may slow due to the evaporation of moisture, and thus lime may become less fragile. In addition to hydration, recarbonation of lime occurs rapidly at room temperature in the presence of moisture. The recarbonation can occur slowly in arid climates of 15 % relative humidity, even though the volume of CO_2 in the atmosphere is only about 0.03 % [49]. Also, the surface layer of hydrated lime may react at higher rates with ambient CO_2 concentrations at higher temperature, providing a more dense layer of carbonate which will tend to retard attrition. The carbonation hardens the lime, while the reaction rate accelerates with the rising temperature. Therefore, the thermal attrition of lime may be different from the common attrition trends observed by others.

The temperature effect on lime attrition during fluidization is represented in Figure 3.10. It clearly shows that the extent of lime attrition exponentially decreases as temperature increases up to 177 °C. The results suggest that the thermal attrition of lime may strongly depend on the hardness changes due to carbonation and hydration, rather than the

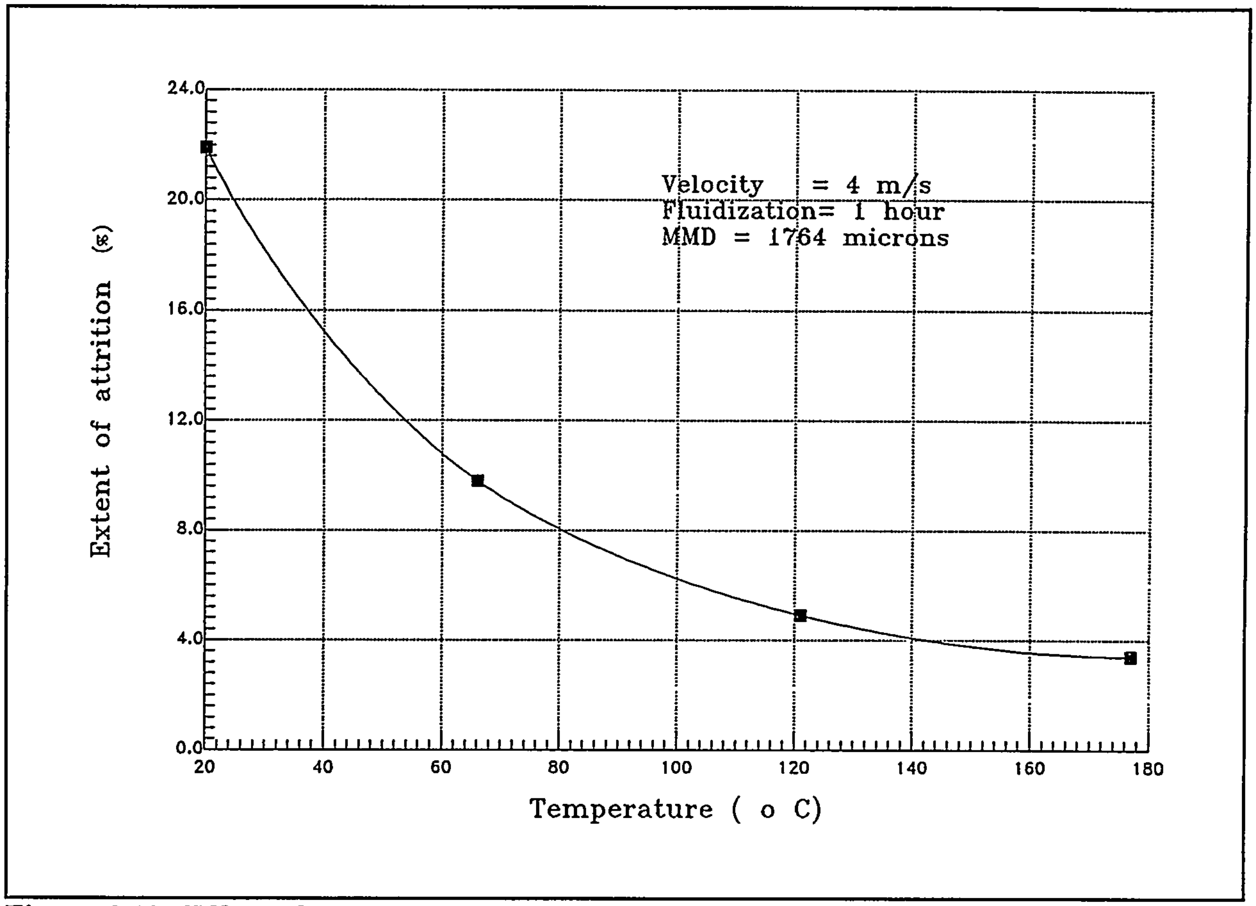


Figure 3.10 Effect of temperature on lime attrition.

decrepitations resulting from the increase of internal pressure with rising temperatures as observed commonly in such solids as limestones and coals.

3.3.2 Development of attrition model

The experimental data presented in Figure 3.3 suggest an exponential decrease of the weight of parent solids in a bed during fluidization. Other investigators [14,35,39] have applied a first order attrition model to estimate the weight changes of bed materials in a fluidized bed, but the extent of attrition obtained experimentally did not follow exactly the attrition model for longer operations than 1 hour.

Based on these findings, a first order attrition model considering the minimum weight as shown in Figure 3.8 is suggested as followings :

$$\frac{dW}{dt} = -k_a(W - W_{min}) \tag{2}$$

where W is the weight of the parent solids in the bed (kg), W_{min} is the minimum weight below which attrition may be essentially negligible , and k_a is the attrition rate constant (s^{-1}). Integrating Equation (2) with the boundary conditions of $t=0$, $W=W_o$, and $t=t$, $W=W$, gives;

$$\ln\left(\frac{W - W_{min}}{W_o - W_{min}}\right) = -k_a t \tag{3}$$

The attrition rate constant, k_a, therefore, can be obtained from the slope of the curve produced by plotting $\ln[(W-W_{min})/(W_o-W_{min})]$ versus time, t. The results are shown in Figure 3.11 for fluidization times to 5 hours. The attrition rate constants, k_a, obtained from the curves are 0.0018 sec^{-1} for 2 m/sec, 0.0038 sec^{-1} for 3 m/sec, 0.0055 sec^{-1} for 4 m/s, and

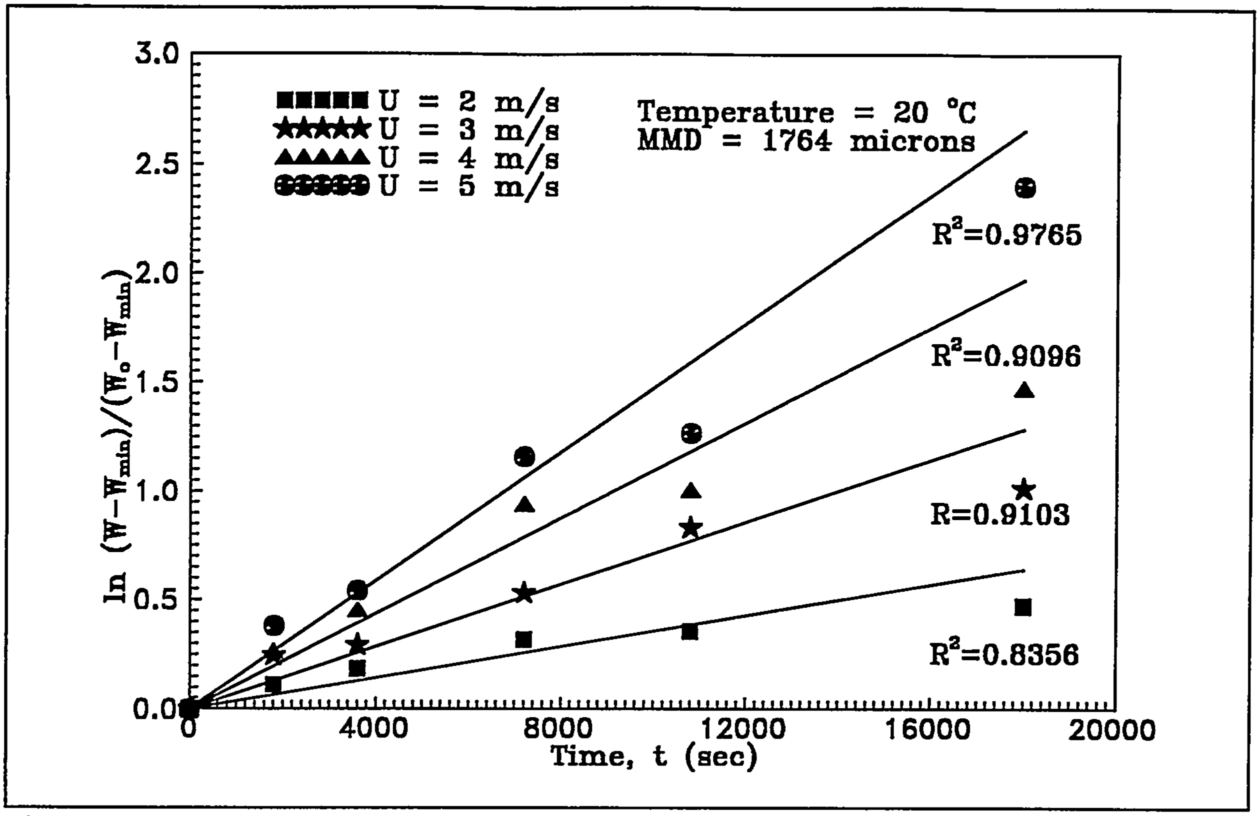


Figure 3.11 Attrition rate constants of lime at different velocities.

0.0080 sec^{-1} for 5 m/sec.

The attrition rate constant, k_a, depends upon the fluid-dynamic induced forces acting on the particles. The attrition rate has been assumed to be directly proportional to the excess energy of the gas above the minimum fluidization velocity by many investigators [36,39,40], or related to the energy transformation from the fluid to the particle [35,41,48]. For fluid-dynamic induced attrition only, attrition may be proportional to the excess energy, E_{exc}, which is defined as :

$$E_{exc} = A(U - U_{mf})\Delta p = W g \ (U - U_{mf}) \qquad (4)$$

where A is the cross sectional area of the reactor (m^2); U, the superficial gas velocity (m/sec), and U_{mf} is the minimum fluidization velocity (m/sec); W, the weight of parent solids in a bed (kg); Δp, the total pressure drop of the bed (kg/m·sec^2); and g, the gravitational constant (m/sec^2). When the superficial gas velocity, U, equals to or becomes less than the minimum fluidization velocity, U_{mf}, attrition may be neglected. But such an assumption may not be reasonable for cases where the attrition process still occurs by chemical reaction or thermal attrition, even when the gas velocity equals to or is less than the minimum fluidization velocity.

Since the rate of attrition increases rapidly with rising gas velocity, as shown in Figure 3.9, and the relative effect of an increase of gas velocity diminishes as the temperature is raised, it is suggested that the relationship between the attrition rate constant and the gas velocity may be expressed as an Arrhenius form. Moreover, the gas velocity may be expressed in terms of the energy supplied by the fluidizing gas into a bed reactor. Thus, the attrition rate constant in an Arrhenius form is written as :

$$k_a = k_o \exp\left(- \frac{E_a}{\psi} \right) \tag{5}$$

where E_a is the pseudo attrition activation energy (kJ/kg), ψ is the energy supplied by the fluidizing gas to the dense zone per unit mass of the solids in the dense zone (kJ/kg), and k_o is the frequency factor which does not affect the gas velocity sensitivity of attrition rates. The activation energy, E_a, represents the quantity of energy required to activate 1 kg of parent solids to a state sufficiently above the average energy level of the solids for which attrition may occur. The ratio of the energy supplied by the fluidizing gas to the mass of parent solids, ψ, is defined as :

$$\psi = \frac{\text{Energy supplied by the fluidizing gas}}{\text{Mass of parent solids in a bed}}$$

The energy supplied in the dense zone, ρ, is the total fluid energy above the condition of minimum fluidization, and is given by the following :

$$\text{energy supplied, } \rho = M_g \left(\frac{U - U_{mf}}{\epsilon} \right) H \tag{6}$$

where M_g is mass flow rate of gas (kg/sec) ; U, superficial velocity of gas (m/s) ; ε, bed voidage ; and H, height of dense zone (m). Replacing the mass flow rate of gas with M_g = $(P\ Q\ M_w)/(R\ T)$, and $Q = UA$, Equation (6) may be written as :

$$\rho = \frac{P\ M_w\ A\ H\ U\ (U - U_{mf})}{R\ T\ \epsilon} \tag{7}$$

where P is the average absolute pressure (kg/m·sec^2) ; M_w, molecular weight of gas (kg/kg-mole) ; A, cross sectional area of bed (m^2) ; R, universal gas constant (kJ/kg-mole·°K) ; and T, temperature (°C). With substitution of Equation (7) into Equation (5), the following equation is obtained :

$$k_a = k_o \exp \left[- \frac{E_a\ R\ T\ \epsilon\ M_s}{P\ M_w\ A\ H\ U\ (U - U_{mf})} \right] \tag{8}$$

where M_s is the mass of parent solids in the bed (kg). If we consider the critical point above which attrition becomes independent of bed mass, the mass of solids, M_s, may be replaced with $C_{s,crit}(A\ H_t)$. The height of the dense zone, H, is also replaced with $\varepsilon\ H_b$, where H_b is the height of bed reactor (m). Then, the above equation is written as :

$$k_a = k_o \exp\left[- \frac{E_a\, R\, T\, C_{s,crit}}{P\, M_w\, U\, (U - U_{mf})} \right] \qquad \textbf{(9)}$$

Equation (9) suggests that the attrition rate constant is affected by the gas properties, such as temperature and molecular weight, as well as by the fluidization velocity. The size of parent solids also affects the attrition rate, since the minimum fluidization velocity varies with size of bed solids. Finally, the weight reduction of the parent solids during fluidization in a bed may be obtained by differentiating Equation (2) with the attrition rate constant, $\boldsymbol{k_a}$:

$$W = (W_o - W_{min})\, e^{-k_a t} + W_{min} \qquad \textbf{(10)}$$

Equations (9) and (10), with the experimental attrition data mentioned previously, provide a means of evaluating the extent of attrition during long term fluidization over wide gas velocities, temperatures, and solid size ranges.

The experimental data obtained from the present attrition tests were compared with the attrition model considering thermal attrition, as described in Equation (9) and (10). The linear relationship between $\boldsymbol{ln\ (k_a)}$ and $\boldsymbol{-1/U(U-U_{mf})}$ as shown in Figure 3.12, indicates that the attrition rate constant, $\boldsymbol{k_a}$, may be expressed in an Arrhenius form, and from the slope the attrition activation energy, $\boldsymbol{E_a}$ and $\boldsymbol{k_o}$ can be obtained as : $\boldsymbol{E_a} = 3.383 \times 10^{-3}$ kJ/kg and $\boldsymbol{k_o} = 1.29 \times 10^{-4}\ sec^{-1}$.

Comparisons between the mechanical attrition data obtained experimentally and the theoretical values computed with the attrition activation energy and $\boldsymbol{k_o}$ are illustrated in Figures 3.13 and 3.14. Two different sizes of limes (MMD=903 and 1764 μm) are applied for verifying the attrition model, and the results are shown in Figure 3.13. Figure 3.14 represents the weight reduction due to attrition at three different velocities (2, 3, and 5 m/s).

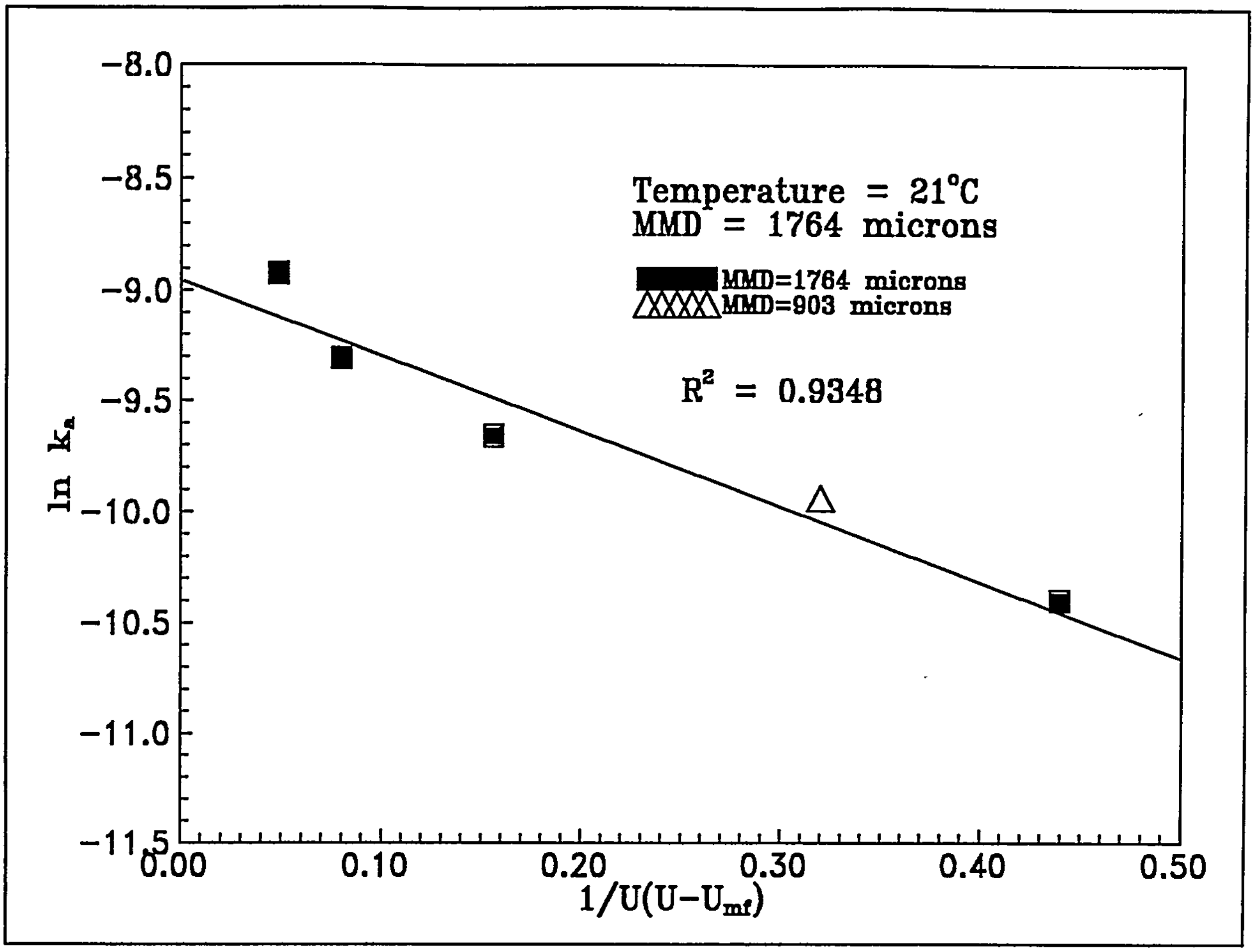


Figure 3.12 Arrhenius form for attrition rate constant.

The theoretical weight loss of solids during fluidization at different gas velocities and solid sizes is in good agreement with observations. However, Equations (9) and (10) underestimate the weight reduction at different temperatures, as shown in Table 3.3. The results suggest that the attrition rate may be affected by solid properties, as well as gas properties, as temperature increases. Lime is hygroscopic and absorbs moisture from the air, and its hardness increases with increasing temperature. As the temperature increases, dehydration and recarbonation occur and the particles become less fragile. Such property changes may significantly affect the attrition of solids at higher temperatures.

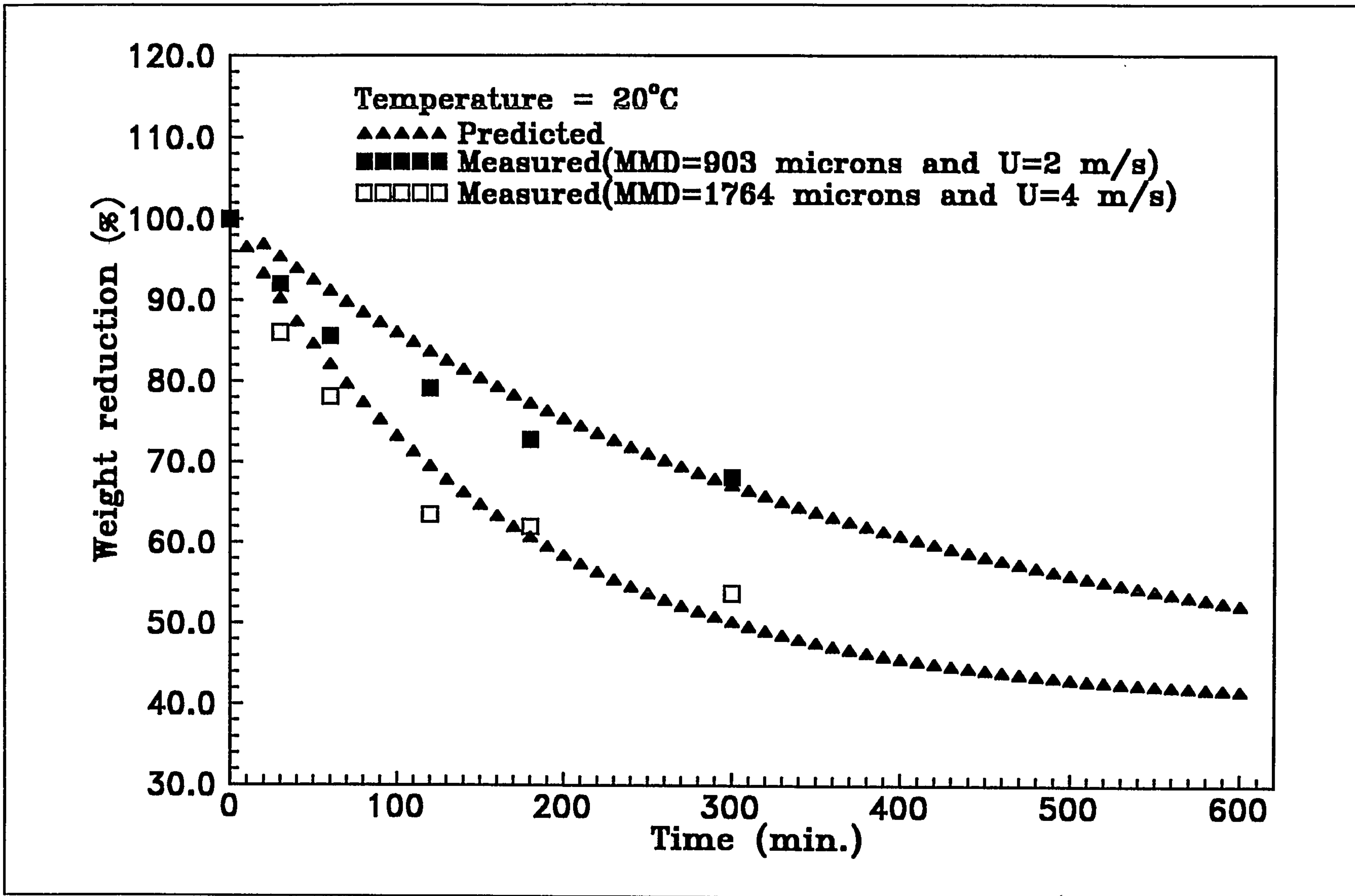


Figure 3.13 Comparison of weight changes calculated and measured.

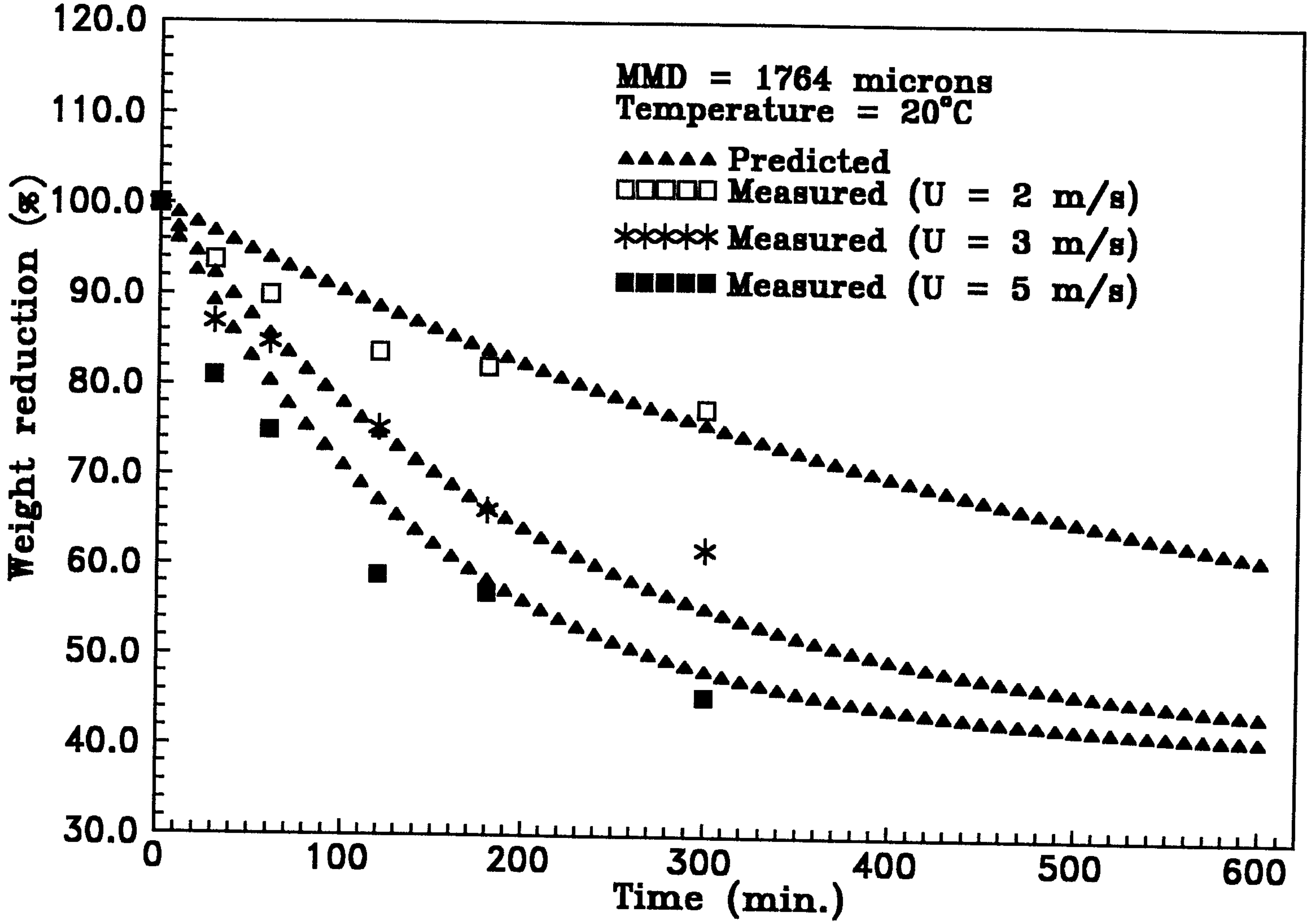


Figure 3.14 Comparison of weight changes calculated and measured.

Table 3.3 Attrition of Lime at Different Temperatures.

	Weight reduction (%) after 1 hour of fluidization	
Temperature (°C)	**Calculated by Equation (9)**	**Measured experimentally**
65	82.7	90
121	83.5	95
177	84.2	96.4

3.3.3 Development of unsteady state population model

Attrition rates Attrition rates were obtained from the tests with lime samples in a batch mode CFBA. The fluidizing gas was air with superficial velocities of 2 and 4 m/sec. Lime sorbents with mass mean diameters of 903 and 1764 μm were injected for the attrition tests. Figure 3.15 shows the weight reductions of the parent solids due to attrition during fluidization in the CFBA. Weight reduction occurs rapidly at the beginning of fluidization, continues, and finally levels off to reach a minimum weight, W_{min}, after 15 hours. A similar trend was also noted by Shamlou et al. [35], Flamant and Chraibi [40], and Keener et al. [13] for the attrition of agglomerates prepared from narrowly classified soda glass beads, manganese chloride particles, and limes, respectively.

The experimental data presented in Figure 3.15 suggest an exponential decrease of the weight of parent solids in a bed during fluidization. Many other investigators [14,35,39] applied a first order attrition model to estimate the weight changes of bed materials in a fluidized bed, but the extent of attrition obtained experimentally did not follow exactly the attrition model for longer operations than 1 hour. Based on these findings, a first order attrition model considering the minimum weight is suggested as :

$$\frac{dW}{dt} = - k_a(W - W_{min}) \tag{11}$$

where W is the weight of the parent solids in the bed (g), W_{min} is the minimum weight for which the attrition may be negligible and thus the weight of bed materials is constant, and k_a is the attrition rate constant (min^{-1}). Integrating Equation (11) with the boundary conditions of $t=0$, $W=W_o$, and $t=t$, $W=W$, gives :

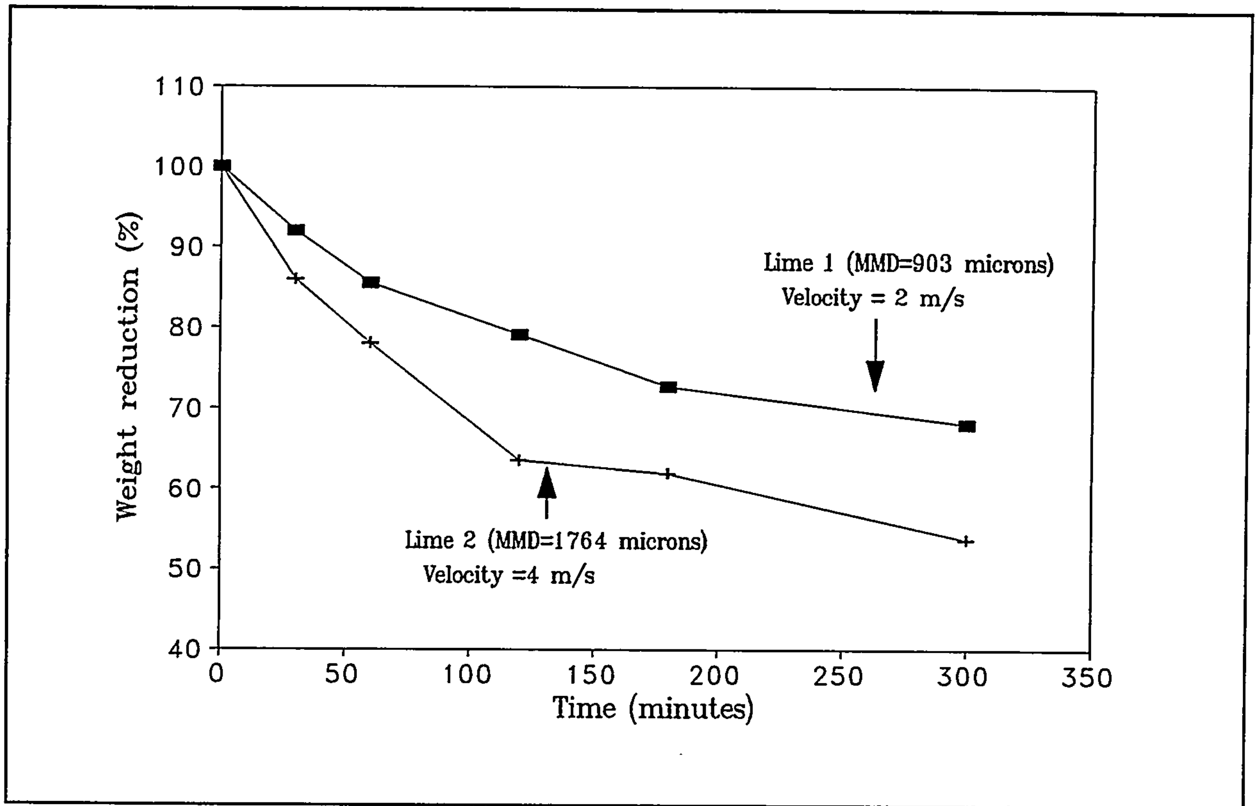


Figure 3.15 Weight reduction of lime sorbents during fluidization.

$$\ln\left(\frac{W - W_{\min}}{W_o - W_{\min}}\right) = - k_a t \qquad (12)$$

The attrition rate constant, k_a, therefore, can be obtained from the slope of the plot of ***ln [(W-W_{min})/(W_o-W_{min})]*** versus time, t. The attrition rate constant, k_a, obtained from the slopes as shown in Figure 3.16 are 0.0018 min^{-1} for the lime with MMD of 903 µm, and gas velocity of 2 m/sec, and 0.0055 min^{-1} for the lime with MMD of 1764 µm and gas velocity of 4 m/sec.

While the weight-based attrition rate has generally been measured in many other attrition tests [13,14,35,40], the size-based attrition rate may be more useful for some applications such as population model and shrinking core model. Therefore, consider the

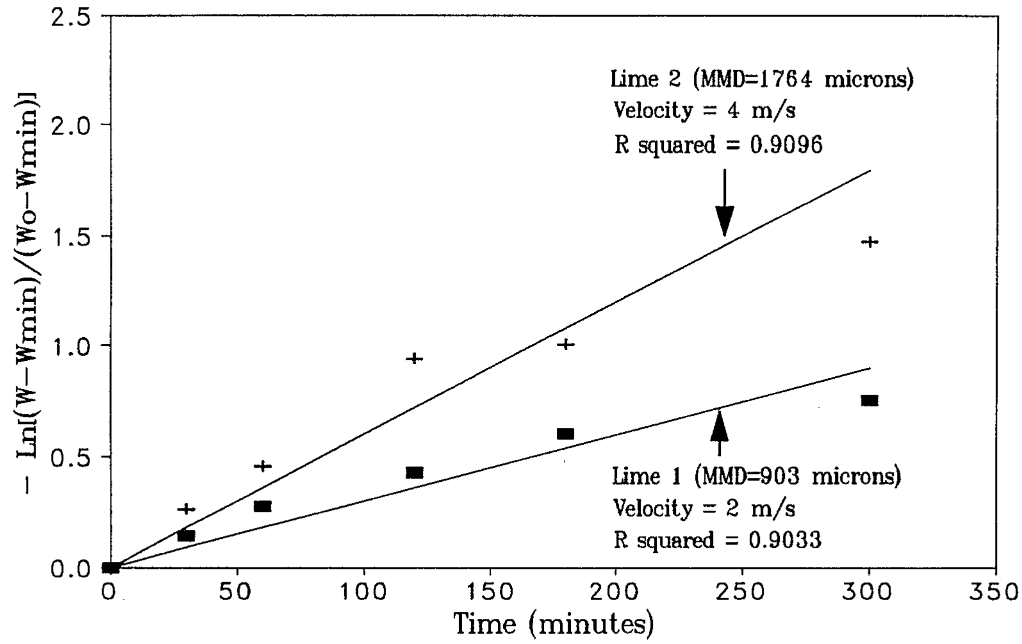


Figure 3.16 Attrition rate constants based on a first order dependency.

relationship between the weight-based and size-based attrition rates. From Equation (11), the size-based attrition rate may be written with the minimum size of parent solids, $d_{p,min}$, as follows :

$$\Re(d_p) = \frac{n\ \pi\ \rho_s}{6}\frac{dd_p^3}{dt} = -\frac{k_a\ n\ \pi\ \rho_s}{6}(d_p^3 - d_{p,\min}^3) \qquad (13)$$

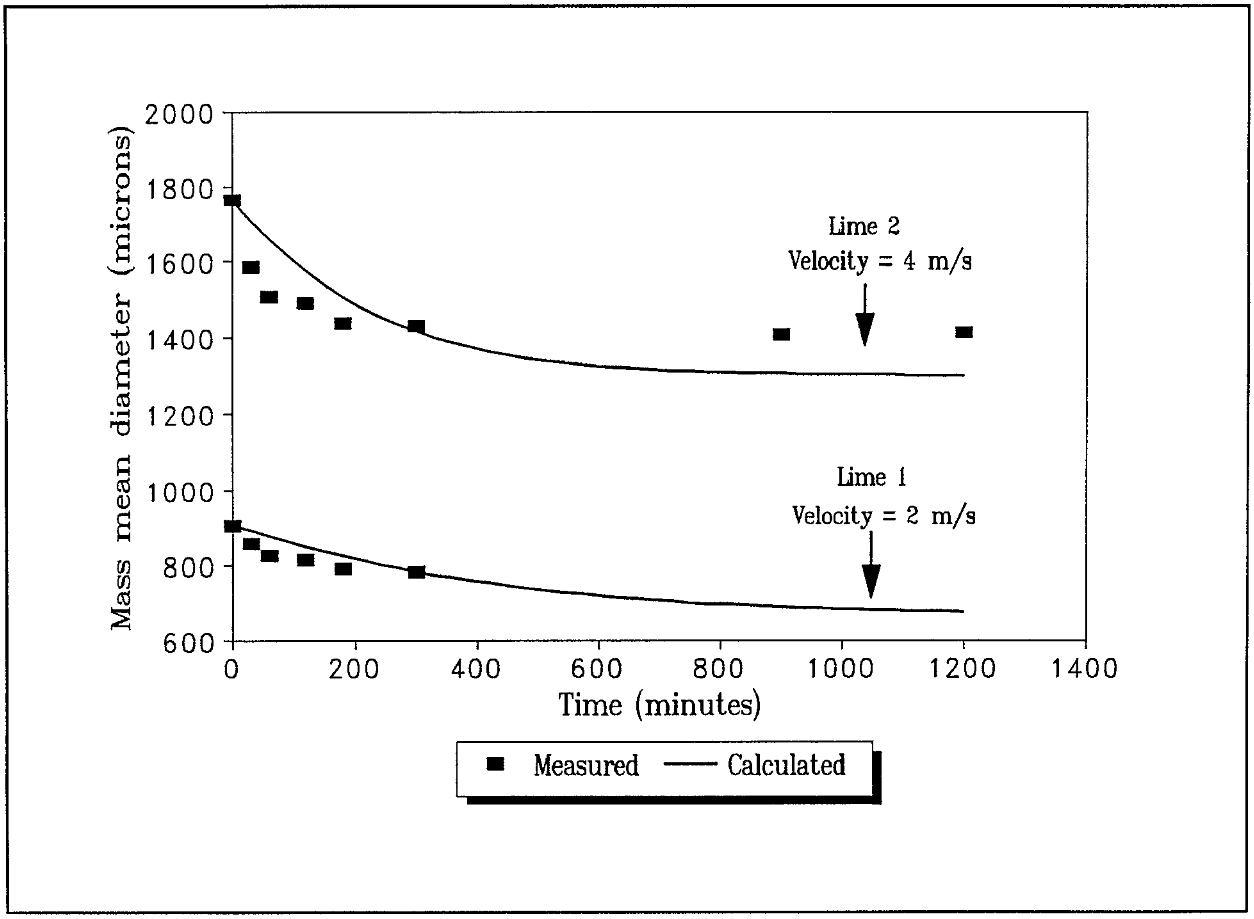


Figure 3.17 Comparison of mass mean diameters measured and calculated.

where n and ρ_s are the total number and density of parent solids in a bed, respectively. k_a is attrition rate constant (s^{-1}), and assumed as independent on solid sizes. The total number of solids, n, is assumed as constant during fluidization of the coarse parent solids, for which terminal velocities are much greater than the gas velocity and thus negligible elutriations are observed. Therefore, the total number, n, and minimum size, $d_{p,min}$, of solids may be obtained from the initial weight, W_o, and mass mean diameter, $d_{p,MMD}$, of the parent solids as : $d_{p,min} = (6W_{min}/n\pi\rho_s)^{1/3}$, and $n = 6W_o/(\pi\rho_s d^3_{p,MMD})$. From the above equation, the attrition rate based on the diameter of solids is given as ;

$$\Re(d_p) = \frac{dd_p}{dt} = -\frac{k_a}{3}\left(d_p - \frac{d^3_{p,\min}}{d_p^2}\right)$$
$$= -\frac{k_a}{3}\left[d_p - \left(\frac{W_{\min}}{W_o}\right)\frac{d^3_{p,MMD}}{d_p^2}\right] \tag{14}$$

Integrating Equation (14) with the boundary conditions of $d_p = d_{p,MMD}$ *at* $t=0$ and $d_p = d_p$ *at* $t=t$ gives the size-based attrition rate as a function of time as follows :

$$\int_{d_{p,MMD}}^{d_p}\left[d_p - \left(\frac{W_{\min}}{W_o}\right)\frac{d^3_{p,MMD}}{d_p^2}\right]^{-1} dd_p = -\frac{k_a}{3}\int_0^t dt$$

$$d_p = \left[\left(1 - \frac{W_{\min}}{W_o}\right)e^{-k_a t} + \frac{W_{\min}}{W_o}\right]^{1/3} d_{p,MMD} \tag{15}$$

The mass mean diameters of parent solids obtained from the size-based attrition rate in Equation (15) were compared with the corresponding experimental MMDs, and are shown in Figure 3.17. The MMDs from Equation (15) agree favorably with the experimental data, noting that the size-based attrition rate was derived under the assumptions of spherical solids and constant total number of solids, and that the MMDs measured with 250g of samples have wide deviations.

Population model application for a batch operation A population model has been considered as an useful tool in determining the particle generation rate and the continuous feeding rate as well as particle size distributions for continuous operations in a fluidized bed. While the particle population models have mainly been developed and applied under the assumptions of steady-state by many people [43,45,46,47,48], an unsteady-state population model is essential in predicting the changes of size distributions of solids for a batch operation of the fluidized bed. The unsteady-state population balance is illustrated in Figure 3.18. Consider the particles lying between the interval d_p and $d_p + \Delta d_p$. An unsteady state material balance around the particle size interval may be stated as follows :

$$\begin{pmatrix} \textit{solids} \\ \textit{feeding} \\ \textit{into bed} \end{pmatrix} + \begin{pmatrix} \textit{solids} \\ \textit{recirculating} \\ \textit{into bed} \end{pmatrix} - \begin{pmatrix} \textit{solids} \\ \textit{elutriated} \\ \textit{from bed} \end{pmatrix} + \begin{pmatrix} \textit{solids entering} \\ \textit{the interval } d_p+\Delta d_p \\ \textit{from larger size} \end{pmatrix}$$

$$- \begin{pmatrix} \textit{solids leaving} \\ \textit{out of the} \\ \textit{interval } d_p \end{pmatrix} + \begin{pmatrix} \textit{mass reductions due to} \\ \textit{attrition within the} \\ \textit{interval } d_p \textit{ and } d_p + \Delta d_p \end{pmatrix} = (\textit{accumulation})$$

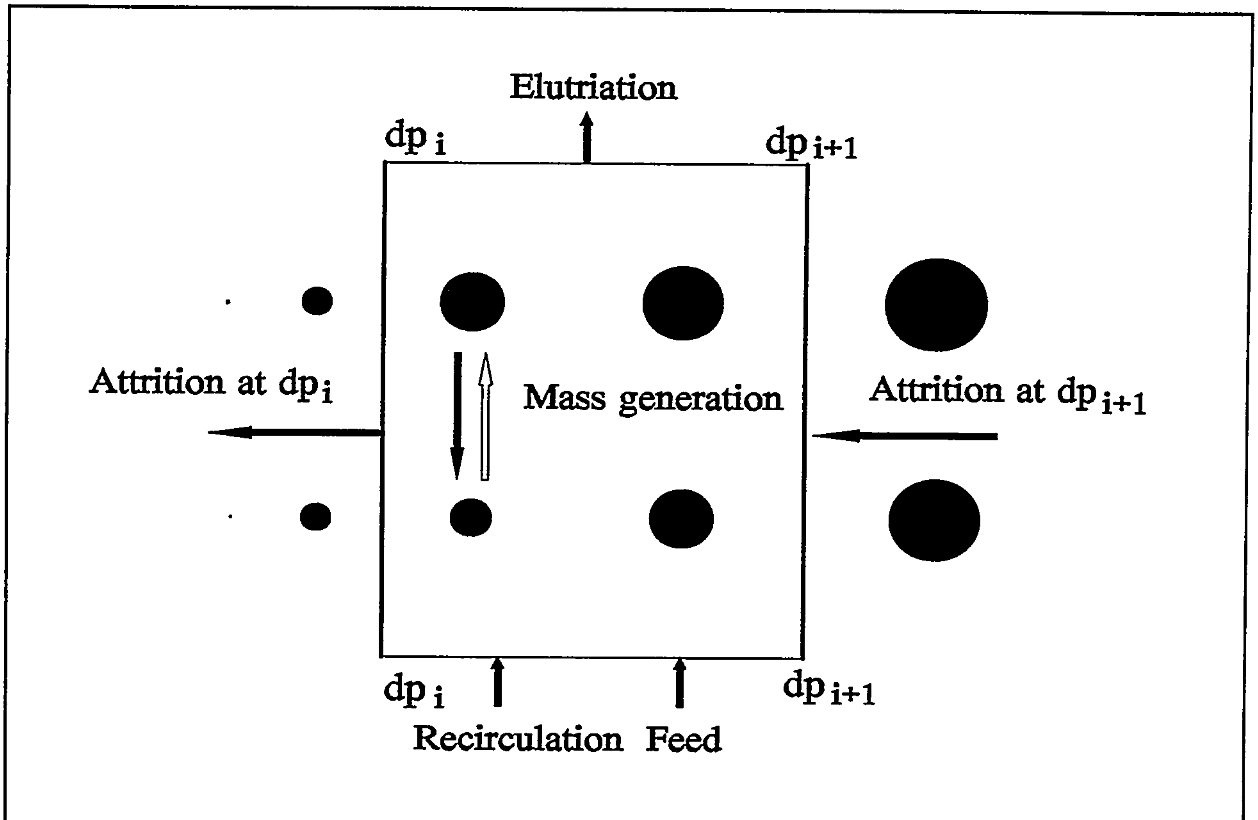


Figure 3.18 Illustration of solid population balance.

The equation corresponding to the above statement is written as :

$$F_o(t)P_o(d_p,t)\Delta d_p + F_r(t)P_r(d_p,t)\Delta d_p - F_e(t)P_e(d_p,t)\Delta d_p + W(t)P_b(d_p,t)\left(\frac{dd_p}{dt}\right)\Big|_{d_p+\Delta d_p}$$

$$- W(t)P_b(d_p,t)\left(\frac{dd_p}{dt}\right)\Big|_{d_p} + \frac{3W(t)P_b(d_p,t)}{d_p}\left(\frac{dd_p}{dt}\right)\Delta d_p = \frac{\partial[W(t)P_b(d_p,t)]}{\partial t}\Delta d_p \qquad \textbf{(16)}$$

where $F_o(t)$ is the solid feeding rate (g/sec), $F_r(t)$, the recirculating rate of solids (g/sec) ; and $F_e(t)$, the elutriation rate (g/sec) at time t. In addition, $W(t)$ is the total weight of solids in a bed (g), and $P_o(d_p, t)$, $P_b(d_p, t)$, $P_e(d_p, t)$, and $P_r(d_p, t)$ are the fractional size distributions (cm^{-1}) of the solid feeding, bed, elutriation, and recirculation, respectively. Dividing by Δd_p on both sides of the above equation and taking limits as $\Delta d_p \rightarrow 0$, the following equation is obtained :

$$F_o(t)P_o(d_p,t) + F_r(t)P_r(d_p,t) - F_e(t)P_e(d_p,t) - W(t)\frac{\partial[\Re(d_p)P_b(d_p,t)]}{\partial d_p}$$

$$+ \frac{3W(t)P_b(d_p,t)}{d_p}\Re(d_p) = \frac{\partial[W(t)P_b(d_p,t)]}{\partial t} \qquad \textbf{(17)}$$

where $\Re(d_p) = dd_p/dt$ is the size-based attrition rate (cm/sec), because the size reduction of lime sorbents occurs due to attrition during fluidization in the CFBA. The recirculating solids flow rate, $F_r(t)$ is obtained from the elutriation rate of solids, $F_e(t)$, and the cyclone efficiency, η_c. The elutriation rate, $F_e(t)$, is a strong function of particle size [22,36,50], and for any particular size is represent by the elutriation constant, $\kappa(d_p)$, as follows :

$$F_e(t)P_e(d_p,t) = \kappa(d_p)W(t)P_b(d_p,t) \qquad (18)$$

Thus, the recirculating rate of solids is written as follows :

$$F_r(t)P_r(d_p,t) = \eta_c F_e(t)P_e(d_p,t) = \eta_c \kappa(d_p)W(t)P_b(d_p,t) \qquad (19)$$

Substituting Equations (18) and (19) into Equation (17) yields a general unsteady-state partial differential equation describing the changes of solid size distribution in the CFBA system as followings :

$$F_o(t)P_o(d_p,t) - (1-\eta_c)\kappa(d_p)W(t)P_b(d_p,t) - W(t)\frac{\partial[\Re(d_p)P_b(d_p,t)]}{\partial d_p} + \frac{3W(t)P_b(d_p,t)}{d_p}\Re(d_p) = \frac{\partial[W(t)P_b(d_p,t)]}{\partial t} \qquad (20)$$

For batch operation of the CFBA, the feeding rate $F_o(t)$ is eliminated, and thus, the following equation is obtained. The equation may be numerically solved to determine the size changes of solid sorbents for a batch operation of CFBA, based on the discrete size distribution of solids, if the elutriation rate, $\kappa(d_p)$, attrition rate, $\Re(d_p)$, and cyclone efficiency ,η_c, are known.

An empirical expression of the elutriation rate for high velocity and large particles is given by Geldart [50] as followings :

$$\frac{\partial[W(t)P_b(d_p,t)]}{\partial t} = -(1-\eta_c)\kappa(d_p)W(t)P_b(d_p,t) - W(t)\frac{\partial[\Re(d_p)P_b(d_p,t)]}{\partial d_p} + \frac{3W(t)P_b(d_p,t)}{d_p}\Re(d_p) \tag{21}$$

$$\kappa(d_p) = 23.7\left(\frac{\rho_g\, U_a\, A_b}{W}\right)\exp\left[-5.4\,\frac{U_t(d_p)}{U_a}\right]^2 \tag{22}$$

where $\kappa(d_p)$ is the elutriation rate constant (cm^{-1}), and ρ_g and W are gas density (g/cm^3) and weight of solids (g), respectively. A_b is the cross-sectional area of the bed (cm^2), and U_a and $U_t(d_p)$ are gas velocity (cm/s) and terminal velocity of solids (cm/s). The terminal velocity is given as :

$$U_t(d_p) = \left[\frac{4\, d_p\, (\rho_s - \rho_g)\, g}{3\, \rho_a\, C_D}\right]^{1/2} \tag{23}$$

where C_D is a drag coefficient (dimensionless), and ρ_s and g are the density of solids (g/cm^3) and gravitational constant (cm/sec^2), respectively. The terminal velocity may be determined by trial and error [51] depending on Reynolds number, $R_e = d_p\rho_g U_t(d_p)/\mu$, where μ is viscosity.

If the size-based attrition rate as given in Equation (15) is substituted into Equation (20), the following equation is obtained :

For the numerical solution of Equation (24), a discrete size distribution should be employed. The fractional weight distributions in a bed, $W_b(d_{pi}, t)$, based on the discrete size, d_{pi}, is defined as follows :

$$\frac{\partial[W(t)P_b(d_p,t)]}{\partial t} = -(1 - \eta_c)\kappa(d_p)W(t)P_b(d_p,t) - \frac{2k_a}{3}W(t)P_b(d_p,t)$$

$$+\frac{5k_a W_{\min} d^3_{p,MMD}}{3W_o d_p^3}W(t)P_b(d_p,t) + \frac{k_a}{3}\left(d_p - \frac{W_{\min} d^3_{p,MMD}}{W_o d_p^2}\right)\frac{\partial[W(t)P_b(d_p,t)]}{\partial d_p} \qquad \textbf{(24)}$$

$$W_b(d_{pi},t) = W(t)\ P_b(d_{pi},t)\ \Delta d_{pi} \qquad \textbf{(25)}$$

$$\sum_{i=1}^{m}\left[\frac{W_b(d_{pi},\ t)}{W(t)}\right] = \sum_{i=1}^{m} P_b(d_{pi},t)\ \Delta d_{pi} = 1 \qquad \textbf{(26)}$$

With substitution of Equations (25) and (26) into Equation (21), the population equation based on the discrete sizes is written as follows :

$$\frac{\partial[W_b(d_{pi},t)]}{\partial t} = -\left[(1-\eta_c)\kappa(d_{pi}) + \frac{2k_a}{3} - \frac{5k_a W_{\min} d^3_{pi,MMD}}{3W_o d_{pi}^3}\right] W_b(d_{pi},t)$$

$$+ \frac{k_a}{3}\left(d_{pi} - \frac{W_{\min} d^3_{pi,MMD}}{W_o d_{pi}^2}\right)\frac{\partial[W_b(d_{pi},t)]}{\partial d_p} \qquad \textbf{(27)}$$

where the initial condition, $W_b(d_{pi},\ t) = W_o(d_{pi})$ *at* $t = 0$, is obtained by measuring the size distribution of the lime sorbents before fluidization. The boundary conditions are given by :

$$\text{for } t > 0, \quad W_b(d_{pi},t) = 0, \text{ at } d_{pi} = 0$$

$$W_b(d_{pi},t) = 0, \text{ at } d_{pi} = d_{p,\max} + \Delta d_p$$

An implicit method based on the backward Euler method is used for the numerical computation of Equation (27). Thus, the following finite difference equation is written :

$$\left(\frac{1+\alpha}{\beta}\right) W_{i,j+1} - \left(\frac{\alpha}{\beta}\right) W_{i+1,j+1} = W_{i,j} \tag{28}$$

where d_{pi} and t are replaced with i and j, respectively, and α and β are :

$$\alpha = \frac{k_a}{3}\left(d_{pi} - \frac{W_{\min} d^3_{pi,MMD}}{W_o d^2_{pi}}\right)\left(\frac{\Delta t}{\Delta d_p}\right) \tag{29}$$

$$\beta = 1 - \left[(1 - \eta_c)\kappa(d_{pi}) + \frac{2k_a}{3} - \frac{5k_a W_{\min} d^3_{pi,MMD}}{3W_o d^3_{pi}}\right]\Delta t \tag{30}$$

Equation (28) may be written in a diagonal matrix form, and thus, the unknowns, $W_{1,j+1}$, $W_{2,j+1}$,...... ,$W_{k,j+1}$ are obtained by iterations, together with the initial and boundary conditions.

The input data necessary for the computations are shown in Table 3.4. Main program and output are also attached in Appendix C. In the computer program, the fractional weights measured at discrete sizes are divided by the difference between the lower and upper ranges and multiplied by the size increment to give the initial fractional weight, $W_{i,o}$, at time, $t=0$ and each size, d_{pi}. In other words, the initial fractional weight at each size within the lower and upper ranges is assumed as the same. The terminal velocities for the computations of the elutriation rate at each size and time interval are obtained by trial and error, depending on the Reynolds number. The size and time interval may be smaller to give more accurate results, depending on the computer's capacity, since size intervals greater than 40 μm and time increments greater than 20 sec may cause an unacceptable computation result.

The fractional size distribution curves obtained from the computations and corresponding measured size distributions after fluidizations of 30 minutes, 1 hour, 2 hours, and 3 hours are shown in Figures 3.19-3.23. The size distributions computed by the unsteady state population model agree well with the experimental data, while slightly lower estimations occur at the lower size ranges because elutriations of solids are considered in the model.

Table 3.4 Batch Operating Conditions of CFBA.

FRACTIONAL WEIGHT OF SOLIDS

Lime 1 (MMD=903 μm)		Lime 2 (MMD=1764 μm)	
Diameter ranges (μm)	$W_b(d_{pb}0)$ (%)	Diameter ranges (μm)	$W_b(d_{pb}0)$ (%)
100 - 297	1.6	300 - 595	0.9
297 - 420	0.1	595 - 841	0.1
420 - 595	0.4	841 - 1008	0.1
595 - 841	31.3	1008 - 1190	4.0
841 - 1000	31.9	1190 - 2000	61.3
1000 - 1190	34.7	2000 - 2380	33.6
Total	100	Total	100

OPERATING CONDITIONS

Density of Particle	2.1 (g/cm^3)
Density of Gas	1.02E-03 (g/cm^3)
Viscosity	1.78E-04 (g/cm/sec)
Gravitational Constant	980.66 (cm/sec^2)
Bed Diameter	7.62 (cm)
Bed Height	250 (cm)
Gas Velocity	200 and 400 (cm/sec)
Attrition Rate Constant	4.82E-5 & 9.09E-5 (sec^{-1})
Size Interval	10 (μm)
Time Interval	10 (sec)

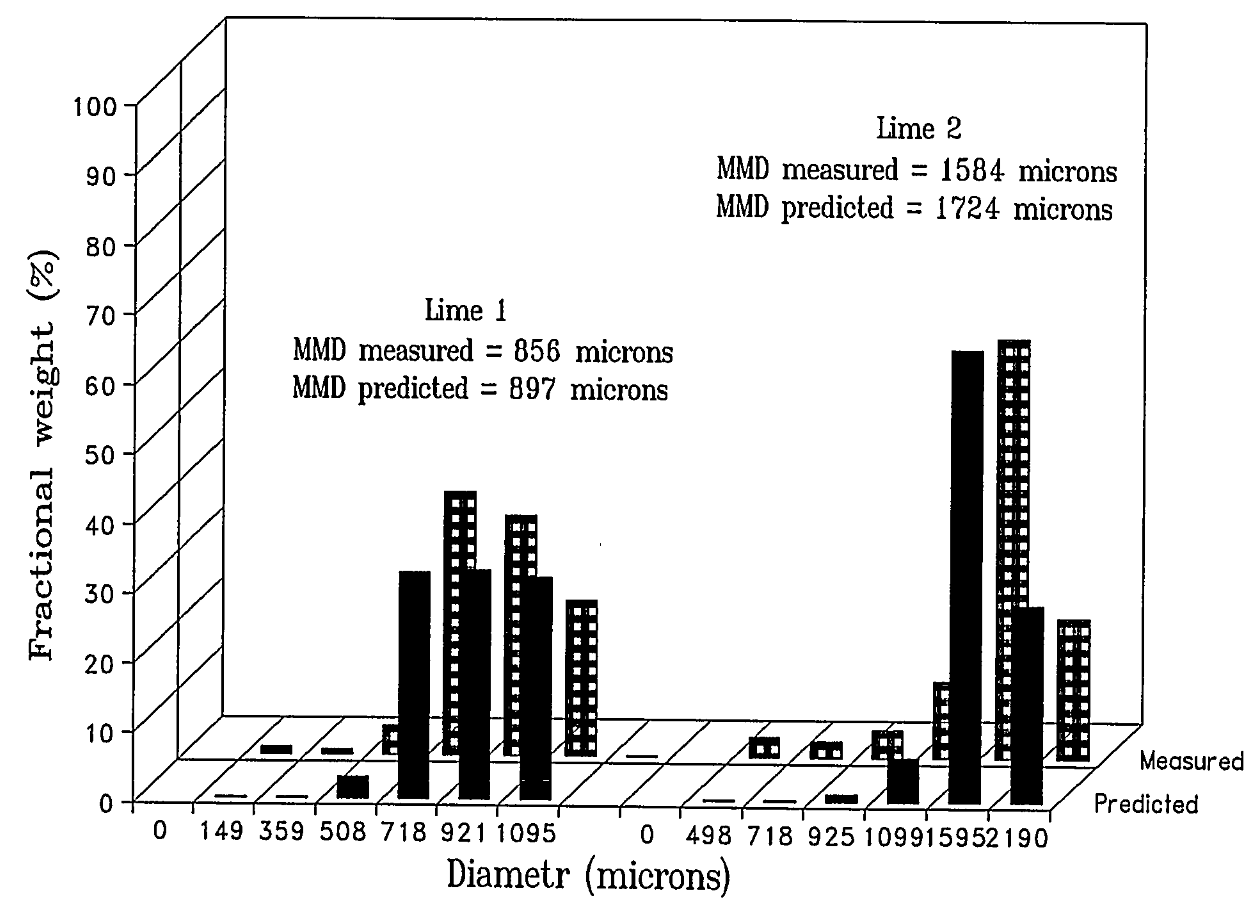


Figure 3.19 Size distribution of lime sorbents after 30 minutes of fluidization. (U = 2 m/s for lime 1 and U = 4 m/s for lime 2)

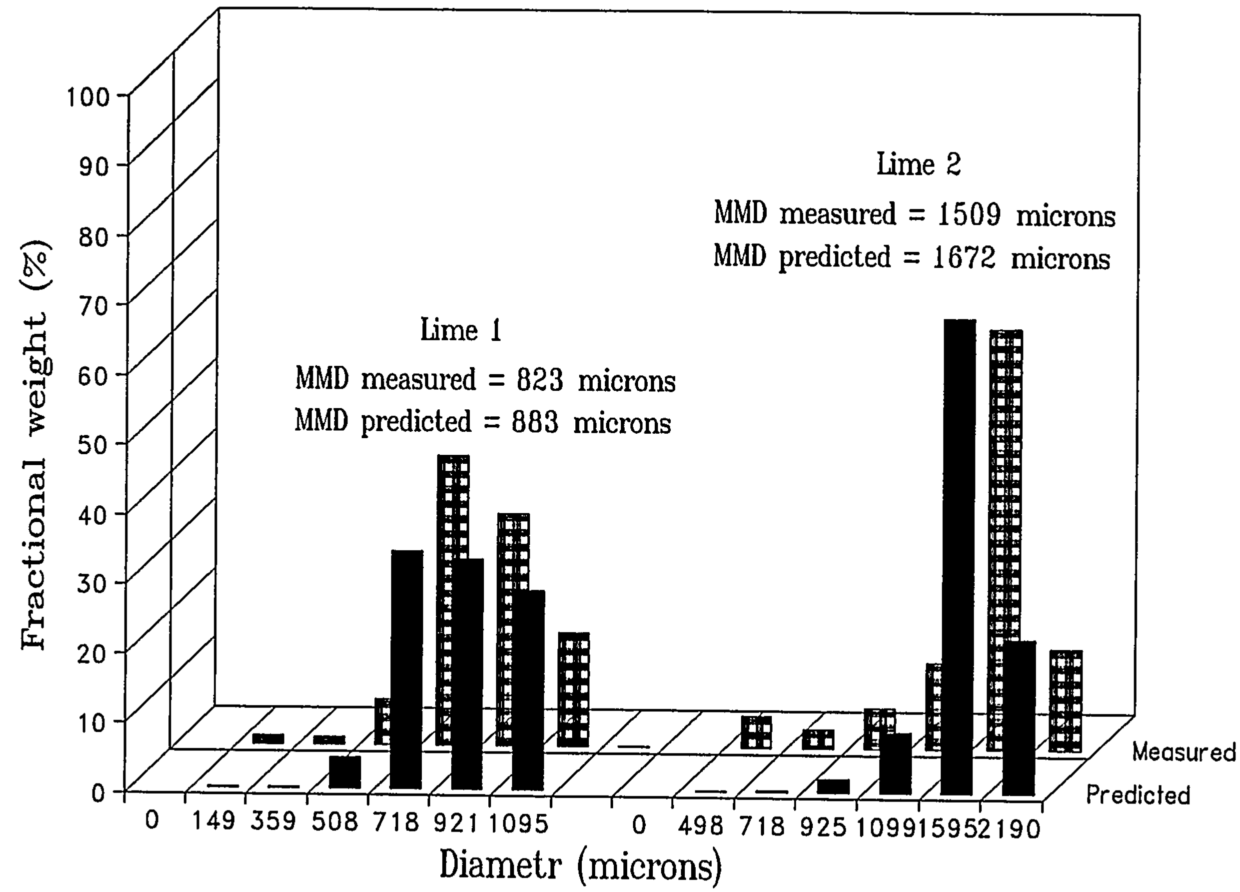


Figure 3.20 Size distribution of lime sorbents after 1 hour of fluidization.
(U = 2 m/s for lime 1 and U = 4 m/s for lime 2)

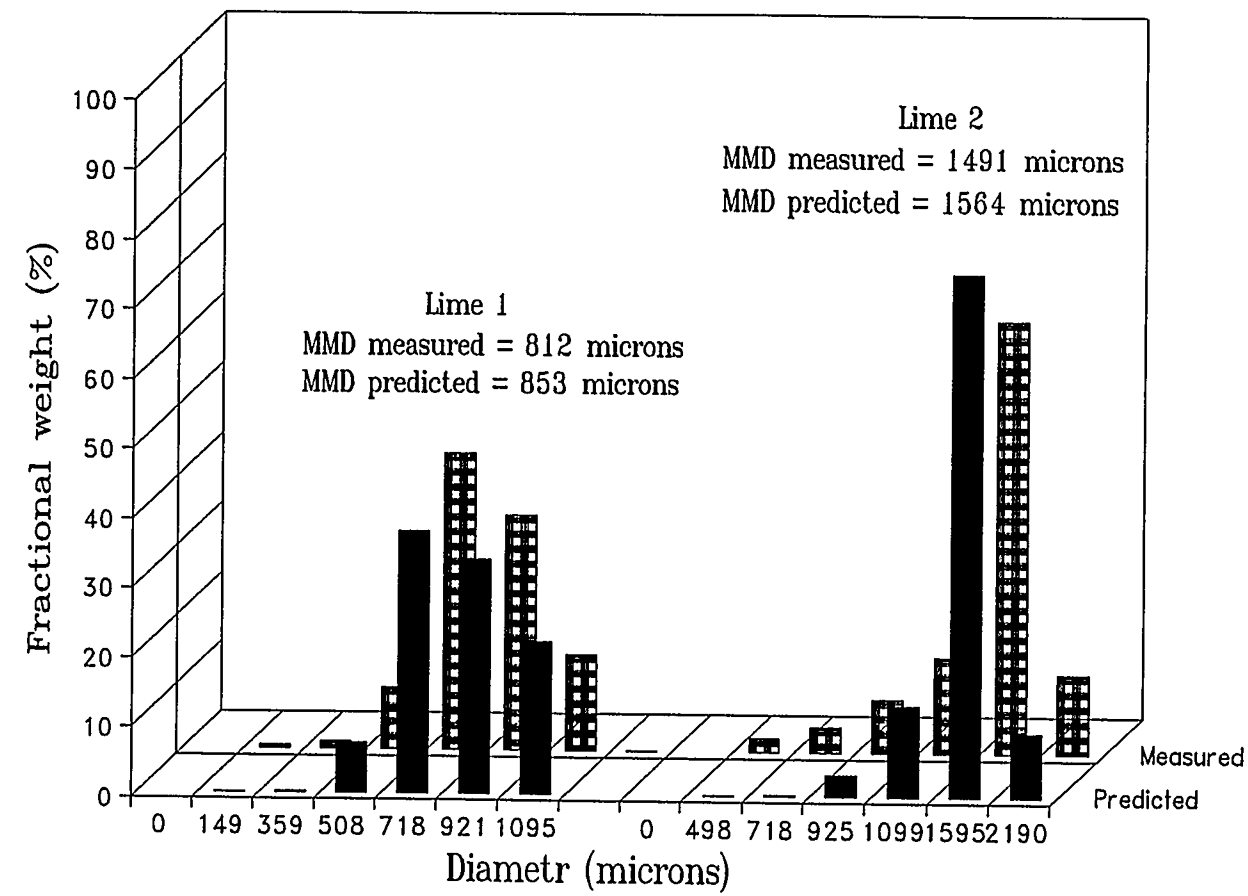


Figure 3.21 Size distribution of lime sorbents after 2 hours of fluidization. (U = 2 m/s for lime 1 and U = 4 m/s for lime 2)

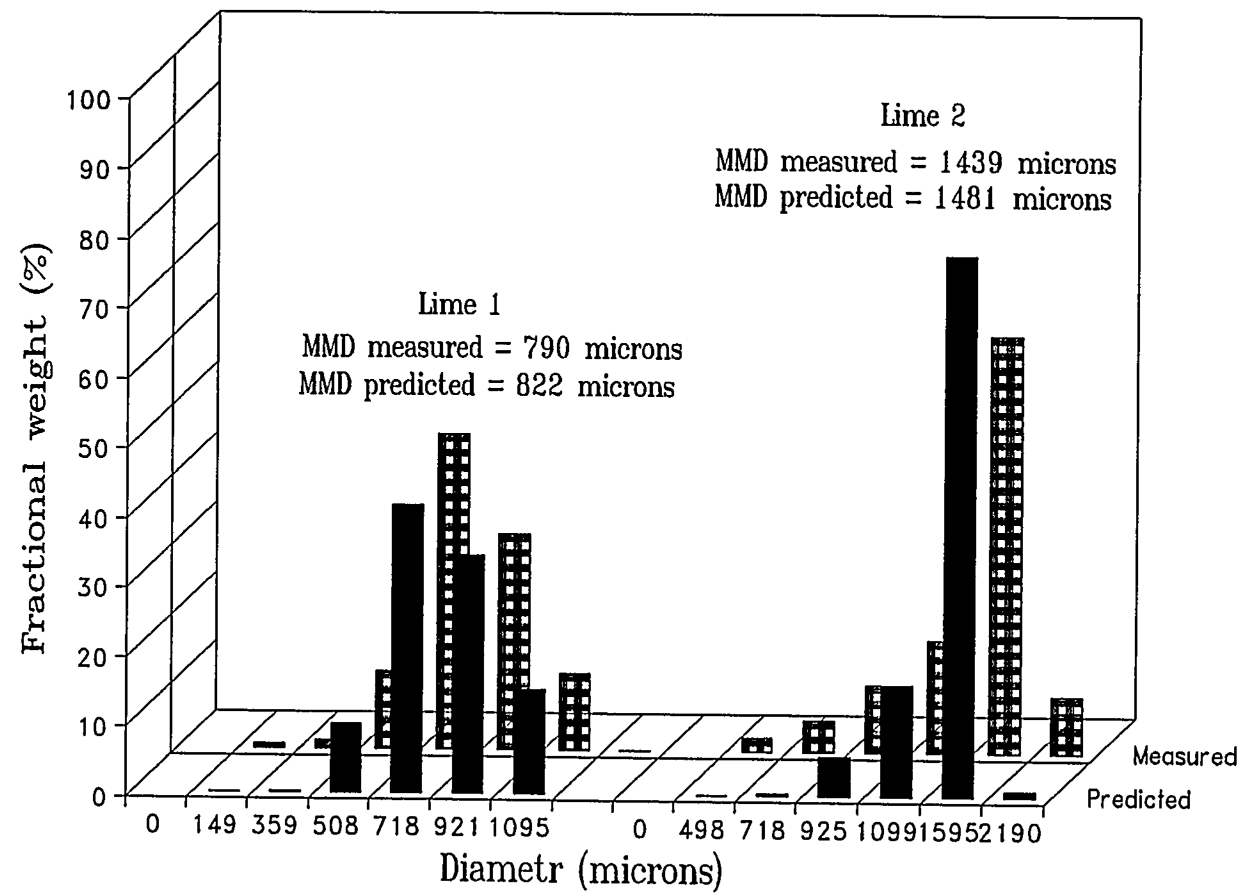


Figure 3.22 Size distribution of lime sorbents after 3 hours of fluidization. (U = 2 m/s for lime 1 and U = 4 m/s for lime 2)

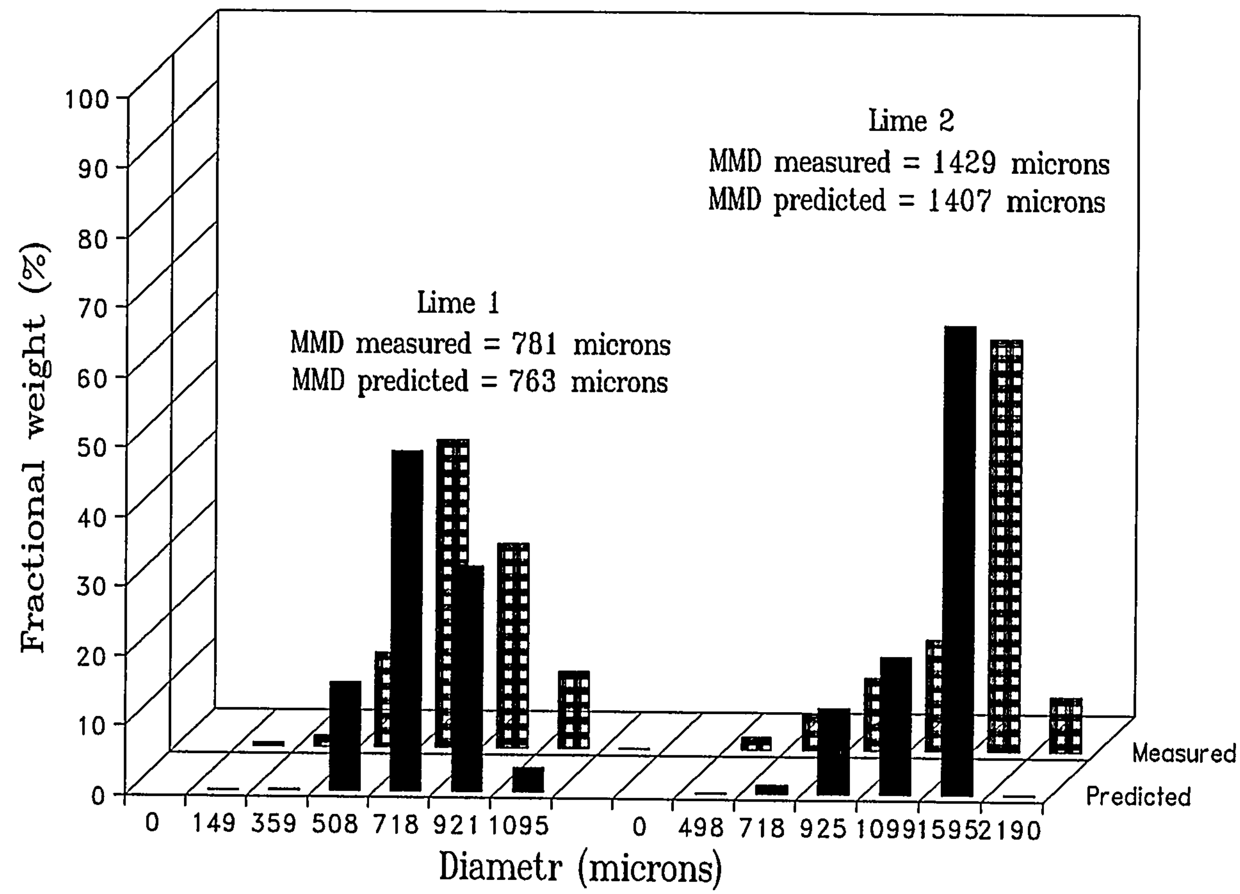


Figure 3.23 Size distribution of lime sorbents after 5 hours of fluidization. (U = 2 m/s for lime 1 and U = 4 m/s for lime 2)

The effect of gas velocity on the size distribution of solids is shown in Figures 3.24 and 3.25. For the output, the same operating conditions and an arbitrary initial size distribution are used at the different velocities. As shown in Figure 3.24, in the initial fractional weight with normal gaussian distribution was chosen for the purpose of illustration. Figures 3.24 and 3.25 show that decreasing the rate of the mass mean diameter at the lower velocity (2 m/s) is greater than that at the higher velocity (4 m/s), while the size range at 2 m/s becomes much wider than at 4 m/s . This suggests that the solids that become smaller by attrition at the higher velocity are easily elutriated, and only relatively coarse solids remain in a bed as the fluidization time increases. As a result the decreasing rate in MMDs of the remaining parent solids may be relatively slower at the higher velocity.

3.4 Conclusions

Attrition of lime sorbent plays a very important role in fluidized bed applications for dry lime FGD processes. The experimental data of lime sorbent attrition from mechanical and thermal attrition tests in a circulating fluidized bed absorber (CFBA) are presented. The results indicate that the predominant attrition mechanism during lime fluidization is surface abrasion due to sorbent particle-to-particle collisions in the vigorous fluidized bed. Previously published attrition investigations found that thermal attrition of limestone, $CaCO_3$, increased with temperature due to crepitation from increased internal pressure as the temperature increases. However, the experimental results for lime sorbent, CaO, presented in this study show that thermal attrition decreases with temperature. This is possibly due to an increase in hardness with rising temperature.

An improved model was developed based upon the experimental attrition behavior in the CFBA. This model more accurately fits the attrition behavior for lime sorbent because it incorporates both mechanical and thermal attrition, while the existing models only account for mechanical attrition. Thermal attrition is incorporated into the model through the attrition rate

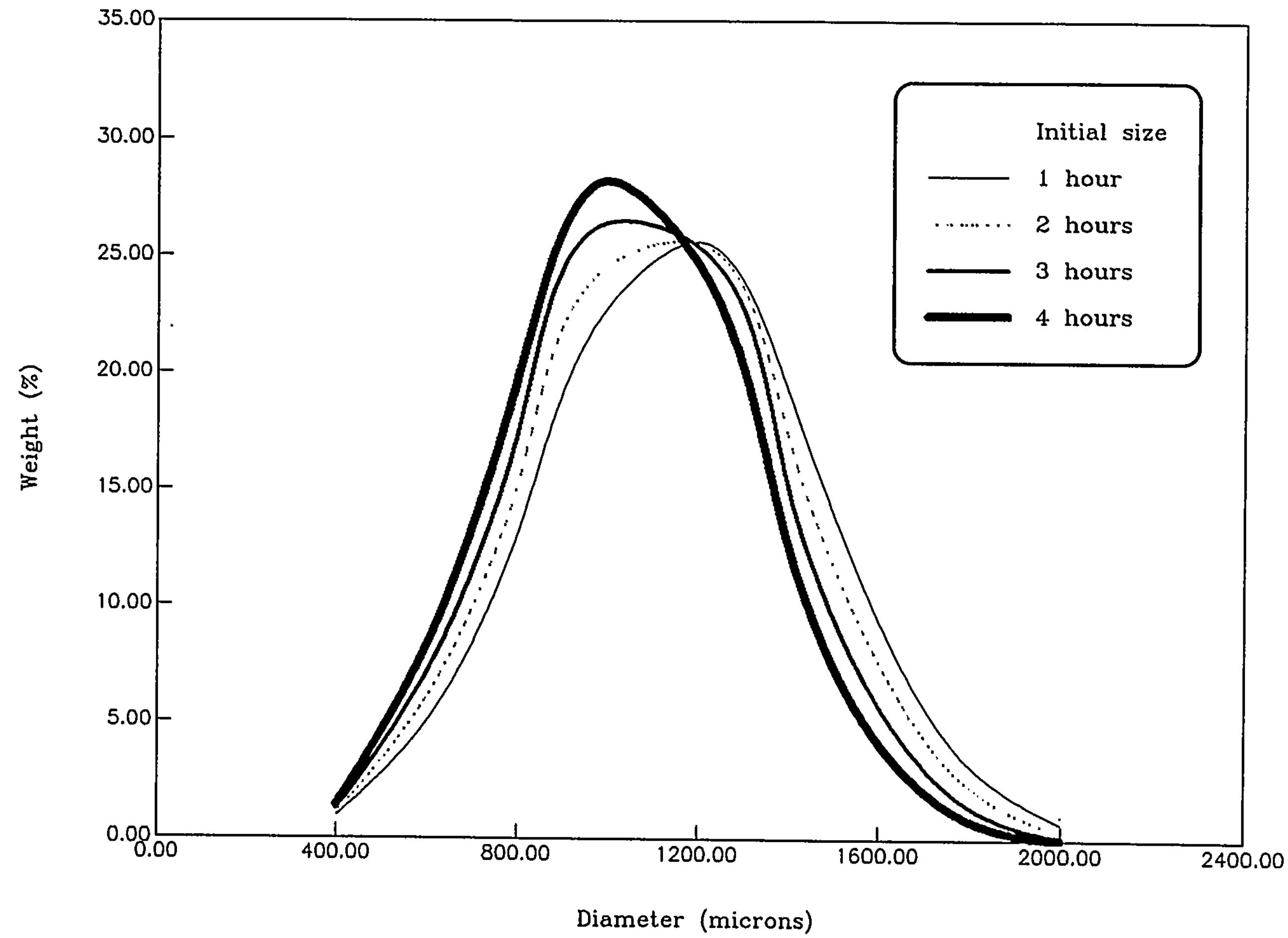


Figure 3.24 Changes of solid size distribution at the velocity of 2 m/s.

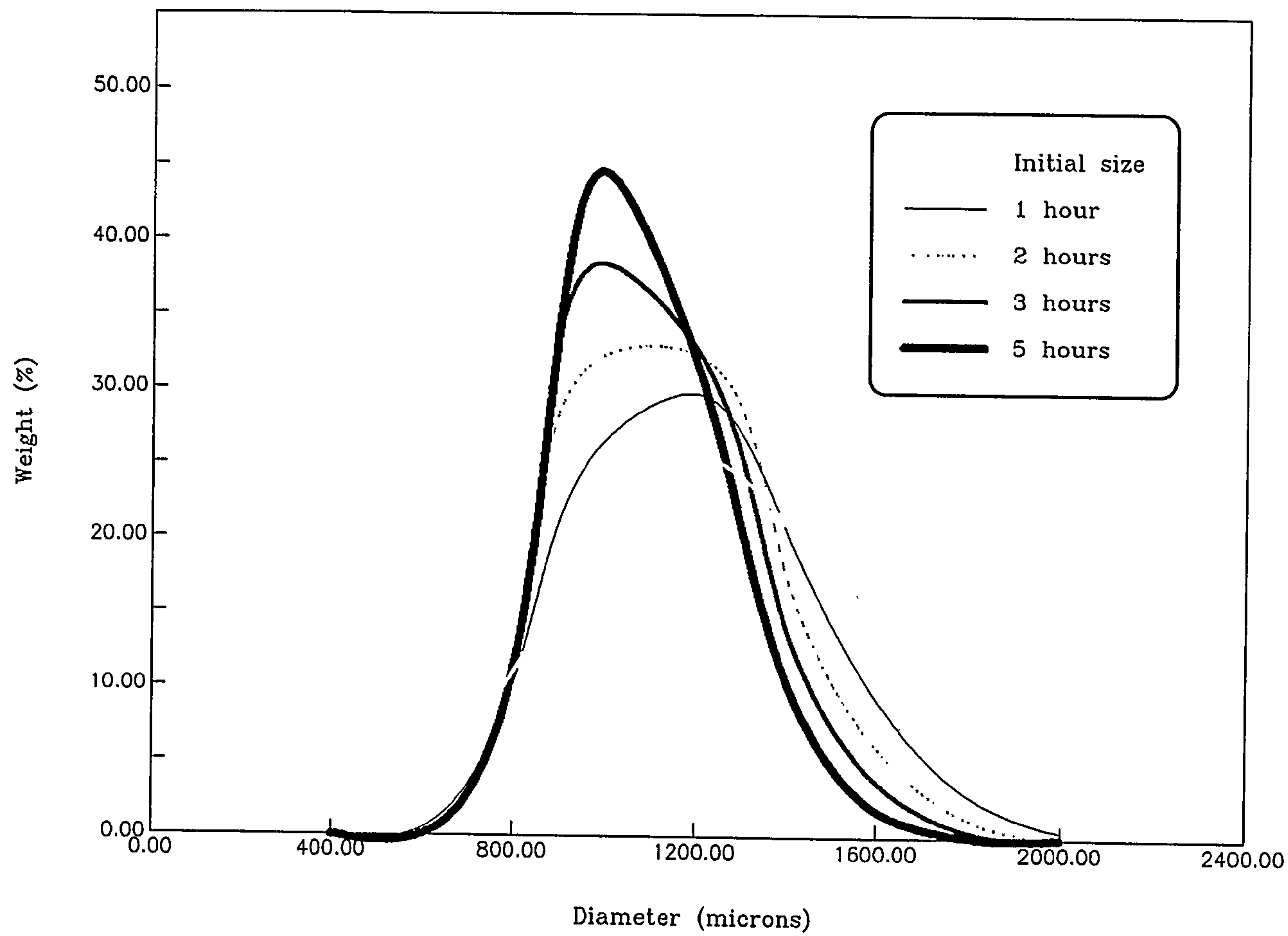


Figure 3.25 Changes of solid size distribution at the velocity of 4 m/s.

constant. The attrition rate constant is expressed in an Arrhenius form using a kinetic model which relates the attrition rate to the gas properties such as temperature and molecular weight and the geometry of the fluidized bed as well as the fluidization velocity.

A shortcoming of the previous models developed by past investigators is the erroneous assumption that as fluidization progresses, attrition decreases to zero. The experiments in this study point out that as fluidization progresses, attrition decreases to a constant level called W_{min}. Hence, the model, which is first order dependent with respect to time, is modified to introduce W_{min}.

The model was validated for lime attrition in the CFBA. The attrition activation energy, E_a, and frequency factor, k_o, for the model, can be obtained as : $E_a = 3.383 \times 10^{-3}$ kJ/kg and $k_o = 1.29 \times 10^{-4}$ sec^{-1}. Using these modeled values, the predicted amount of mechanical and thermal attrition is in good agreement with the experimentally obtained data.

The experimental data obtained from attrition tests in a CFBA are also interpreted as both the weight-based attrition rate and size-based attrition rate. The weight-based attrition rate constants obtained from a first order model with a minimum weight are 0.0029 min^{-1} for the lime of 903 μm in MMD at the gas velocity of 2 m/sec, and 0.0055 min^{-1} for the lime of 1764 μm in MMD at the gas velocity of 4 m/sec. In addition, an unsteady state population model was employed to predict the changes in size distribution of bed materials during fluidization. The solid size distribution predicted by the population model at various time intervals during fluidization agreed well with the size distributions obtained experimentally for the corresponding time intervals. The model developed in this study is applicable for batch and continuous modes of fluidization where the particle size reduction in the bed load is predominantly a result of attrition and elutriation. This has widespread significance since mechanical attrition and elutriation is frequently seen in fast fluidized beds and in circulating fluidized beds used in other industrial applications.

3.5 Recommendations

The experiments indicated that material properties were a more significant factor than factors related to the reactor environment, such as fluidizing gas velocity and bed temperature. As a result, the attrition activation energy and the rate constants obtained experimentally using commercial lime are applicable to lime only. Note the constants are independent of lime particle size. However, these constants can not be applied to other materials. In many practical processes such as FGD systems, combustors, and reactors, attrition may be complicated by the fact that the starting bed particles are transformed by reaction during fluidization. For example, in a CFBA used for FGD, the bed particles are lime, however as FGD progresses, the lime reacts with the SO_2 and transforms the bed particles to calcium sulfate. Calcium sulfate in this case has very different material properties from lime, and an attrition data base for this product, $CaSO_4$, must be established to accurately predict the attrition relationships. Therefore it is recommended that attrition rate constants be established for other materials used for FGD for design of industrial applications.

CHAPTER 4. SULFUR DIOXIDE REMOVAL IN A CFBA

4.1 Literature Review

Because dry scrubbing flue gas desulfurization (FGD) processes are low cost, they have received considerable attention over the past several years. Extensive studies on process optimization have been prompted [2]. Higher sorbent utilization, however, is still required to improve the economics of the dry injection method. Recently, water injection and cooling of the flue gas has been evaluated as another conceivable way to enhance the utilization of dry calcium-based sorbents [5]. It not only activates the sorbent reactivity, but also conditions the flue gas for improved ESP performance by lowering the gas resistivity.

The low temperature reaction of dry calcium-based sorbents with SO_2 under water injection into a reactor has rarely been studied in a systematic fashion. Earlier investigations [52,53] primarily dealt with high temperatures for the application of the sorbent injection into coal-fired boilers. In addition, water injection techniques are not yet well developed, especially for a fluidized bed reactor. Klingspor et al. [54] found that the relative humidity has a dramatic impact on the reaction between SO_2 and limestone. Their results indicated that the reaction rate is virtually equal to zero at a relative humidity below 20%, but above a relative humidity of 20% the reaction rate increases exponentially.

Yoon et al. [55] developed a coolside desulfurization (BLI) process which involves hydrated lime injection and, optionally, additive injection followed by flue gas humidification by evaporation of water spray. Their 1 MW-scale field tests using hydrated lime at a Ca/S molar ratio of 2.5 showed that the overall SO_2 removal increased from 50% without humidification to 65% with humidification at 25-30°F approach to saturation temperature.

Moyeda et al. [56] investigated sulfur capture from flue gas with humidification in power plant ducts. They investigated three humidification techniques including 1) physical wetting by pre-slurrying the duct injected sorbent, 2) spraying of water into the duct, resulting in free steam inertial impaction of the water droplet on the sorbent, and 3) prehumidifing the gas stream and injecting cool sorbent to promote condensation, where liquid water collects on the surface of the cool sorbent particle. Their experimental results indicated that physical contact between the spray water and the sorbent particles is necessary to achieve enhanced reaction rates.

Gooch et al. [17] also investigated the low-temperature SO_2 removal of lime and additives in cases of post furnace humidification, charge augmented humidification, and water vapor adsorption. They concluded that a spray of pure water without additives will be sufficient if the wetting efficiency between sorbent particles and water droplets can be improved by newly developed humidification techniques.

A novel desulfurization technology, which combines dry scrubbing using solid sorbents with a circulating fluidized bed absorber (CFBA) reactor, has been developed by Keener et al. [12] and Jiang [14]. The main features of CFBA are high sorbent/gas mixing ratios, excellent heat and mass transfer, and recycle of sorbents and, subsequently, higher SO_2 removal efficiencies with higher sorbent utilizations than any other dry sorbent injection scrubber. They installed a commercialized nozzle in order to spray water into the CFBA, and observed a dramatic increase of SO_2 removal efficiency in the CFBA.

The experimental observations from the CFBA operations [14,57] indicated that the commercial nozzle used had physical limitations on the degree of particle wetting. Therefore, a novel method for injecting water into a CFBA was designed and applied to a bench-scale CFBA unit to increase the sorbent wetting and SO_2 removal efficiency [13]. The objective of this study is to evaluate the novel water injection technique for SO_2 removal. Also, the experiments investigate lime sorbent utilization under various operating conditions for a low temperature CFBA. Included in this investigation are the effects of water injection rate, the number of holes in the nozzle design and the nozzle spray height with and without sorbent recycle, gas velocity, batch load size, and extent of attrition.

4.2 Experimental Approach

A bench-scale CFBA reactor was constructed with a special nozzle design for water injection, as shown in Figure 2.3. As explained in Chapter 2, the CFBA used for experiments consisted of a tubular reactor with a gas heating system, a sorbent injection system, a water injection system, and a gas-solid separation/recycle system. In addition, the reactor was equipped with gas sampling ports for data acquisition and monitoring of gas flow, concentration, temperature and pressure.

4.2.1 Design of toroidal ring nozzle

For the enhancement of SO_2 removals in a CFBA, a new toroidal type of pressurized spray nozzle was designed and installed at the bottom of bed. Its installation and water spray are illustrated in Figures 4.1- 4.5. As shown in Figure 4.1, the nozzle can reduce wall wetting and thus maximize the wetting efficiency without disturbance of the fluidizing gas stream.

The toroidal ring type of nozzle was made from 1/4 inch copper tubing. The shape and size of the copper tubing was designed to minimize any effects on the gas stream and fluidization. Very tiny 175 μm water injection orifices were drilled on the upper side of the toroidal copper tubing at an 85° angle to horizontal. This special angle was designed to maximize the water trajectory travel distance with respect to the sorbent. Thus the probability of a water droplet colliding with fluidized solid sorbent was maximized. Also, this design minimized wall wetting. A filter was placed before the water pump to prevent contaminants from clogging the small nozzle holes. A high pressure pump was employed to insure good

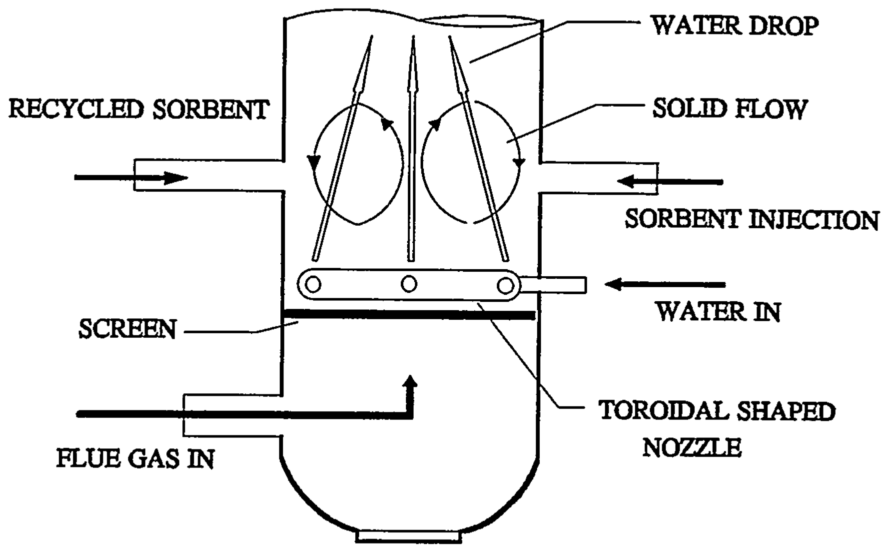


Figure 4.1 Installation of a toroidal ring nozzle.

atomization. For this study, three identical nozzles with varying numbers of holes were tested; one nozzle had 2 holes, another nozzle had 3 holes, and a third nozzle had 4 holes. Experiments were conducted varying the water injection rate also. Rates of 30 ml/min to 70ml/min were tested.

4.2.2 Experimental procedure

The SO_2 removal tests under water injection were carried out in a batch mode in the circulating fluidized bed absorber (CFBA) with Dravo limes of 903 μm (Lime 1) and 1764 μm (Lime 2) in mass mean diameter (MMD). Inlet gas temperature was about 177 °C and superficial gas velocity was 4 m/s for Lime 1 (903 μm) and 4 - 5 m/s for Lime 2 (1764 μm),

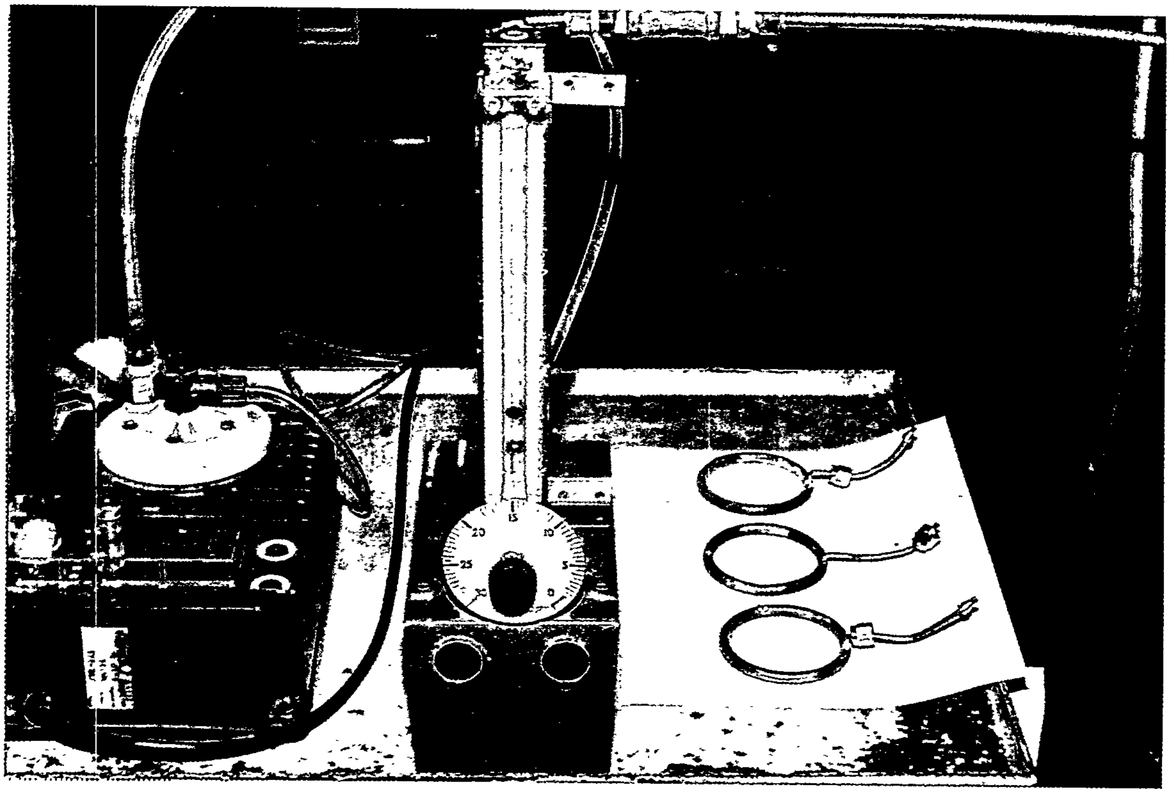


Figure 4.2 Water pump and toroidal ring nozzles

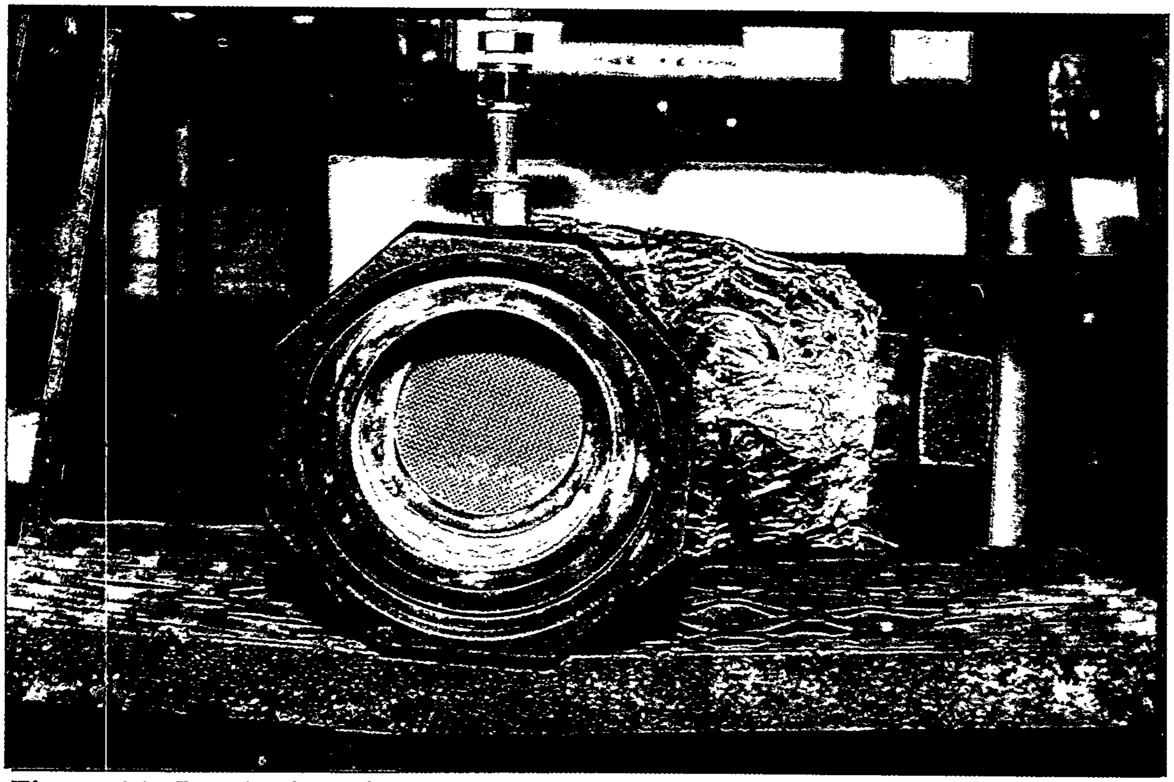


Figure 4.3 Installation of nozzle in a CFBA

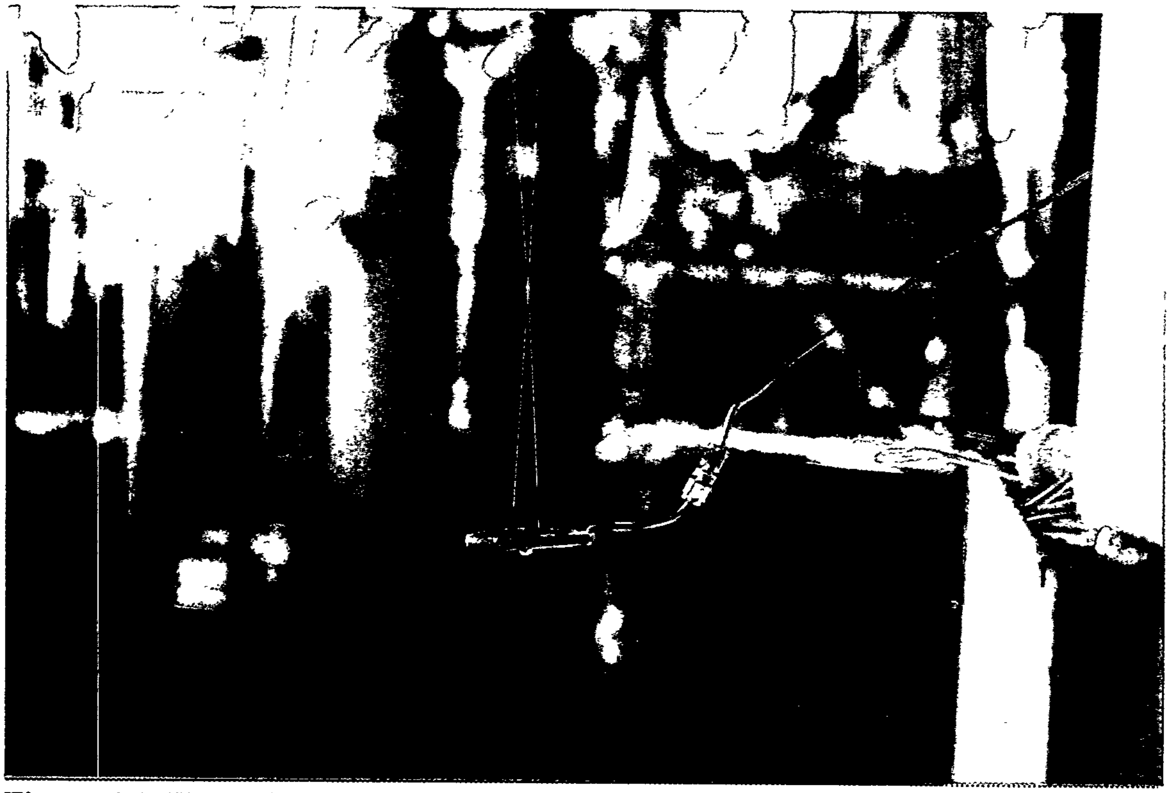


Figure 4.4 Water injection with 2-hole nozzle

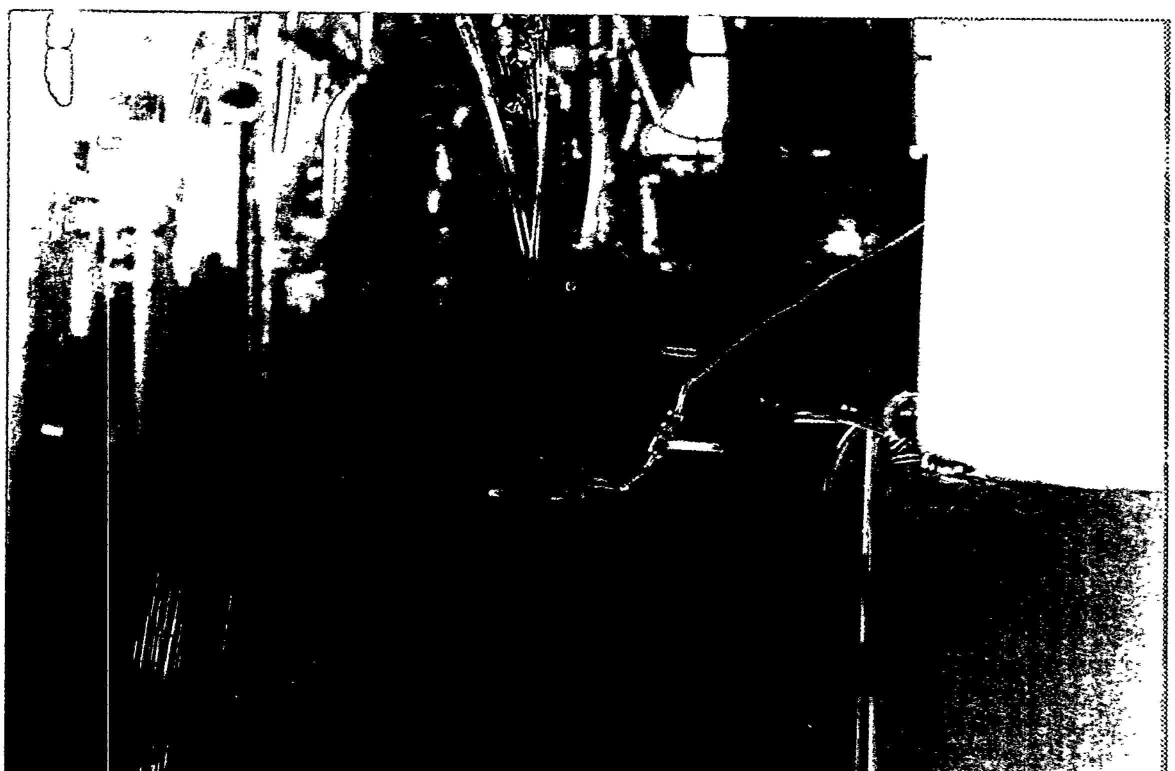


Figure 4.5 Water injection with 4-hole nozzle

respectively. SO_2 gas was injected into the bed just before sorbent feeding, and its inlet concentration was kept as 3000 ppm to simulate the flue gas emitted from a power plant.

For a sulfation test, 0.5 - 0.75 kg of lime was injected so that the initial pressure drop in a bed reactor reached about 15 - 20 cm H_2O. Following the sorbent injection, water was continuously sprayed into the bed with/without circulation of the sorbents elutriated and captured by the first cyclone. The inlet and outlet SO_2 concentrations were continuously measured with a Horiba SO_2 analyzer and recorded in a computer during the tests. Temperature and pressure drop were also recorded into a data acquisition system. As soon as the CFBA unit was turned off, the bed materials and the fines captured by cyclones were collected for determination of total sulfur content and hydration. The total sulfur content and hydration were determined with a LECO sulfur analyzer and a thermogravimetric analyzer (951 TGA, Du Pont Co.), respectively.

The nozzle installed inside the CFBA was taken off and cleaned after each sulfation test. Otherwise, nozzle clogging caused failure in operation of the CFBA. Special care for nozzle clogging was required for these tests. Water flow through the nozzle was controlled by a rotameter connected to a water pump, which was calibrated as shown in Appendix A.

4.3 Results and Discussions

4.3.1 SO_2 removal efficiency in a CFBA

CFBA experiments were conducted in the CFBA to determine the SO_2 removal efficiency under different wetting conditions. First, the effect of the water injection rate was examined. No significant reaction of the sorbent with the SO_2 gas was observed prior to water injection for all of the experiments at 177° C. Figure 4.6 shows the experimental results of the SO_2 removal efficiency for three different water injection rates using a 2-hole nozzle.

The experiments were conducted using a 1 kg batch load of Lime 1 (MMD = 903

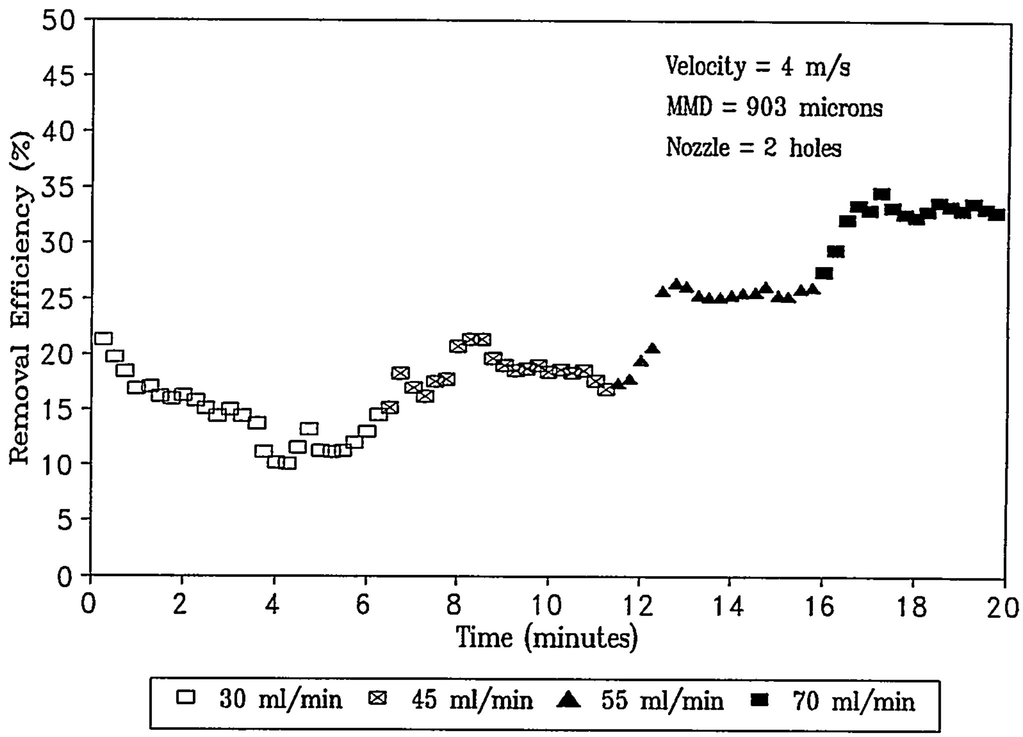


Figure 4.6 SO_2 removal efficiency versus time for various water injection rates.

μm) at a superficial gas velocity of 4 m/s with recycle of collected cyclone 1 fines. Water injection was initially set at 30 ml/min. A steady state SO_2 removal efficiency was attained for each water injection rate tested prior to stepping up the water injection rate from 30 ml/min to 45 ml/min to 55 ml/min and finally to 70 ml/min. The results indicated that the SO_2 removal efficiency was a strong function of the water injection rate. The SO_2 removal efficiency dramatically increased with water injection. As shown in Figure 4.6, the removal efficiency was enhanced from 10 % to 35 % as the water injection rate increased from 30 ml/min to 70 ml/min.

The effect of the number of nozzle holes on the SO_2 removal was examined using the CFBA with and without recycle of the attritted fines. The results indicated that the water spray height through the holes was a very important parameter. First, a stationary bed without circulation was studied. The results comparing a 2-hole nozzle and one with a 4-hole nozzle are illustrated in Figure 4.7. These experiments were conducted using a 0.75 kg load of Lime 2 (MMD = 1764 μm) with a gas velocity of 5 m/s, and a water injection rate of 60 ml/min. Figure 4.7 shows that increasing the number of holes did not significantly increase the SO_2 removal efficiency. Since the water injection flow rate was not changed for the two nozzle experiments, the water pressure decreased for the nozzle with more holes. As a result, the height of water spray for the nozzle with more holes decreased; hence wetting of the densely populated upper region of the bed was limited.

Figure 4.8 compares the 2-hole nozzle with the 3-hole nozzle For a fluidized bed with circulation. These tests were conducted with Lime 2 and at a gas velocity of 5 m/s and a water injection rate of 60 ml/min. Circulation of the fine solids did not start initially ; it took 20 minutes to collect enough to recycle. Figure 4.8 shows that for the first 20 minutes, when there was no recycle, the nozzle with three holes produced a higher SO_2 removal efficiency than the nozzle with two-holes. This is similar to the results shown in Figure 4.7 for no recycle. However, after recycle began, Figure 4.8 shows that the removal efficiency for the 2- hole nozzle was higher than that of the 3-hole nozzle. These results are due to the fact that the densely populated zone in the bed with recycle was located at a higher bed position

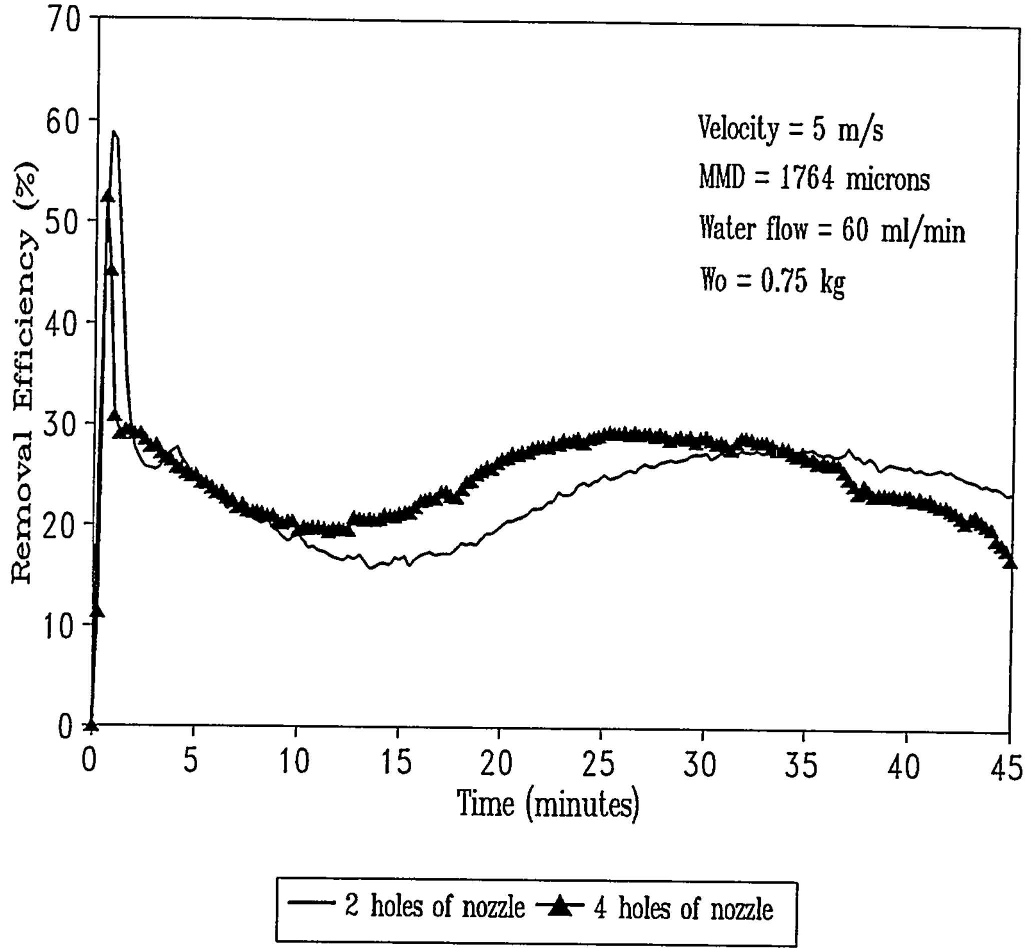


Figure 4.7 Effect of the number of nozzle holes on SO_2 removal efficiency without circulation.

than in the stationary bed without recycle. Again, the water spray height was reduced for the nozzle with 3-holes, hence effective wetting of the dense zone is limited even more. These results suggest that the water spray height is a more significant factor than the number of holes in the nozzle.

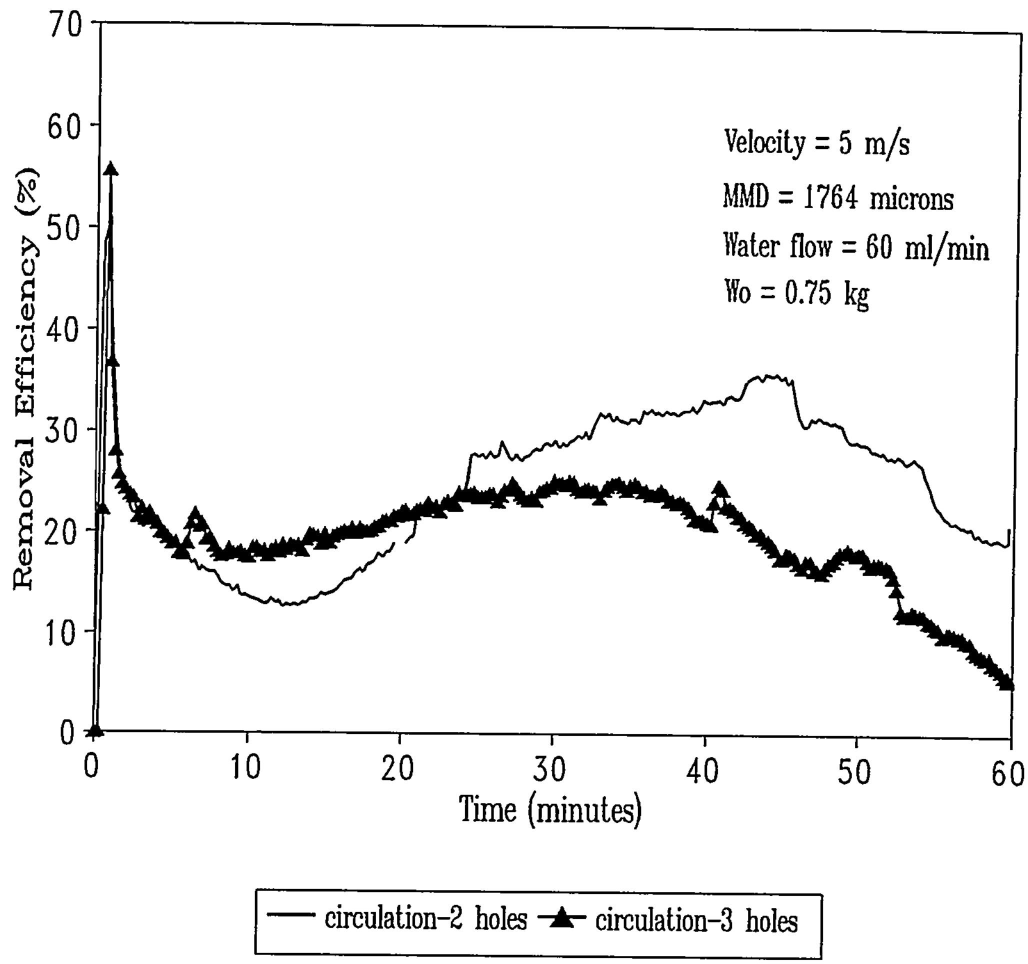


Figure 4.8 Effect of the number of nozzle holes on SO_2 removal efficiency with circulation.

To verify this finding, four extra CFBA runs were conducted using the 2-hole and the 3-hole nozzles. Comparison of the nozzles was made at two flow rates, 30 ml/min and 40 ml/min. Figure 4.9 confirms that the water spray height is indeed a more significant factor than the number of holes in the nozzle. The highest SO_2 removal efficiency was obtained with a water injection rate of 40 ml/min through the 2-hole nozzle. It was observed that the water sprayed higher for the water flow rate of 40 ml/min on the 2-hole nozzle compared to the 3-hole design. The SO_2 removal efficiency and the wetting efficiency in the recycled bed were increased by increasing the water spray height. The droplet size and water pressure

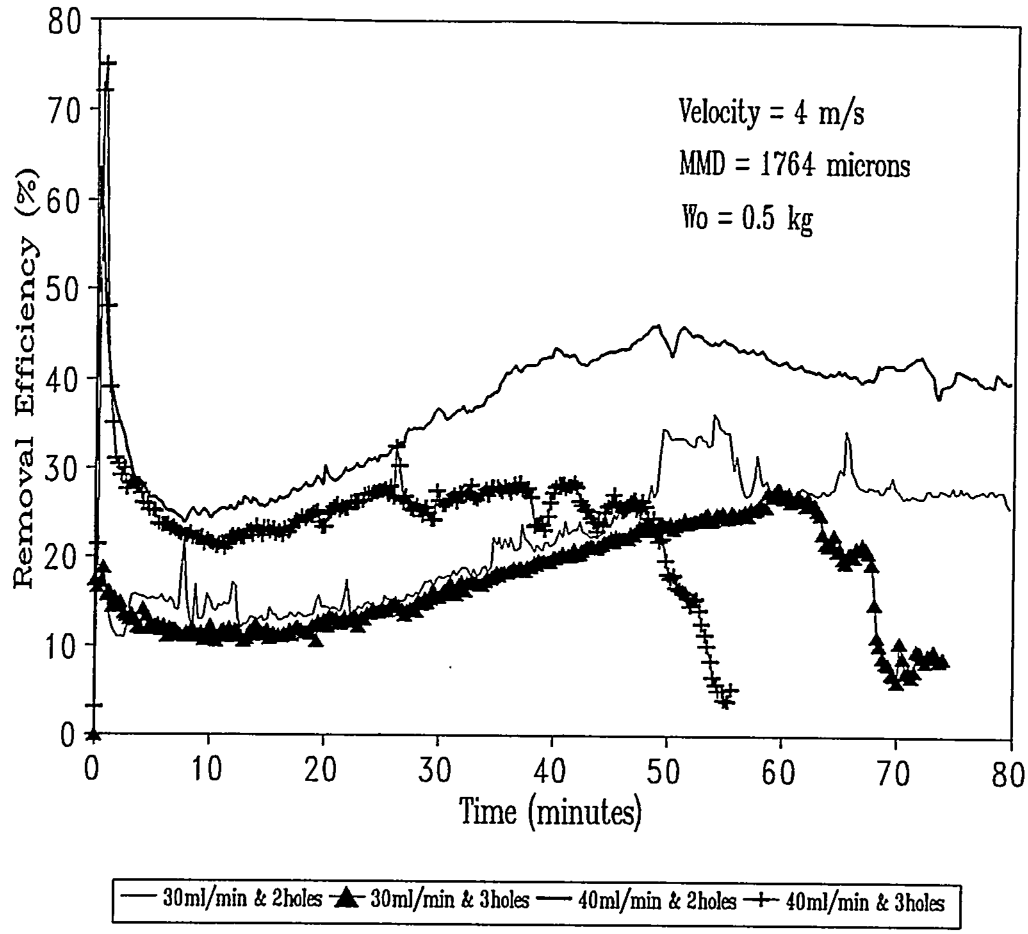


Figure 4.9 Effect of water injection rate and number of holes on SO_2 removal efficiency.

allow for adjustments for increasing the spray height.

The effect of the gas velocity during fluidization was examined. Figure 4.10 compares two gas velocities, 4 m/s and 5 m/s. These experiments were conducted using Lime 2 in a stationary fluidized bed with the 2-hole nozzle at a water injection rate of 40 ml/min without recycle. The SO_2 removal efficiency increased slightly at the lower gas velocity. These results are thought to be due to the fact that the lower gas velocity lowered the position of the dense zone of the bed; hence improved wetting efficiency resulted. Also, the lower gas velocity provided a longer gas residence time. However it must be noted that lowering the gas velocity reduces the extent of mixing in the fluidized bed.

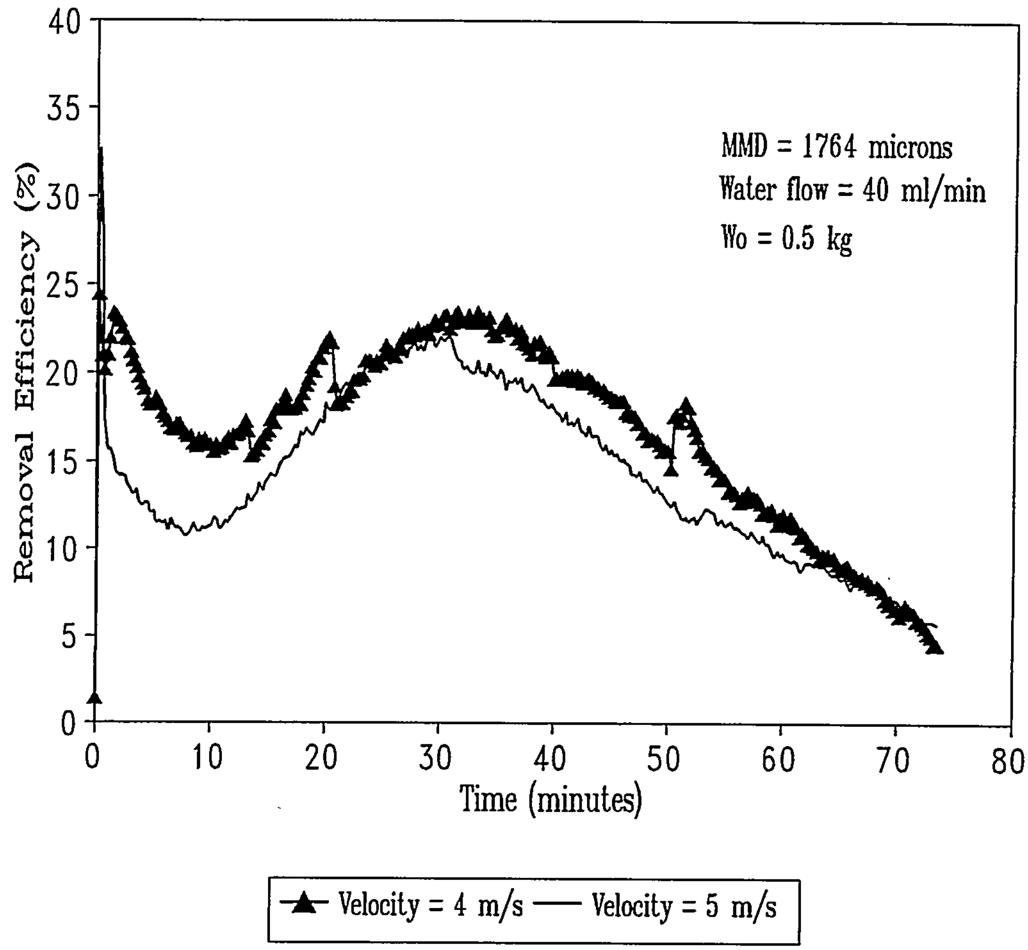


Figure 4.10 Effect of gas velocity on SO_2 removal efficiency.

The effects of bed loading on SO_2 removal efficiency with water injection are shown in Figure 4.11 for two different bed loads, 0.5 kg and 0.75 kg. A stationary bed with water injection flow rate of 40 ml/min for Lime 2 without recycle was used. At the beginning, when hydration and attrition were minimal, the SO_2 removal efficiency was the same for both bed loadings; but after hydration and attrition began, the SO_2 removal efficiency significantly increased for the larger batch load. SO_2 removal efficiency apparently increases with an increase of bed loading. This can be understood by realizing that the higher batch load provides more sorbent and thus increases the Ca/SO_2 ratio.

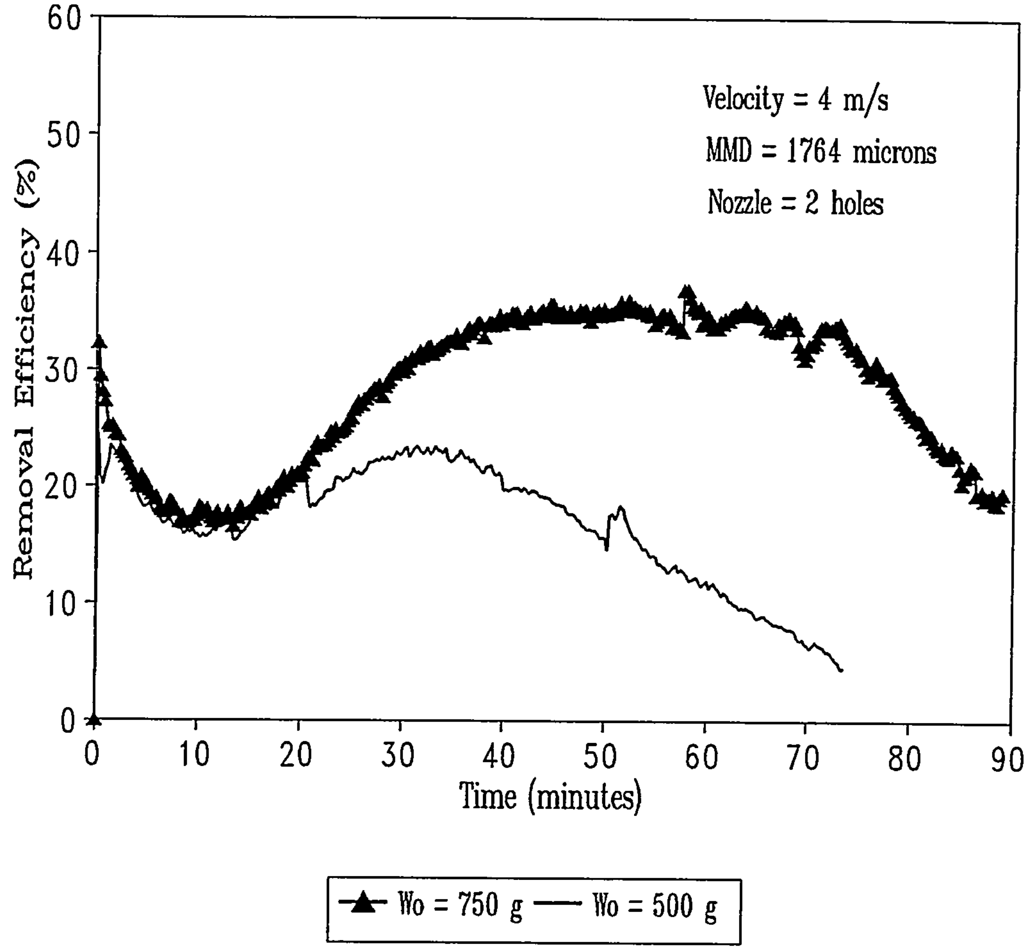


Figure 4.11 Effect of the initial weight of sorbents on SO_2 removal efficiency.

The effect of the water injection flow rate on the extent of attrition and on the SO_2 removal efficiency was studied. Two different water injection flow rates were used, 40 ml/min and 50 ml/min. The CFBA experiments were conducted using Lime 2 at a gas velocity of 5 m/s. The extent of attrition was monitored by measuring the weight of the sorbent captured by the cyclone at regular intervals throughout the run. As shown in Figure 4.12 for both water injection rates, the maximum extent of attrition occurred when the SO_2 removal efficiency was at a maximum. Figure 4.12 also shows that the extent of attrition was greater for the higher water injection flow rate. This is due to the fact that wetted or hydrated lime is more susceptible to attrition because it is more fragile. Once attritted, the sorbent can be better utilized since fresh unreacted sorbent is exposed for further reaction in the gas stream.

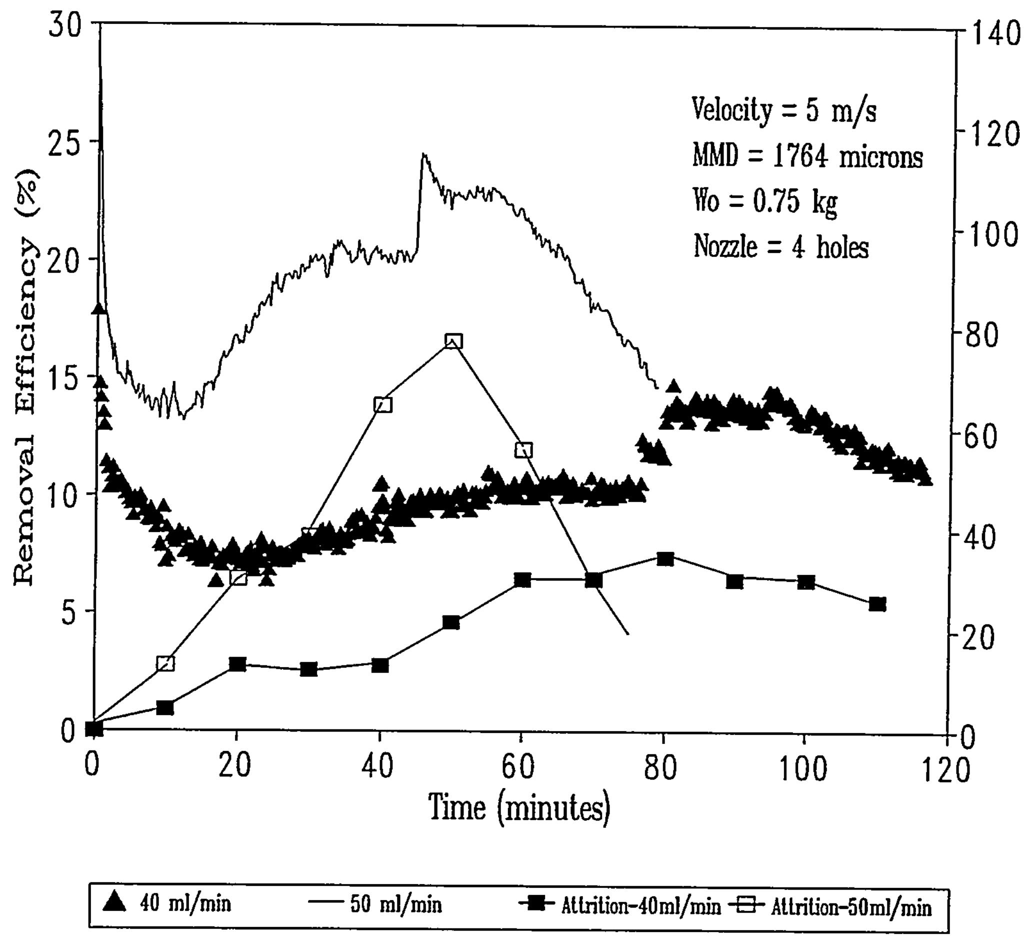


Figure 4.12 SO_2 **removal and attrition at different water injection rate.**

Figure 4.13 shows lime attrition under wet condition. Compared to the typical attrition under dry condition, as shown in Figure 3.3, it occurs slowly at early fluidization. However, as lime becomes hydrated after 20 to 60 minutes, its attrition rapidly increases because hydrated limes are much more fragile than dry limes. As shown in Figure 4.13, attrition occurs more rapidly as water injection rate increases. This result is similar with Jiang's findings [14], which were obtained from the measurement of bed pressure drop.

Regression analysis with the experimental data, shown in Figure 4.13, gives the following equations for the bed weight reduction due to attrition during fluidization. The solid lines in Figure 4.13 are obtained from these equations.

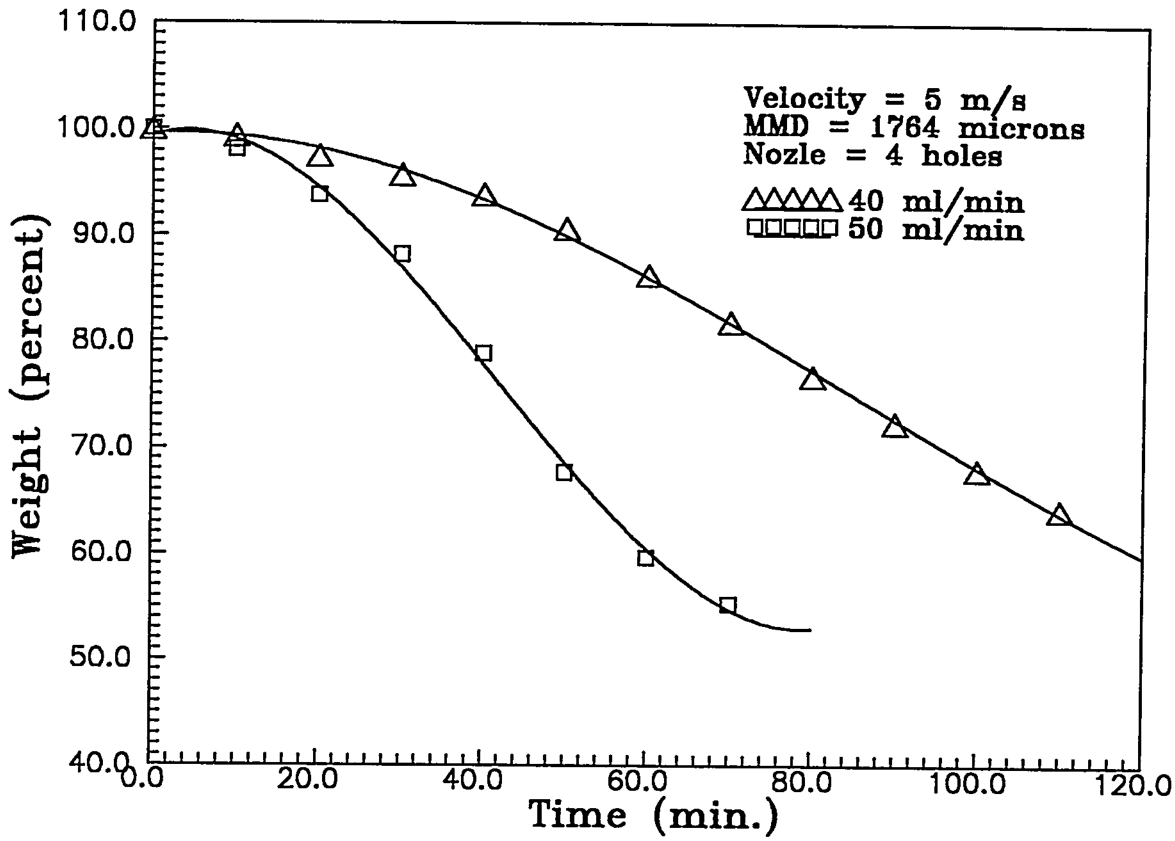


Figure 4.13 Weight reduction of lime during fluidization with water injection.

For the water injection of 40 ml/min ;

$$W_{bed} = 2.20888\times10^{-5}\ t^3 - 0.00573015\ t^2 + 0.0382953\ t + 99.6018 \tag{31}$$

For the water injection of 50 ml/min ;

$$W_{bed} = 0.000227247\ t^3 - 0.0283294\ t^2 + 0.232186\ t + 99.3985 \tag{32}$$

where W_{bed} is weight (g) of lime, and t, time (minute). Note that these empirical equations are applicable to lime fluidization under similar operating conditions.

Figure 4.14 shows lime utilizations as a function of time at different water injection rates. The lime utilization increase slowly at early fluidization, similarly with the extent of attrition as shown in Figure 4.12. As lime is getting hydrated and attritted, its utilization rapidly approaches to 100 %, depending upon the water injection rate.

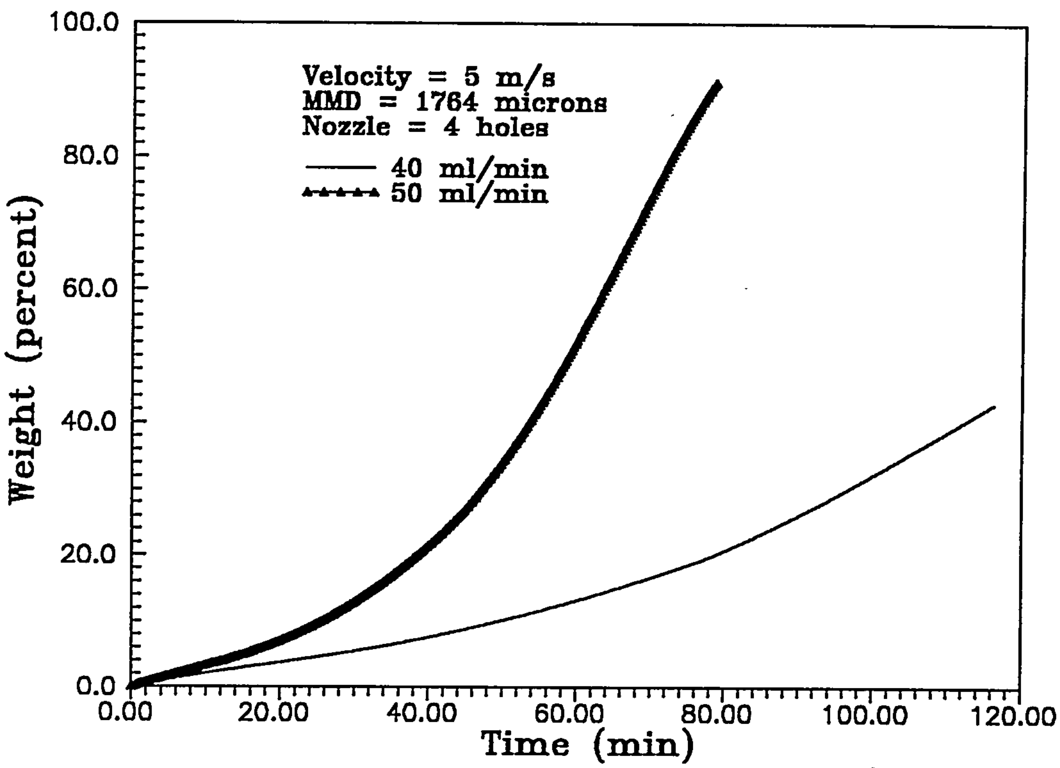


Figure 4.14 Lime utilization at different water injection rates.

4.4 Conclusions

Water injection in dry lime injection FGD processes plays a very important role for the SO_2 removal efficiency. The experimental data obtained from circulating fluidized bed absorber (CFBA) operations under water injection through a newly designed toroidal ring nozzle were presented. For the batch tests conducted, a maximum SO_2 removal of 35% was measured. However, sorbent utilization approached 100% under specific operating conditions. The results suggest that the removal efficiency is a strong function of the water injection rate. In addition, the experimental results indicated that the height of the water spray is a more significant parameter than the number of holes for optimum nozzle design. Also, it was indicated that the spray height should reach the dense zone of the bed for optimum wetting efficiency. No significant effect was found for different gas velocities. Also, it was shown that larger batch loads increased SO_2 removal efficiency. Finally, it was determined that the maximum SO_2 removal efficiency occurred when the extent of attrition was at a maximum, and it was determined that attrition and utilization significantly increased as the sorbent wetting and hydration increased. Further investigations may be worthwhile to evaluate a nozzle design that sprays out smaller droplets, as this would result in a more uniform wetting of the sorbent.

4.5 Recommendations

A specific research objective of this study was to evaluate a novel toroidal water injection system in the CFBA to determine if high degrees of SO_2 removal are obtainable. The experimental results presented above may be useful for the next stage of development of the water injection techniques. In order to obtain sufficient operating information on the novel water injection system, however, further investigation of wetting efficiency for the nozzle is recommended for its quantitative evaluation. In addition, a kinetic study is suggested for identifying sorbent reactivity in the CFBA with the novel water injection system. Both future works are briefly described as follows.

Wetting efficiency of nozzles The CFBA is one of the dry scrubber processes, although it includes a water injection system. It was designed for solids to become completely dried at the top of bed while water is continuously injected. Thus, it is reasonable to assume that the water sprayed into a bed is either vaporized, or captured by the solid sorbents, or penetrated as a vapor through a bed. The penetration can be expressed as the product of rates assuming that the water is neither evaporated nor captured by solids as :

$$\wp = (1 - \phi_e) (1 - \eta_w)$$

where $\wp$ is the penetration (moles/mole) ; ϕ_e, evaporation (moles/mole) ; and η_w, wetting efficiency (moles/mole), respectively. Then the wetting efficiency, η_w, can be obtained as :

$$\eta_w = 1 - \frac{\wp}{(1 - \phi_e)}$$

The penetration, $\wp$ may be obtained by measuring the wet-bulb temperature at the outlet if no penetration of droplets is assumed. The evaporation, ϕ_e, may be determined by computation based on heat and mass balances in an empty CFBA. Therefore, a simulation work for the evaporation in the CFBA and measurement of penetration are necessary for evaluation of the novel water injection system.

Kinetic study with modified TGA apparatus TGA (Thermogravimetric Analyzer) is an instrument that can continuously measure the amount and rate of weight change of material, either as a function of increasing temperature, or isothermally as a function of time. With modification of the TGA, the kinetic information on the hydration and sulfation of limes can be obtained, and may be applied for CFBA operation.

A modified TGA is designed as illustrated in Figure 4.15. The modified TGA

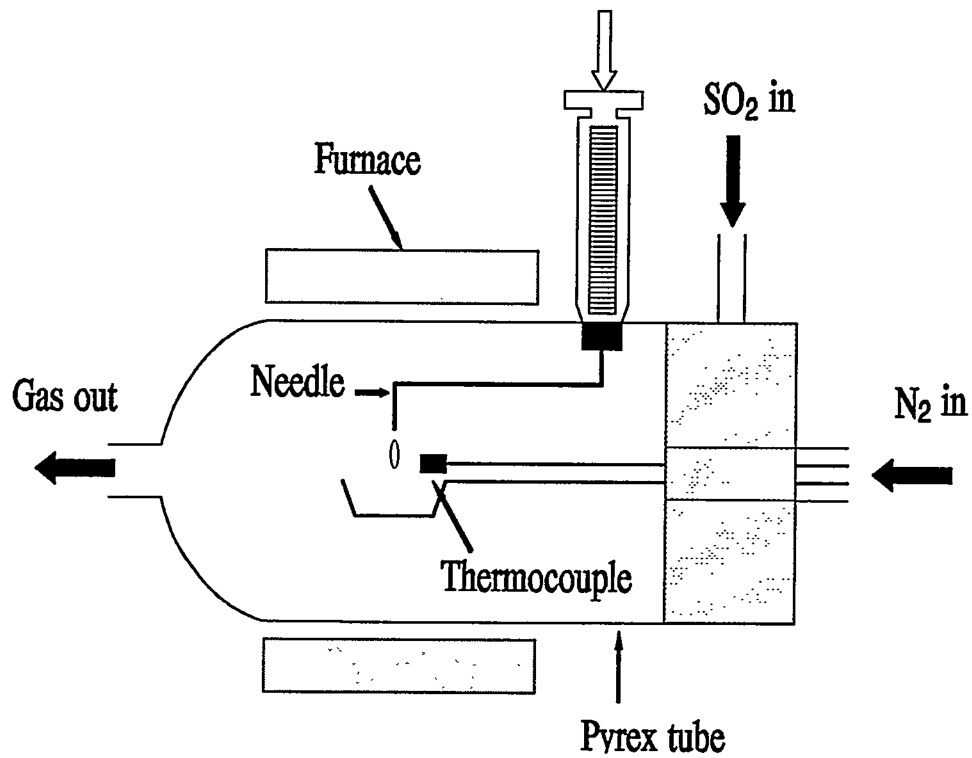


Figure 4.15 A modified thermogravimetric analyzer (TGA).

includes a syringe in order to simulate water injection into a CFBA. Water may be added onto the lime sample placed in a TGA through the needle attached to the syringe.

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APPENDIX A

CFBA UNIT CALIBRATION

Measurement of Cyclone Efficiency The collection efficiencies of the first and second cyclones were measured with $NaHCO_3$ of 77.6, 73.0, and 46.1μm in mass mean diameters. The measurements of collection efficiencies are summarized in Table A.1. The first cyclone captured 97.0% and 99.5% of the particles with the mass mean diameter of 77.6 and 73.0μm at the velocity of 2 m/s and 2.5 m/s, respectively. The solids captured by the first cyclone are recirculated into a bed reactor. The circulation rate can be expressed as $\gamma(dp) = \eta(dp) \times \kappa(dp)$, where $\gamma(dp)$ = circulation rate, $\eta(dp)$ = collection efficiency of cyclone, and $\kappa(R)$ = elutriation rate. Therefore, over 99% of the particle greater than 73 μm in MMD is elutriated from the bed and recirculated into the bed reactor. The second cyclone efficiencies measured with particle of 46.1μm (MMD) were 97.54% and 99.89% at 2 m/s and 2.5 m/s, respectively.

Table A.1 Collection efficiencies of 1st. and 2nd. cyclones.[1]

Velocity	1st.Cyclone	2nd.Cyclone
2.00 m/s	97.00 %[2]	97.54 %[4]
2.52 m/s	99.47 %[3]	99.89 %[4]

1) Test Materials : $NaHCO_3$

2) Test Size : <44μ(1.1%), 44-63μ(15.5%), 63-75μ(40.4%), 75-90μ(27.8%), 90-150μ(15.2%)

3) Test Size : <44μ(4.5%), 44-63μ(26.9%), 63-75μ(32.4%), 75-90μ(21.0%), 90-150μ(15.2%)

4) Test Size : <44μ(20.5%), 44-63μ(79.5%)

Air Flow Calibrations Calibrations of air flow rate and pressure drop have been done before the operation of bench scale unit. This unit has three rotameters controlling air flow through a bed reactor, sorbent injection and circulation system, and five magnehelics for measurements of pressure drop along the bed reactor. The rotameter calibrations were carried out with a wet test meter, a bubble meter and a roots meter (Model 5M125TC, Dresser Systems, Inc.), and the magnehelics were adjusted by using a manometer.

The rotameters for sorbent injection and circulation system were calibrated with a wet meter whose correction factor was determined by a bubble meter. The air flow rate and the correction factor of wet meter at standard conditions are calculated by using the following equation for each test :

$$V_s = (P_m/P_s)(T_s/T_m)V_m$$

where V_s = volume at standard conditions (25 °C, 760mmHg)

P_m = barometric pressure corrected for internal meter pressure, mmHg

T_m = temperature of meter, K

P_s = barometric pressure at standard conditions, 760 mmHg

T_s = temperature at standard conditions, K=298.16

V_m = volume as measured by wet meter, liter

$$\text{Error} = (V_w - V_b)/V_b$$

where V_w = air volume in a wet meter, liter

V_b = air volume in a bubble meter, liter

$$\text{Correction Factor} = 1/(1+\text{Error})$$

The calibration curves for the rotameter 1 (sorbent injection system), for the rotameter 2 (circulation system), and main flow conroller are illustrated in Figure A.1. The squared correlation coefficients (R^2) of two rotameters (2nd. and 3rd.) are larger than 0.99. Air flow of a bed reactor can be controlled with a large rotameter, which was already calibrated as shown in Figure A.2. Its calibration curve is verified by using a roots meter (Model 5M125TC, Dresser Systems, Inc.).

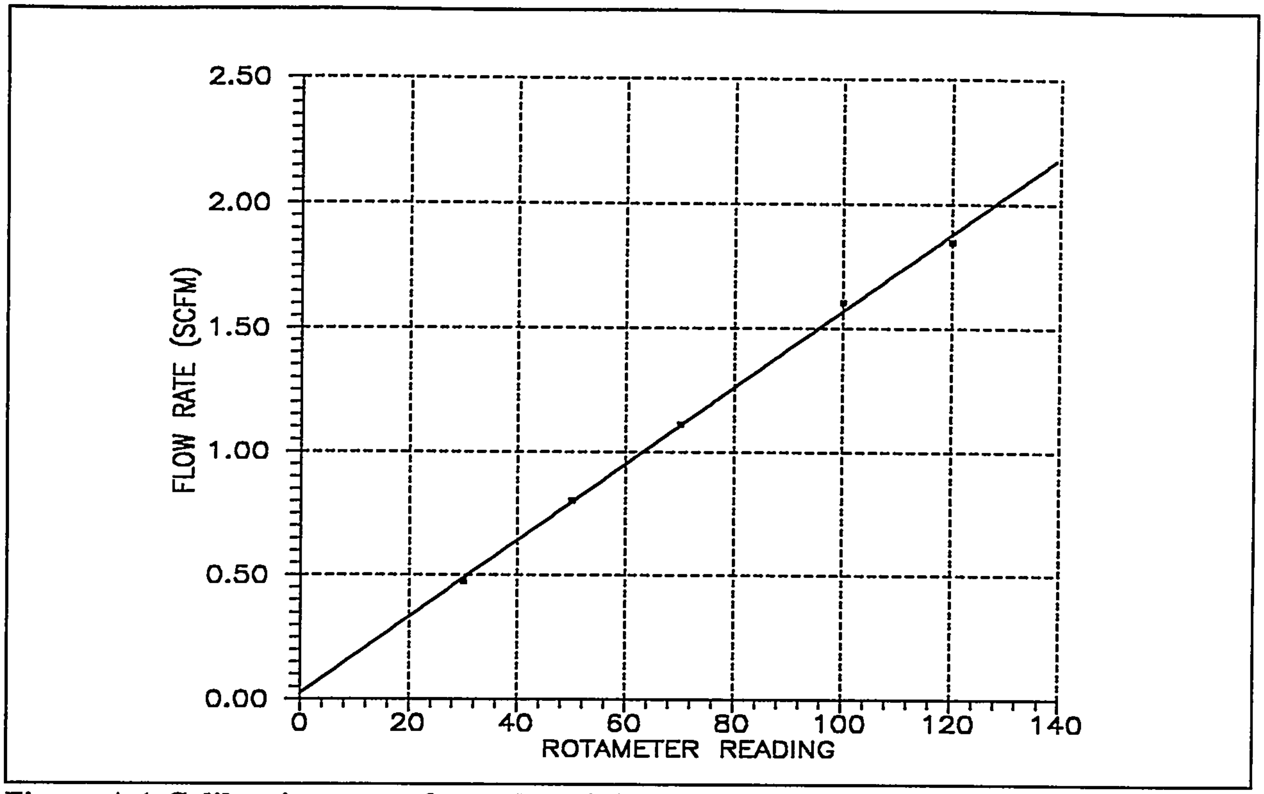

Figure A.1 Calibration curve for sorbent injection.

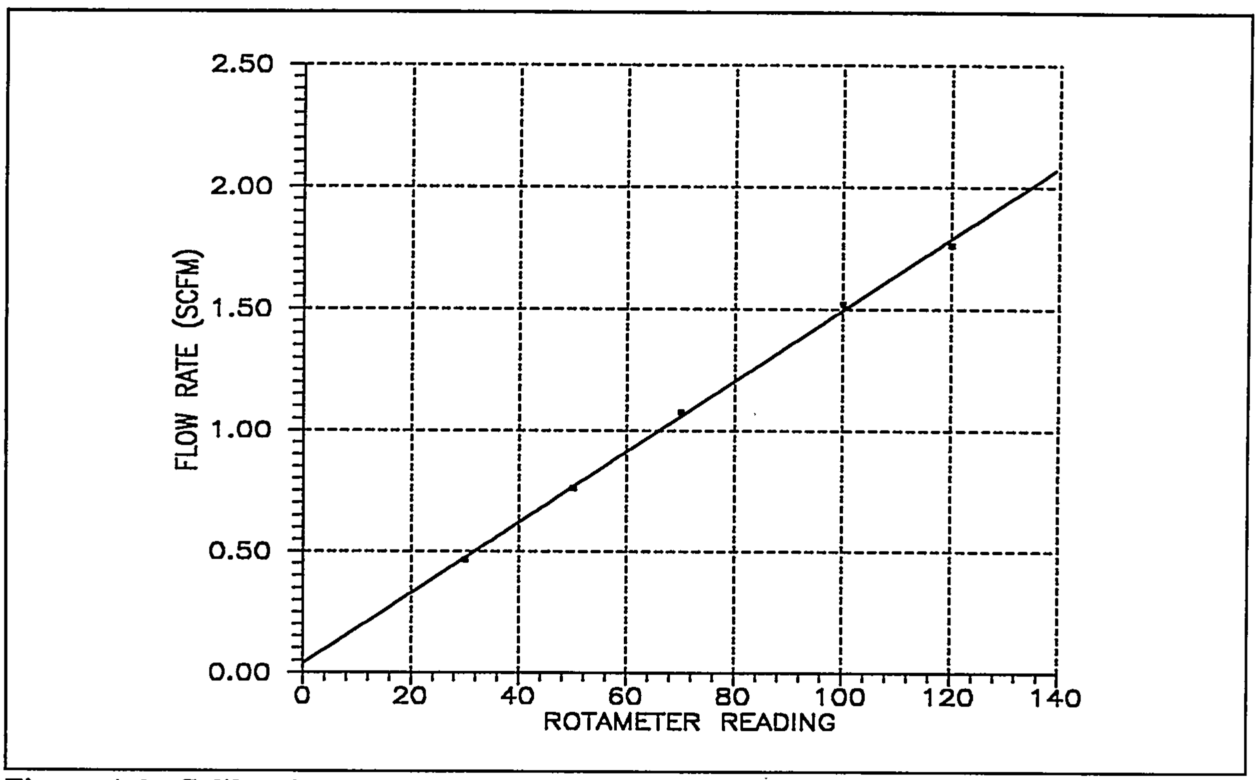

Figure A.2 Calibration curve for recirculation.

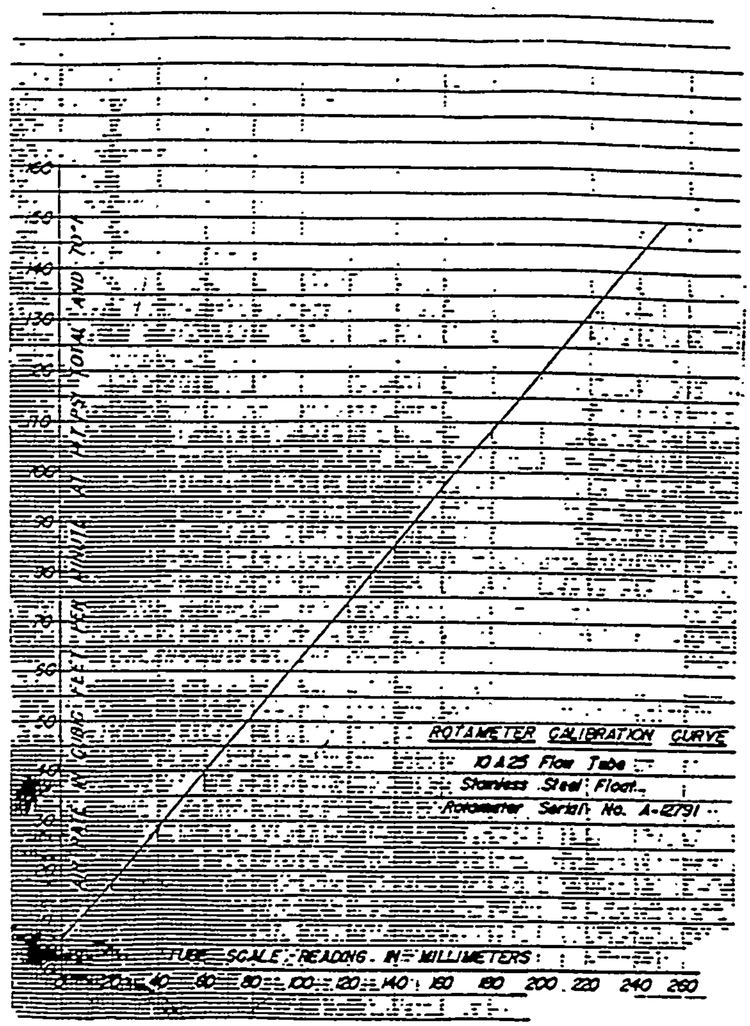

Figure A.3 Calibration curve for main air flow.

Water Injection Water injection through nozzle was calibrated and its calibration curve is given in Figure A.3. The rotameter connected to nozzle has two readings ; white ball reading and black ball reading. The white ball reading is used for high water flow, and the black ball raeding for low water flow.

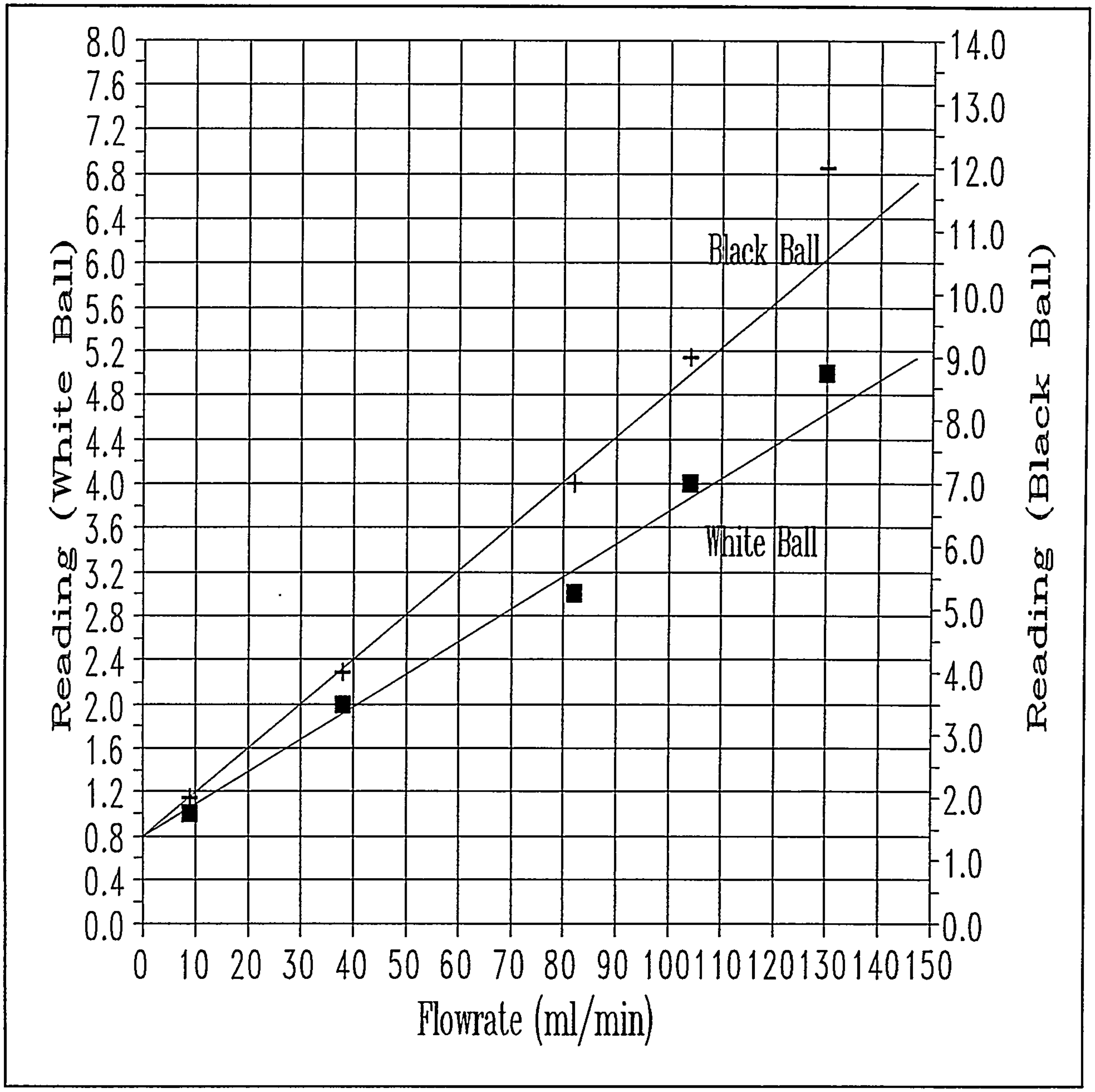

Figure A.4 Calibration of water injection through a nozzle

APPENDIX B

ANALYTICAL METHODS AND MEASUREMENTS

Size Distribution Measurements The size distribution for each sample has been measured by sieving method, which is most widely used and reliable method of determining the particle size and distribution of materials larger than 40 μm.

(1) Lime 1 (MMD =1764 microns)

Minimum micron	mesh	Maximum micron	mesh	Mean micron	Weight(g) (1)	(2)	Ave. weight	Weight (%)	DiaxWeight% micron	Ave Dia./Weight %
400.0	50	595.0	30	497.5	2.40	2.20	2.30	0.92	4.57	1.85E-05
595.0	30	841.0	20	718.0	0.10	0.10	0.10	0.04	0.29	5.57E-07
841.0	20	1008.0	18	924.5	0.30	0.20	0.25	0.10	0.92	1.08E-06
1008.0	18	1190.0	16	1099.0	8.80	11.20	10.00	4.00	43.92	3.64E-05
1190.0	16	2000.0	10	1595.0	149.20	157.70	153.45	61.33	978.23	3.85E-04
2000.0	10	2380.0	8	2190.0	89.40	78.80	84.10	33.61	736.13	1.53E-04
				SUM	250.20	250.20	250.20	100.00		5.94E-04

Mass Mean Dimeter = 1764.06
Surface Mean Dia. = 1682.12

(2) Lime 2 (MMD =903 microns)

Minimum micron	mesh	Maximum micron	mesh	Mean micron	Weight(g) (1)	(2)	Ave. weight	Weight (%)	DiaxWeight% micron	Ave Dia./Weight %
0.0	~	297.0	50	148.5	4.30	4.00	4.15	1.65	2.45	1.11E-04
297.0	50	420.0	40	358.5	0.10	0.30	0.20	0.08	0.29	2.22E-06
420.0	40	595.0	30	507.5	0.70	1.20	0.95	0.38	1.92	7.46E-06
595.0	30	841.0	18	718.0	74.90	82.10	78.50	31.27	224.51	4.35E-04
841.0	20	1000.0	18	920.5	82.10	78.10	80.10	31.91	293.69	3.47E-04
1000.0	18	1190.0	16	1095.0	89.20	85.10	87.15	34.71	380.12	3.17E-04
				SUM	251.30	250.80	251.05	100.00		1.22E-03

Mass Mean Dimeter = 902.99
Surface Mean Dia. = 819.58

Surface Area Measurements The total surface area including those of pores and crevices in the particles is measured with Monosorb Surface Area Analyzer (Model MS-12, Quantachrome Co.). The analyzer measures the quantity of a gas adsorbed on a solid surface, by sensing the change in thermal conductivity of a flowing mixture of an adsorbate and an inert carrier gas, usually nitrogen and helium. The total surface area can be determined form the weight of adsorbate required to cover the surface with one molecular layer, which is governed by the BET equation. Therefore, the surface area measured by this method may be termed as a BET surface area.

Table A.1 BET surface area measurements.

Sample #	Counts (sq m)	Weight of cell and sample (g)	Weight of sample (g)	Specific Area (sq m/g)	Surface Area (sq m/g) Min.	Max.	Ave.
Lime-1	1.98	12.5895	1.5257	1.30	1.30	1.26	1.27
	2.00	12.4303	1.5930	1.26			
	1.48	9.4173	1.1639	1.27			
Lime-2	1.83	12.3672	1.3034	1.40	1.40	1.30	1.36
	1.43	11.9332	1.0959	1.30			
	1.72	9.4964	1.2430	1.38			

Weight of Blank Cell - cell-1 :	11.0638 g
cell-2 :	10.8373 g
cell-3 :	8.2534 g

Bulk Density The bulk density of granular solids varies with the degree of bed packing-whether it is loose or dense. The order of magnitude of differences between loose and compacted bed voidage ranges normally from 5 to 20 %. For our purpose, the bulk density of each sample was measured under the gravity flow of bulk solids through the pipe.

Table A.2 Bulk density measurements.

Sample #	Hi (cm)	Hf (cm)	Total Height(cm)	Volume (cu.cm)	Weight (g)	Bulk Density (g/cu.cm)	Ave. Bulk Density (g/cu.cm)
Lime 1	12.000	24.000	12.000	84.821	86.600	1.021	1.122
	24.000	36.300	12.300	86.941	99.100	1.140	
	36.300	52.500	16.200	114.508	138.000	1.205	
Lime 2	14.000	21.600	7.600	53.720	53.400	0.994	1.041
	21.600	36.000	14.400	101.785	104.300	1.025	
	36.000	53.300	17.300	122.283	135.100	1.105	

* Note : Bulk Density of Gravity Folw through the Packed Column
Column (Plexi Glass) Diameter = 3.0 cm (1.375 inches)

Pore Size Measurement Pore size measurements were performed with Micrometrics Poresizer 9310. The volume of mercury is forced into the pores of a sample by different pressures. The mercury is intruded into the pores in the sample under increasing pressure, resulting in a linear decrease of electrical capacitance of a capillary tube with increasing pore volume. The capacitance changes are converted to volume change of mercury intruded into pores. The mercury porosimetry is based on the capillary law governing liquid penetration into small pores. For cylindrical pores, the capillary law is expressed as:

$$D = -(1/4P) \times \gamma\cos\theta$$

where D = pore diameter

P = pressure

γ = surface tension (484 dynes/cm for mercury)

θ = contact angle (130° is assumed)

The samples tested are lime-1 (between 1095 μ and 2380 μ), and lime-2 (between 595

Table A.3 Pore size measurements.

ITEM	LIME-1			LIME-2		
	(1)	(2)	Ave.	(1)	(2)	Ave.
TOTAL INTRUSION VOLUME (cu.cm/g)	0.32	0.34	0.33	0.34	0.49	0.42
TOTAL PORE AREA (sq.m/g)	1.09	1.31	1.20	0.47	1.35	0.91
MEDIAN PORE DIAMETER (microns by VOLUME)	1.14	1.09	1.11	4.83	1.92	3.38
MEDIAN PORE DIAMETER (microns by AREA)	0.95	0.88	0.91	1.34	0.78	1.06
AVERAGE PORE DIAMETER (microns)	1.19	1.03	1.11	2.92	1.46	2.19
BULK DENSITY (g/cu.cm)	1.47	1.43	1.45	1.25	1.31	1.28
APPARENT (SKELETAL) DENSITY (g/cu.cm)	2.80	2.77	2.78	2.18	3.74	2.96
% CAPILLARY	92.24	83.71	87.98	91.54	74.02	82.78

μ and 1095 μ). The measurements are summarized in Table A.3.

Microscopic Observation Sorbents particle characterization such as crystal habit, particle morphology, and size distribution may provide information useful in identifying solids attrition. The visual observation of solid characterization was carried out with the microscope connected to an image analysis system.

Total Sulfur Analysis Total sulfur contained in reacted sorbents was measured with LECO Sulfur Analyzer for the mass balance of SO_2 removal in CFBA.

Table A.5 Shape factor of lime obtained from microscope.

No.	t=0	No.	t=0.5hr	No.	t=1hr	No.	t=2hr	No.	t=3hr	No.	t=5hr	No.	t=15hr	No.	t=20hr
1	0.74	1	0.423	1	0.648	1	0.631	1	0.942	1	0.799	1	0.865	1	0.872
2	0.43	2	0.548	2	0.506	2	0.592	2	0.723	2	0.662	2	0.822	2	0.803
3	0.856	3	0.585	3	0.665	3	0.972	3	0.566	3	0.906	3	0.795	3	0.762
4	0.854	4	0.695	4	0.82	4	0.618	4	0.56	4	0.659	4	0.892	4	0.746
5	0.709	5	0.818	5	0.76	5	0.646	5	0.789	5	0.671	5	0.711	5	0.707
6	0.672	6	0.834	6	0.743	6	0.607	6	0.904	6	0.896	6	0.854	6	0.947
7	0.561	7	0.801	7	0.827	7	0.582	7	0.719	7	0.887	7	0.501	7	0.689
8	0.531	8	0.806	8	0.71	8	0.669	8	0.783	8	0.542	8	0.479	8	0.771
9	0.732	9	0.682	9	0.868	9	0.996	9	0.799	9	0.492	9	0.754	9	0.86
10	0.845	10	0.627	10	0.696	10	0.352	10	0.658	10	0.709	10	0.373	10	0.874
11	0.739	11	0.599	11	0.945	11	0.774	11	0.749	11	0.903	11	0.752	11	0.951
12	0.905	12	0.636	12	0.937	12	0.658	12	0.63	12	0.885	12	0.733	12	0.78
13	0.814	13	0.745	13	0.42	13	0.845	13	0.754	13	0.707	13	0.664	13	0.808
14	0.923	14	0.71	14	0.907	14	0.745	14	0.894	14	0.592	14	0.662	14	0.903
15	0.869	15	0.793	15	0.629	15	0.773	15	0.53	15	0.595	15	0.754	15	0.727
16	0.943	16	0.91	16	0.859	16	0.679	16	0.658	16	0.752	16	0.884	16	0.778
17	0.507	17	0.866	17	0.76	17	0.889	17	0.694	17	0.624	17	0.797	17	0.647
18	0.694	18	0.689	18	0.849	18	0.592	18	0.752	18	0.71	18	0.782	18	0.944
19	0.682	19	0.58	19	0.914	19	0.82	19	0.722	19	0.722	19	0.865	19	0.655
20	0.854	20	0.795	20	0.789	20	0.843	20	0.715	20	0.657	20	0.633	20	0.812
21	0.608	21	0.573	21	0.812	21	0.925	21	0.661	21	0.695	21	0.64	21	0.876
22	0.741	22	0.879	22	0.766	22	0.933	22	0.722	22	0.854	22	0.614	22	0.674
23	0.495	23	0.833	23	0.677	23	0.845	23	0.769	23	0.742	23	0.931	23	0.848
24	0.662	24	0.766	24	0.865	24	0.489	24	0.863	24	0.847	24	0.844	24	0.902
25	0.627	25	0.613	25	0.901	25	0.578	25	0.876	25	0.879	25	0.575	25	0.952
26	0.786	26	0.523	26	0.766	26	0.663	26	0.767	26	0.466	26	0.706	26	0.529
27	0.881	27	0.948	27	0.855	27	0.993	27	0.829	27	0.838	27	0.661	27	0.702
28	0.747	28	0.733	28	0.863	28	0.784	28	0.889	28	0.571	28	0.901	28	0.673
29	0.75	29	0.813	29	0.794	29	0.793	29	0.932	29	0.57	29	0.709	29	0.886
30	0.932	30	0.838	30	0.793	30	0.597	30	0.911	30	0.81	30	0.598	30	0.856
31	0.948	31	0.837	31	0.669	31	0.841	31	0.875	31	0.862	31	0.645	31	0.899
32	0.91	32	0.563	32	0.678	32	0.853	32	0.711	32	0.663	32	0.707	32	0.855
33	0.618	33	0.549	33	0.813	33	0.892	33	0.816	33	0.754	33	0.912	33	0.898
34	0.846	34	0.413	34	0.86	34	0.867	34	0.891	34	0.58	34	0.704	34	0.794
35	0.68	35	0.81	35	0.522	35	0.838	35	0.576	35	0.566	35	0.86	35	0.547
36	0.813	36	0.527	Max	0.945	36	0.835	36	0.853	36	0.48	36	0.711	36	0.87
37	0.901	37	0.974	Min	0.42	37	0.635	37	0.633	37	0.703	37	0.719	37	0.812
Max	0.948	38	0.891	Ave	0.768	38	0.494	38	0.982	38	0.792	38	0.572	38	0.895
Min	0.43	39	0.842			39	0.468	39	0.87	39	0.719	39	0.808	39	0.512
Ave	0.751	40	0.822			40	0.876	40	0.73	Max	0.906	40	0.704	40	0.899
		41	0.898			41	0.849	41	0.549	Min	0.466	41	0.728	41	0.611
		42	0.85			42	0.734	42	0.81	Ave	0.711	42	0.572	42	0.885
		43	0.421			43	0.702	43	0.977			43	0.817	43	0.911
		44	0.685			44	0.86	44	0.673			44	0.66	44	0.79
		45	0.627			45	0.778	45	0.584			45	0.49	45	0.648
		Max	0.974			46	0.854	46	0.749			46	0.804	46	0.663
		Min	0.413			47	0.611	47	0.827			47	0.827	47	0.647
		Ave	0.719			48	0.541	48	0.705			48	0.718	48	0.798
						49	0.961	Max	0.982			49	0.941	49	0.82
						50	0.974	Min	0.53			50	0.45	50	0.683
						51	0.488	Ave	0.761			51	0.686	51	0.644
						Max	0.996					52	0.658	Max	0.952
						Min	0.352					53	0.683	Min	0.512
						Ave	0.741					54	0.89	Ave	0.784
												Max	0.941		
												Min	0.373		
												Ave	0.728		

APPENDIX C

FINITE DIFFERENCE EQUATION AND FORTRAN PROGRAM FOR POPULATION MODEL

C.1 Numerical Solution

For the numerical solution of Equation (27), an implicit method based on the backward Euler method was applied. Equation (27) is written as ;

$$\frac{W_{i,j+1} - W_{i,j}}{\Delta t} = -\left[(1-\eta_c)\kappa(d_{pi}) + \frac{2k_a}{3} - \frac{5k_a W_{\min} d^3_{pi,MMD}}{3W_o d^3_{pi}}\right] W_{i,j} + \frac{k_a}{3}\left(d_{pi} - \frac{W_{\min} d^3_{pi,MMD}}{W_o d^2_{pi}}\right)\frac{W_{i+1,j+1} - W_{i,j+1}}{\Delta d_p} \qquad \text{(C.1)}$$

Then Equation (28) is obtained by arranging the above equation. Equation (28) may be written in a matrix form as ;

$$\begin{bmatrix} \frac{1+\alpha}{\beta} & -\frac{\alpha}{\beta} & 0 & 0 & .. & 0 & 0 \\ 0 & \frac{1+\alpha}{\beta} & -\frac{\alpha}{\beta} & 0 & .. & 0 & 0 \\ 0 & 0 & 0 & ... & & 0 & 0 \\ 0 & 0 & 0 & ... & & \frac{1+\alpha}{\beta} & -\frac{\alpha}{\beta} \\ 0 & 0 & 0 & ... & & 0 & \frac{1+\alpha}{\beta} \end{bmatrix} \begin{bmatrix} W_{1,j+1} \\ W_{2,j+1} \\ \vdots \\ W_{k-2,j+1} \\ W_{k-1,j+1} \end{bmatrix} = \begin{bmatrix} W_{1,j} \\ W_{2,j} \\ \vdots \\ W_{k-2,j} \\ W_{k-1,j} + (\frac{\alpha}{\beta}) W_{k,j+1} \end{bmatrix} \qquad \text{(C.2)}$$

Therefore, the unknowns, Wi,j+1 in Equation (A.2) are determined with initial and boundary conditions. The FORTRAN program for the solution is given in the following pages.

C.2 Main Program and Subroutines

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      THIS IS A MAIN PROGRAM FOR NUMERICAL SOLUTION OF UNSTEADY-STATE  C
C      THE PROGRAM CALLS THE FOLLOWING SUBROUTINES :                    C
C                                                                       C
C      CFBADAT : READ INPUT DATA                                        C
C      CFBAOUT : WRITE COMPUTATION RESULTS                              C
C      UMFTERM : COMPUTE MINIMUM FLUIDIZATION VELOCITY AND TERMINAL     C
C                VELOCITY                                               C
C      UNPOPUL : COMPUTE THE PARTIAL DIFFERENTIAL EQUATION IN AN        C
C                UNSTEADY-STATE POPULATION MODEL                        C
C      DIAG    : SOLVE THE TRIDIAGONAL EQUATIONS.  CALLED BY UNPOPUL.   C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT REAL*8 (A-H,O-Z)

      COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
      COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,TIME,Ka,ETAc
      COMMON/A3/N,Ntime
      COMMON/A4/dpAve,dpL1,dpH1,dpW1
      COMMON/A5/TITLE
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK

      REAL*8 dpAve(10),W(1000),dp(10),Ut(10),ReUt(10)
      REAL*8 dpL1(10),dpH1(10),dpW1(10),dpL(10),dpH(10),dpW(10)
      REAL*8 Umf(10),Umf1(10),Umf2(10)
      CHARACTER TITLE*60,WHICH1*6,WHICH2*6,WHICH3*6,CHECK*6

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      READ INPUT DATA                                                  C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL CFBADAT

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      WRITE INPUT DATA                                                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL CFBAOUT

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      COMPUTATION OF MINIMUM FLUIDIZATION AND TERMINAL VELOCITY        C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      Ndp=N
      DO 10 I=1,N
   10 dp(I)=dpAve(I)

      CALL UMFTERM(dp,Ndp,Ut,ReUt,Umf1,Umf2,Umf,0)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      WRITE Umf and Ut                                                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL CFBAOUT

      DO 20 I=1,N
   20 WRITE(6,15)dpAve(I),Umf1(I)/100.,Umf2(I)/100.,ReUt(I),
     *Ut(I)/100.
   15 FORMAT(5X,3(F10.3),5X,2(F10.3)/)
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     SOLUTION OF THE UNSTEADY STATE POPULATION MODEL                   C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL CFBAOUT

      Ddp=Ddp1
      Dt=Dt1
      DO 30 I=1,N
      dpL(I)=dpL1(I)
      dpH(I)=dpH1(I)
   30 dpW(I)=dpW1(I)

      CALL UNPOPUL(dpL,dpH,dpW,Ndp,W,Ddp,Dt)

      STOP
      END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     THIS SUBROUTINE READS INPUT DATA NECESSARY FOR COMPUTATIONS.     C
C     THE DATA CAN BE GIVEN THROUGH THE SCREEN OR DATA FILE.  THE      C
C     VARIABLES FOR INPUT DATA ARE DESCRIBED AS FOLLOWS :              C
C                                                                      C
C     dpAve(I) : MEAN DIAMETER (microns)                               C
C     dpL(I)   : LOW LIMITS OF SIZE RANGES (microns)                   C
C     dpH(I)   : HIGH LIMITS OF SIZE RANGES (microns)                  C
C     dpW(I)   : WEIGHT OF SOLIDS AT EACH DISCRETE SIZE (g)            C
C     pDensity : DENSITY OF SOLIDS (g/cm3)                             C
C     gDensity : GAS DENSITY (g/cm3)                                   C
C     Viscosity: VISCOSITY OF GAS (g/cm/sec)                           C
C     Gravity  : GRAVITATIONAL CONSTANT (cm/sec2)                      C
C     BedDiam  : DIAMETER OF BED REACTOR (cm)                          C
C     BedHeight: HEIGHT OF BED REACTOR (cm)                            C
C     ETAc     : COLLECTION EFFICIENCY OF THE FIRST CYCLONE (%)        C
C     gVelocity: GAS VELOCITY (cm/sec)                                 C
C     N        : NUMBER OF DISCRETE SIZES                              C
C     Ka       : ATTRITION RATE CONSTANT (/sec)                        C
C     Ddp1     : SIZE INTERVAL FOR POPULATION MODEL (microns)          C
C     Dt1      : TIME INTERVAL FOR POPULATION MODEL (sec)              C
C     Ntime    : NUMBER OF ITERATION FOR POPULATION MODEL              C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      SUBROUTINE CFBADAT

      IMPLICIT REAL*8 (A-H,O-Z)

      COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
      COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,TIME,Ka,ETAc
      COMMON/A3/N,Ntime
      COMMON/A4/dpAve,dpL1,dpH1,dpW1
      COMMON/A5/Title
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK

      REAL*8 dpAve(10),dpL1(10),dpH1(10),dpW1(10),Ka

      CHARACTER TITLE*60,WHICH1*6,WHICH2*6,WHICH3*6,CHECK*6

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     INPUT DATA                                                       C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      WRITE(*,1)
    1 FORMAT(////////////////
     *        5X,'                                                   '/
     *        5X,'                                                   '/
     *        5X,'THIS PROGRAM IS WRITTEN FOR APPLICATION OF CFBA.   '/
     *        5X,'                         by                        '/
     *        5X,'                   SANG-KWUN LEE                   '/
     *        5X,'              UNIVERSITY OF CINCINNATI             '/
     *        5X,'    CIVIL & ENVIRONMENTAL ENGINEERING DEPT.        '/
     *        5X,'                CINCINNATI, OH 45219               '/
     *        5X,'                   (513) 556-3687                  '/
     *        5X,'                                                   '/
     *        5X,'                                                   '/
     *        5X,'                                                   '///
     *        5X,'      Strike the RETURN key to continue....     '/////)
      READ(*,*)
   50 FORMAT(A6)
      WRITE(*,2)
    2 FORMAT(//////////4X, '                                   '/
```

```
     *         5X, '          DO YOU WANT TO RUN THIS PROGRAM             '/
     *         5X, '        WITH DATA FILE NAMED AS "CFBA.DAT" ?          '/
     *         5X, '                                                      '/
     *         5X, '                   Enter (Y/N)        '///////////)
      READ(*,3)WHICH1
    3 FORMAT(A6)
      IF(WHICH1.EQ.'Y'.OR.WHICH1.EQ.'y')GO TO 100
    9 WRITE(*,12)
   12 FORMAT(/////////////////////////////////1X,'Enter TITLE, and strike
     * RETURN key to continue... ')
      READ(*,150)TITLE
  150 FORMAT(A60)
      WRITE(*,*)'How many dpAve (MMD or SMD) do you have ?'
      READ(*,*)N
      DO 10 I=1,N
      WRITE(*,11)I
   11 FORMAT(1X,'Enter (',I2,') Low and High Limits, Mean (microns), and
     * Weight (g) of discrete sizes')
   10 READ(*,*)dpL1(I),dpH1(I),dpAve(I),dpW1(I)
      WRITE(*,*)'Enter Particle Density (g/cm3)'
      READ(*,*)pDensity
      WRITE(*,*)'Enter Gas Density : 1.2046E-3(g/cm3)'
      READ(*,*)gDensity
      WRITE(*,*)'Enter Viscosity : 1.78E-4 (g/cm/sec)'
      READ(*,*)Viscosity
      WRITE(*,*)'Enter Gravitational Constant : 980.66(cm/sec2)'
      READ(*,*)Gravity
      WRITE(*,*)'Enter Bed Diameter (cm)'
      READ(*,*)BedDiam
      WRITE(*,*)'Enter Bed Height (cm)'
      READ(*,*)BedHeight
      WRITE(*,*)'Enter collection efficiency of the first cyclone (%)'
      READ(*,*)ETAc
      WRITE(*,*)'Enter Gas Velocity (cm/sec)'
      READ(*,*)gVelocity
      WRITE(*,*)'Enter Attrition Rate Constant (/sec)'
      READ(*,*)Ka
      WRITE(*,*)'Enter size interval (microns) for the population model'
      READ(*,*)Ddp1
      WRITE(*,*)'Enter time interval (sec) for the population model'
      READ(*,*)Dt1
      WRITE(*,*)'Enter number of iteration based on time for P-Model'
      READ(*,*)Ntime
      CHECK='CHECK'

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     CHECK INPUT DATA                                                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL CFBAOUT

      WRITE(*,*)'The input data are correct? (Y or N)'
      READ(*,50)CHECK
      IF(CHECK.EQ.'N'.OR.CHECK.EQ.'n')GO TO 9

      WRITE(*,22)
   22 FORMAT(//////////,4X,'    Which equation do You want to use for'/,
     *        5X,'   MINIMUM FLUIDIZATION VELOCITY ?                 '/,
     *        5X,'                                                   '/,
     *        5X,'   Enter -"Y" for YEN & YU"s eqn OR "B" for BABU"s eqn'
     *////////////)
```

```
      READ(*,50)WHICH2
      WRITE(*,23)
   23 FORMAT(///////////,4X,'     Do You want to write the MINIMUM FLUIDI
     *ZATION'/5X,'   VELOCITY & TERMINAL VELOCITY ?                    '/,
     *        5X,'                                                     '/,
     *        5X,'      Enter (Y/N)   '/////////////)
      READ(*,50)WHICH3
      WRITE(*,24)
   24 FORMAT(////////////////1X,'              Please wait.............'
     */////////////)
      GO TO 200

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     READ DATA FROM FILE                                              C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

  100 READ(5,150)TITLE
      READ(5,*)N
      DO 20 I=1,N
   20 READ(5,*)dpL1(I),dpH1(I),dpAve(I),dpW1(I)
      READ(5,*)pDensity
      READ(5,*)gDensity
      READ(5,*)Viscosity
      READ(5,*)Gravity
      READ(5,*)BedDiam
      READ(5,*)BedHeight
      READ(5,*)ETAc
      READ(5,*)gVelocity
      READ(5,*)Ka
      READ(5,*)Ddp1
      READ(5,*)Dt1
      READ(5,*)Ntime
      READ(5,50)CHECK
      READ(5,50)WHICH2
      READ(5,50)WHICH3

  200 RETURN
      END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     THIS SUBROUTINE WRITES THE COMPUTATION RESULTS AS WELL AS INPUT  C
C     DATA.                                                            C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      SUBROUTINE CFBAOUT

      IMPLICIT REAL*8 (A-H,O-Z)

      COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
      COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,TIME,Ka,ETAc
      COMMON/A3/N,Ntime
      COMMON/A4/dpAve,dpL1,dpH1,dpW1
      COMMON/A5/TITLE
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK

      REAL*8 dpAve(10),dpL1(10),dpH1(10),dpW1(10),Ka

      CHARACTER TITLE*60,WHICH1*6,WHICH2*6,WHICH3*6,CHECK*6

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     WRITE THE INPUT DATA                                             C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      IF(CHECK.EQ.'POPUL1')GO TO 15
      IF(CHECK.NE.'CHECK')GO TO 3
      WRITE(*,4)TITLE
      WRITE(*,6)
      DO 1 I=1,N
    1 WRITE(*,5)I,dpL1(I),dpH1(I),dpAve(I),dpW1(I)
      WRITE(*,8)pDensity,gDensity,Viscosity,Gravity,BedDiam,BedHeight,ET
     *Ac,gVelocity,Ka,Ddp1,Dt1,Ntime
      GO TO 100

    3 IF(CHECK.EQ.'N'.OR.CHECK.EQ.'n')GO TO 10
      WRITE(6,4)TITLE
    4 FORMAT(/75('-')/5X,'TITLE = ',A60/75('-')//)
      WRITE(6,6)
    6 FORMAT(///75('-')/5X,'DATA INPUT'/75('-')//29x,'Minimum ',4x,
     *'Maximum ',2x,'Mean (um) ',2x,'Weight (%)  ')
      DO 2 I=1,N
    2 WRITE(6,5)I,dpL1(I),dpH1(I),dpAve(I),dpW1(I)
      WRITE(6,8)pDensity,gDensity,Viscosity,Gravity,BedDiam,BedHeight,ET
     *Ac,gVelocity,Ka,Ddp1,Dt1,Ntime
    5 FORMAT(5X,'Particle Dia.(',I2,')   =',4(F10.3,2x))
    8 FORMAT(/5X,'Density of Particle       =',F15.3,'    (g/cm3)'/
     *       5X,'Density of Gas            =',E15.3,'    (g/cm3)'/
     *       5X,'Viscosity                 =',E15.3,'    (g/cm/sec)'/
     *       5X,'Gravitational Constant    =',F15.3,'    (cm/sec2)'/
     *       5X,'Bed Diameter              =',F15.3,'    (cm)'/
     *       5X,'Bed Height                =',F15.3,'    (cm)'/
     *       5x,'Efficiency of 1st cyclone =',F15.3,'    (%)'/
     *       5x,'Gas Velocity              =',F15.3,'    (cm/sec)'/
     *       5x,'Attrition Rate Constant   =',F15.8,'    (/sec)'/
     *       5x,'Size Interval             =',F15.3,'    (microns)'/
     *       5x,'Time Interval             =',F15.3,'    (sec)'/
     *       5x,'Number of Iteration       =',I11)
      CHECK='N'
      GO TO 100

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     PRINT Umf, and TERMINAL VELOCITY                                 C
```

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
   10 IF(WHICH3.EQ.'N'.OR.WHICH3.EQ.'n')GO TO 100
      WRITE(6,11)
   11 FORMAT(1H1///70('-')/5X,'MINIMUM FLUIDIZATION VELOCITY AND TERMINA
     *L VELOCITY'/70('-')//)
      WRITE(6,12)
   12 FORMAT(5X,'  Particle   Minimum Fluidization    Terminal  Velocity
     *'/5X,'  Diameter   Velocity (m/sec)            (m/sec)'/
     *5X,'  (microns)  --------------------    ------------------'/
     *5X,'             Yen        Babu            Re #        Ut    '/
     *5X,'  ------------------------------------------------------'/)
      CHECK='POPUL1'
      GO TO 100
   15 WRITE(6,16)('MMD =',dpAve(I),I=1,N)
   16 FORMAT(1H1////5x,'Changes in size distributions of solids in a bed
     * as a function of time'/5x,70('-')///2x,'Time(min)',1x,'Tot-Wt(g)'
     *,1x,9(A6,F5.0,2x))

  100 RETURN
      END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      THIS SUBROUTINE COMPUTES THE MINIMUM FLUIDIZATION VELOCITY AND   C
C      TERMINAL VELOCITY.  TWO EMPIRICAL EQUATIONS FOR THE MINIMUM      C
C      FLUIDIZATION VELOCITY IS GIVEN AND CAN BE CHOSEN BY USER.        C
C      THE SUBROUTINE NEEDS THE FOLLOWING VARIABLES :                   C
C                                                                       C
C      dp(Ndp)= DIAMETER OF SOLIDS                                      C
C      Ndp    = NUMBER OF DIAMETERS GIVEN FOR COMPUTATIONS              C
C      Nterm  = "1" FOR COMPUTATION OF TERMINAL VELOCITY ONLY           C
C             = "0" FOR BOTH COMPUTATIONS OF Umf AND Ut                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      SUBROUTINE UMFTERM(dp,Ndp,Ut,ReUt,Umf1,Umf2,Umf,Nterm)

      IMPLICIT REAL*8 (A-H,O-Z)

      COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
      COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,Time,Ka,ETAc
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK
      REAL*8 dp(10),Ut(10),ReUt(10),Umf1(10),Umf2(10)
      REAL*8 Ar(10),ReMF1(10),ReMF2(10),Umf(10)

      CHARACTER WHICH2*6

      IF(Nterm.EQ.1)GO TO 250

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      MINIMUM FLUIDIZATION VELOCITY : Umf(1) and Umf(2)                C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      DO 3 I=1,Ndp
      dp(I)=dp(I)/10**4
      Ar(I)=dp(I)**3*gDensity*(pDensity-gDensity)*Gravity/
     *Viscosity**2
      ReMF1(I)=(33.7**2+0.0408*Ar(I))**0.5-33.7
      ReMF2(I)=(25.25**2+0.0651*Ar(I))**0.5-25.25
      Umf1(I)=ReMF1(I)*Viscosity/gDensity/dp(I)
    3 Umf2(I)=ReMF2(I)*Viscosity/gDensity/dp(I)
      IF(WHICH2.EQ.'Y'.OR.WHICH2.EQ.'y')GO TO 200
      DO 5 I=1,Ndp
    5 Umf(I)=Umf2(I)
      GO TO 250
  200 DO 6 I=1,Ndp
    6 Umf(I)=Umf1(I)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      COMPUTATION OF TERMINAL VELOCITY (Ut)                            C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

  250 DO 20 I=1,Ndp
   21 Ut(I)=Gravity*(pDensity-gDensity)*dp(I)**2/18.0/Viscosity
      ReUt(I)=dp(I)*gDensity*Ut(I)/Viscosity
      IF(ReUt(I).LT.0.4)GO TO 20
      Ut(I)=(4.0/225.0*(pDensity-gDensity)**2*Gravity**2/gDensity/
     *Viscosity)**(1.0/3.0)*dp(I)
      ReUt(I)=dp(I)*gDensity*Ut(I)/Viscosity
      IF(ReUt(I).GE.0.4.AND.ReUt(I).LT.500.0)GO TO 20
      Ut(I)=(3.1*Gravity*(pDensity-gDensity)*dp(I)/gDensity)**0.5
      ReUt(I)=dp(I)*gDensity*Ut(I)/Viscosity
      IF(ReUt(I).GE.500.0)GO TO 20
      GO TO 21
   20 CONTINUE
```

```
RETURN
END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     THE SUBROUTINE, UNPOPUL SOLVES A PARTIAL DIFFERENTIAL           C
C     EQUATION OF THE UNSTEADY STATE POPULATION MODEL BY THE FINITE   C
C     DIFFERENTIAL METHODS.  IT RETURNS WITH W(I), WHICH IS SOLID     C
C     WEIGHT OF EACH SIZE, dp(I) AT AN ARBITARY TIME,t.               C
C                                                                     C
C     THE VARIABLES ARE DEFINED AS ;                                  C
C                                                                     C
C     W(I)   = WEIGHT OF SOLIDS WITH DIAMETER OF dp(I) AT AN ARBITARY C
C              TIME IN A BED                                          C
C     Dt     = TIME INTERVAL                                          C
C     Ddp    = SIZE INTERVAL                                          C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      SUBROUTINE UNPOPUL(dpL,dpH,dpW,Ndp,W,Ddp,Dt)

      IMPLICIT REAL*8 (A-H, O-Z)

      COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
      COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,TIME,Ka,ETAc
      COMMON/A3/N,Ntime
      COMMON/A4/dpAve,dpL1,dpH1,dpW1
      COMMON/A5/TITLE
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK

      REAL*8 dp(1000),W(1000),A(1000),B(1000),DD(10)
      REAL*8 KAPA(1000),Ka,Umf(10),Umf1(10),Umf2(10)
      REAL*8 dpW(10),dpH(10),dpL(10),Ut(10),ReUt(10),dpmin(1000)

      CHARACTER CHECK*6

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     SET INITIAL CONDITIONS                                          C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      J=0
      Wtotal=500.
      W(0)=0
      dp(0)=dpL(1)-Ddp
      I=1
      DO 100 IN=1,Ndp
   10 dp(I)=dp(I-1)+Ddp
      dpmin(I)=1400./1764.*dp(I)
      IF(dp(I).GT.dpH(IN))GO TO 100
      W(I)=dpW(IN)/(dpH(IN)-dpL(IN))*Ddp*Wtotal/100.
      I=I+1

      GO TO 10

  100 CONTINUE

      Time=0.
      WRITE(6,700)TIME,Wtotal,(dpW(IN),IN=1,Ndp)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     SET BOUNDARY CONDITIONS                                         C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      NR=I
      W(NR)=0.

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
C     ITERATION OF FINITE DIFFERENCE EQUATION BY IMPLICIT METHOD.       C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     AN IMPLICIT METHOD IS BASED ON THE BACKWARD EULER METHOD, AND     C
C     CALLS THE SUBROUTINE, DIAG(A,B,W,I) TO DETERMINE UNKNOWN VALUES.  C
C     THE SUBROUTINE, UMFTERM IA ALSO CALLED TO DETERMINE THE TERMINAL  C
C     VELOCITY NECESSARY FOR THE COMPUTATION OF ELUTRIATION RATE        C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

    1 J=J+1
      DO 300 I=1,NR-1
      DD(1)=dp(I)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     COMPUTE TERMINAL VELOCITY AS A FUNCTION OF SOLID DIAMETER         C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL UMFTERM(DD,1,Ut,ReUt,Umf1,Umf2,Umf,0)

      IF(Ut(1).LT.gVelocity)GO TO 2
      KAPA(I)=0.
      GO TO 3

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     Levenspiel's eqn for elutriation constant (see p.179,Fuildi.Eng)  C
C                                                                       C
C   2 KAPA(I)=1.1*10**(-5)*pDensity*(3.1415/6*BedDiam**2)/Wtotal*(1-    C
C    *Ut(1)/gVelocity)**2                                               C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     Geldart's equation for elutriation constant, KAPA(I)              C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

    2 KAPA(I)=gVelocity*gDensity*31.4*(3.1415/6.*BedDiam**2)/Wtotal*
     *DEXP(-4.27*Ut(1)/gVelocity)

    3 ALPA=Ka*Dt/(dp(I+1)-dp(I))*(dp(I)-dpmin(I))
      BETA=1.-((1.-ETAc/100.)*KAPA(I)+3.*Ka-3.*Ka*dpmin(I)/dp(I))*Dt
      A(I)=(1+ALPA)/BETA
  300 B(I)=-ALPA/BETA

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     SOLVE A DIAGONAL MATRIX EQUATION                                  C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL DIAG(A,B,W,NR-1)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     WRITE THE COMPUTATION RESULTS                                     C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      Wtotal=0.
      I=0
      DO 800 IN=1,Ndp
      dpWb=0.
  900 IF(dp(I).GT.dpH(IN))GO TO 801
      dpWb=dpWb+W(I)
      I=I+1
      GO TO 900
```

```
 801 Wtotal=Wtotal+dpWb
 800 dpW(IN)=dpWb

     TIME=J*Dt/60
     WRITE(6,700)TIME,Wtotal,(dpW(I)/Wtotal*100,I=1,Ndp)
 700 FORMAT(1x,F9.3,2x,F8.3,3x,F10.5,3x,F10.5,3x,F10.5,3x,F10.5,3x,
    *F10.5,3x,3(F10.5,3x))

     IF(J.GT.Ntime)GO TO 1000
     GO TO 1

1000 RETURN
     END
```

INPUT File = 4MS.DAT

```
Attritiion test : MMD=1764 microns,Velocity=4 m/s,Temp.=70 F
6,                                         Number of size interval
400.0,595.0,497.5,0.92,                    Lower, Upper, Mean, Weight(%)
595.0,841.0,718.0,0.04,
841.0,1008.0,924.5,0.1,
1008.0,1190.0,1099.0,4.0,
1190.0,2000.0,1595.0,61.33,
2000.0,2380.0,2190.0,33.61,
2.100,                                     Particle density (g/cm3)
1.0246E-03,                                Gas density (g/cm3)
1.78E-04,                                  Viscosity (g/cm/sec)
980.660,                                   Gravitational constant (cm/sec2)
7.620,                                     Diameter of bed (cm)
250.000,                                   Height of bed (cm)
0.000,                                     Collection efficiency of cyclone (%)
400.000,                                   Gas velocity (cm/sec)
9.09e-5,                                   Attrition rate constant (/sec)
10.000,                                    Size increments (microns)
20.000,                                    Time increments (sec)
900,                                       Number of iteration based on time
Y                                          Data check - O.K. (Y or N)
Y                                          Use of Wen's equation for Umf(Y/N)
Y                                          Write minimum fluidization and
                                           terminal velocity (Y or N)
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     THE SUBROUTINE, DIAG(A,B,C,NR) SOLVES THE TRIDIAGONAL EQUATION,  C
C     WHICH CONSISTS OF A TRIDIAGONAL MATRIX.                          C
C     A(NR) AND B(NR) ARE COEFFICIENTS OF ELEMENTS, AND C(NR) ARE THE  C
C     N-UNKNOWN VARIABLES TO BE DETERMINED.  AFTER THE COMPUTATION IS  C
C     COMPLETED, THE SOLUTION IS STORED IN ARRAY C(1), C(2)...C(NR).   C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      SUBROUTINE DIAG(A,B,C,NR)

      REAL*8 A(NR),B(NR),C(NR)

      C(NR)=C(NR)/A(NR)
      DO 100 I=NR-1,1,-1
  100 C(I)=(C(I)-B(I)*C(I+1))/A(I)
      RETURN
      END
```

C.3 INPUT DATA and OUTPUT for Figure 3.19 - 3.23

Input File = 2MS.DAT

```
Attritiion test : MMD=903 microns,Velocity=2 m/s,Temp.=70 F
6,                                         Number of size interval
100.0,297.0,148.5,1.65,                    Lower, Upper, Mean, Weight(%)
297.0,420.0,358.5,0.08,
420.0,595.0,507.5,0.38,
595.0,841.0,718.0,31.27,
841.0,1000.0,920.5,31.91,
1000.0,1190.0,1095.0,34.71,
2.100,                                     Particle density (g/cm3)
1.0246E-03,                                Gas density (g/cm3)
1.78E-04,                                  Viscosity (g/cm/sec)
980.660,                                   Gravitational constant (cm/sec2)
7.620,                                     Diameter of bed (cm)
250.000,                                   Height of bed (cm)
0.000,                                     Collection efficiency of cyclone (%)
200.000,                                   Gas velocity (cm/sec)
4.82e-5,                                   Attrition rate constant (/sec)
10.000,                                    Size increments (microns)
20.000,                                    Time increments (sec)
900,                                       Number of iteration based on time
Y                                          Data check - O.K. (Y or N)
Y                                          Use of Wen's equation for Umf(Y or
N)
Y                                          Write minimum fluidization and
                                           terminal velocity (Y or N)
```

OUTPUT File = 2MS.OUT

TITLE = Attritiion test : MMD=903 microns,Velocity=2 m/s,Temp.=70 F

DATA INPUT

		Minimum	Maximum	Mean (um)	Weight (%)
Particle Dia.(1)	=	100.000	297.000	148.500	1.650
Particle Dia.(2)	=	297.000	420.000	358.500	.080
Particle Dia.(3)	=	420.000	595.000	507.500	.380
Particle Dia.(4)	=	595.000	841.000	718.000	31.270
Particle Dia.(5)	=	841.000	1000.000	920.500	31.910
Particle Dia.(6)	=	1000.000	1190.000	1095.000	34.710

Density of Particle	=	2.100	(g/cm3)
Density of Gas	=	.102E-02	(g/cm3)
Viscosity	=	.178E-03	(g/cm/sec)
Gravitational Constant	=	980.660	(cm/sec2)
Bed Diameter	=	7.620	(cm)
Bed Height	=	250.000	(cm)
Efficiency of 1st cyclone	=	.000	(%)
Gas Velocity	=	200.000	(cm/sec)
Attrition Rate Constant	=	.00004820	(/sec)
Size Interval	=	10.000	(microns)
Time Interval	=	20.000	(sec)
Number of Iteration	=	900	

MINIMUM FLUIDIZATION VELOCITY AND TERMINAL VELOCITY

Particle Diameter (microns)	Minimum Fluidization Velocity (m/sec)		Terminal Velocity (m/sec)	
	Yen	Babu	Re #	Ut
148.500	.015	.033	9.453	1.106
358.500	.088	.179	55.093	2.670
507.500	.168	.323	110.406	3.779
718.000	.304	.535	220.988	5.347
920.500	.441	.720	363.218	6.855
1095.000	.553	.861	520.502	8.258

Changes in size distributions of solids in a bed as a function of time

Time(min)	Tot-Wt(g)	MMD = 149.	MMD = 359.	MMD = 508.	MMD = 718.	MMD = 921.	MMD =1095.
.000	500.000	1.65000	.08000	.38000	31.27000	31.91000	34.71000
.333	501.747	1.31949	.07753	1.64878	30.41248	31.99503	34.54670
.667	500.650	1.12397	.07745	1.66663	30.49062	32.06136	34.57997
1.000	499.881	.99296	.07732	1.68344	30.54893	32.10679	34.59056
1.333	499.285	.89570	.07717	1.69972	30.59687	32.14128	34.58926
1.667	498.793	.81887	.07700	1.71567	30.63854	32.16915	34.58077
2.000	498.370	.75570	.07682	1.73141	30.67602	32.19259	34.56746
2.333	497.997	.70228	.07664	1.74700	30.71050	32.21287	34.55069
2.667	497.661	.65619	.07646	1.76248	30.74275	32.23078	34.53134
3.000	497.353	.61580	.07627	1.77787	30.77324	32.24685	34.50997
3.333	497.069	.57997	.07608	1.79319	30.80235	32.26143	34.48697
3.667	496.803	.54786	.07590	1.80846	30.83032	32.27481	34.46266
4.000	496.554	.51885	.07571	1.82368	30.85734	32.28719	34.43724
4.333	496.317	.49247	.07552	1.83886	30.88356	32.29872	34.41088
4.667	496.092	.46832	.07533	1.85401	30.90909	32.30952	34.38372
5.000	495.877	.44612	.07514	1.86914	30.93404	32.31969	34.35587
5.333	495.670	.42562	.07495	1.88424	30.95847	32.32931	34.32741
5.667	495.470	.40660	.07477	1.89932	30.98245	32.33845	34.29841
6.000	495.278	.38891	.07458	1.91438	31.00602	32.34716	34.26894
6.333	495.091	.37240	.07440	1.92943	31.02924	32.35549	34.23903
6.667	494.910	.35696	.07421	1.94446	31.05214	32.36348	34.20875
7.000	494.733	.34246	.07403	1.95948	31.07475	32.37115	34.17811
7.333	494.561	.32884	.07385	1.97449	31.09710	32.37855	34.14717
7.667	494.393	.31601	.07367	1.98950	31.11921	32.38569	34.11593
8.000	494.229	.30389	.07350	2.00449	31.14110	32.39260	34.08443
8.333	494.068	.29244	.07332	2.01947	31.16279	32.39929	34.05269
8.667	493.910	.28160	.07315	2.03445	31.18430	32.40579	34.02072
9.000	493.755	.27131	.07297	2.04942	31.20565	32.41210	33.98855
9.333	493.602	.26155	.07280	2.06438	31.22684	32.41825	33.95618
9.667	493.452	.25227	.07263	2.07934	31.24788	32.42424	33.92364
10.000	493.304	.24343	.07247	2.09430	31.26879	32.43009	33.89093
10.333	493.159	.23501	.07230	2.10925	31.28958	32.43580	33.85806
10.667	493.015	.22698	.07213	2.12420	31.31026	32.44138	33.82505
11.000	492.873	.21931	.07197	2.13914	31.33082	32.44685	33.79190
11.333	492.733	.21199	.07181	2.15408	31.35129	32.45221	33.75862
11.667	492.594	.20498	.07165	2.16902	31.37166	32.45747	33.72522
12.000	492.457	.19827	.07149	2.18396	31.39194	32.46263	33.69171
12.333	492.322	.19185	.07133	2.19889	31.41214	32.46769	33.65809
12.667	492.187	.18569	.07118	2.21382	31.43226	32.47268	33.62436
13.000	492.054	.17979	.07102	2.22875	31.45231	32.47758	33.59054
13.333	491.923	.17412	.07087	2.24368	31.47230	32.48240	33.55663
13.667	491.792	.16868	.07072	2.25861	31.49221	32.48715	33.52263
14.000	491.663	.16345	.07057	2.27353	31.51206	32.49183	33.48854
14.333	491.534	.15842	.07043	2.28846	31.53186	32.49645	33.45438
14.667	491.407	.15359	.07028	2.30338	31.55160	32.50101	33.42014
15.000	491.280	.14893	.07013	2.31831	31.57129	32.50551	33.38583
15.333	491.155	.14445	.06999	2.33323	31.59093	32.50995	33.35145
15.667	491.030	.14013	.06985	2.34815	31.61053	32.51434	33.31701
16.000	490.906	.13597	.06971	2.36307	31.63008	32.51867	33.28250
16.333	490.783	.13196	.06957	2.37799	31.64958	32.52296	33.24793
16.667	490.660	.12810	.06943	2.39291	31.66905	32.52721	33.21330
17.000	490.538	.12436	.06930	2.40783	31.68848	32.53141	33.17861
17.333	490.417	.12076	.06916	2.42275	31.70787	32.53557	33.14387
17.667	490.297	.11729	.06903	2.43767	31.72723	32.53969	33.10909
18.000	490.177	.11393	.06890	2.45260	31.74656	32.54377	33.07425
18.333	490.058	.11068	.06877	2.46752	31.76586	32.54781	33.03936
18.667	489.939	.10755	.06864	2.48244	31.78512	32.55182	33.00443
19.000	489.821	.10452	.06852	2.49736	31.80436	32.55580	32.96945
19.333	489.703	.10159	.06839	2.51228	31.82357	32.55974	32.93443
19.667	489.586	.09875	.06827	2.52720	31.84276	32.56366	32.89936
20.000	489.469	.09601	.06814	2.54213	31.86192	32.56754	32.86426
20.333	489.353	.09335	.06802	2.55705	31.88106	32.57140	32.82912
20.667	489.238	.09079	.06790	2.57197	31.90017	32.57523	32.79394
21.000	489.122	.08830	.06778	2.58690	31.91927	32.57903	32.75872
21.333	489.007	.08589	.06766	2.60183	31.93834	32.58281	32.72347
21.667	488.893	.08355	.06755	2.61675	31.95740	32.58656	32.68819
22.000	488.779	.08129	.06743	2.63168	31.97643	32.59029	32.65287
22.333	488.665	.07910	.06732	2.64661	31.99545	32.59400	32.61752
22.667	488.552	.07698	.06721	2.66153	32.01446	32.59769	32.58213
23.000	488.439	.07492	.06709	2.67646	32.03344	32.60136	32.54672
23.333	488.326	.07292	.06698	2.69139	32.05241	32.60501	32.51128
23.667	488.214	.07099	.06687	2.70633	32.07137	32.60863	32.47581
24.000	488.101	.06911	.06677	2.72126	32.09031	32.61224	32.44031
24.333	487.990	.06729	.06666	2.73619	32.10924	32.61584	32.40478
24.667	487.878	.06552	.06656	2.75113	32.12816	32.61941	32.36923
25.000	487.767	.06380	.06645	2.76606	32.14706	32.62297	32.33365
25.333	487.656	.06214	.06635	2.78100	32.16596	32.62651	32.29805
25.667	487.546	.06052	.06625	2.79594	32.18484	32.63004	32.26242
26.000	487.435	.05895	.06615	2.81088	32.20371	32.63356	32.22676
26.333	487.325	.05743	.06605	2.82582	32.22257	32.63705	32.19109
26.667	487.215	.05595	.06595	2.84076	32.24142	32.64054	32.15539
27.000	487.105	.05451	.06585	2.85570	32.26027	32.64401	32.11966
27.333	486.996	.05311	.06575	2.87064	32.27910	32.64747	32.08392
27.667	486.887	.05175	.06566	2.88559	32.29793	32.65092	32.04815
28.000	486.778	.05043	.06557	2.90053	32.31674	32.65435	32.01237
28.333	486.669	.04915	.06547	2.91548	32.33556	32.65778	31.97656
28.667	486.560	.04791	.06538	2.93043	32.35436	32.66119	31.94073
29.000	486.452	.04669	.06529	2.94538	32.37316	32.66459	31.90489
29.333	486.344	.04552	.06520	2.96033	32.39195	32.66799	31.86902
29.667	486.236	.04437	.06511	2.97528	32.41073	32.67137	31.83313
30.000	486.128	.04326	.06502	2.99024	32.42951	32.67474	31.79723
30.333	486.020	.04218	.06494	3.00519	32.44828	32.67810	31.76131
30.667	485.912	.04112	.06485	3.02015	32.46705	32.68146	31.72537
31.000	485.805	.04010	.06477	3.03511	32.48582	32.68480	31.68941
31.333	485.698	.03910	.06468	3.05007	32.50457	32.68814	31.65343
31.667	485.591	.03813	.06460	3.06503	32.52333	32.69147	31.61744
32.000	485.484	.03719	.06452	3.07999	32.54208	32.69479	31.58143
32.333	485.377	.03627	.06444	3.09496	32.56083	32.69810	31.54541
32.667	485.271	.03538	.06436	3.10992	32.57957	32.70141	31.50937
33.000	485.164	.03451	.06428	3.12489	32.59831	32.70471	31.47331
33.333	485.058	.03366	.06420	3.13986	32.61705	32.70800	31.43724
33.667	484.952	.03284	.06412	3.15483	32.63578	32.71128	31.40115

34.000	484.846	.03204	.06405	3.16980	32.65451	32.71456	31.36504
34.333	484.740	.03126	.06397	3.18477	32.67324	32.71784	31.32893
34.667	484.634	.03050	.06390	3.19975	32.69197	32.72110	31.29279
35.000	484.528	.02975	.06382	3.21472	32.71069	32.72436	31.25664
35.333	484.422	.02903	.06375	3.22970	32.72941	32.72762	31.22048
35.667	484.317	.02833	.06368	3.24468	32.74813	32.73087	31.18431
36.000	484.212	.02765	.06361	3.25966	32.76685	32.73411	31.14812
36.333	484.106	.02698	.06354	3.27464	32.78557	32.73735	31.11191
36.667	484.001	.02633	.06347	3.28963	32.80429	32.74059	31.07570
37.000	483.896	.02570	.06340	3.30461	32.82300	32.74382	31.03946
37.333	483.791	.02509	.06333	3.31960	32.84172	32.74704	31.00322
37.667	483.686	.02449	.06326	3.33459	32.86043	32.75026	30.96696
38.000	483.582	.02390	.06320	3.34958	32.87915	32.75348	30.93069
38.333	483.477	.02333	.06313	3.36457	32.89786	32.75669	30.89441
38.667	483.372	.02278	.06307	3.37957	32.91657	32.75990	30.85812
39.000	483.268	.02224	.06300	3.39456	32.93528	32.76311	30.82181
39.333	483.163	.02171	.06294	3.40956	32.95400	32.76631	30.78549
39.667	483.059	.02120	.06288	3.42456	32.97271	32.76950	30.74916
40.000	482.955	.02070	.06281	3.43956	32.99142	32.77270	30.71281
40.333	482.851	.02021	.06275	3.45456	33.01013	32.77589	30.67646
40.667	482.747	.01973	.06269	3.46956	33.02885	32.77908	30.64009
41.000	482.643	.01927	.06263	3.48457	33.04756	32.78226	30.60371
41.333	482.539	.01882	.06258	3.49957	33.06627	32.78544	30.56732
41.667	482.435	.01838	.06252	3.51458	33.08499	32.78862	30.53092
42.000	482.331	.01795	.06246	3.52959	33.10371	32.79179	30.49450
42.333	482.228	.01753	.06240	3.54460	33.12242	32.79497	30.45808
42.667	482.124	.01712	.06235	3.55962	33.14114	32.79814	30.42164
43.000	482.020	.01672	.06229	3.57463	33.15986	32.80130	30.38520
43.333	481.917	.01633	.06224	3.58965	33.17858	32.80447	30.34874
43.667	481.814	.01595	.06218	3.60467	33.19730	32.80763	30.31227
44.000	481.710	.01558	.06213	3.61969	33.21602	32.81079	30.27579
44.333	481.607	.01522	.06208	3.63471	33.23474	32.81395	30.23930
44.667	481.504	.01487	.06203	3.64973	33.25347	32.81711	30.20280
45.000	481.401	.01453	.06197	3.66476	33.27219	32.82026	30.16629
45.333	481.297	.01419	.06192	3.67978	33.29092	32.82341	30.12976
45.667	481.194	.01387	.06187	3.69481	33.30965	32.82656	30.09323
46.000	481.091	.01355	.06182	3.70984	33.32838	32.82971	30.05669
46.333	480.989	.01324	.06178	3.72488	33.34712	32.83286	30.02014
46.667	480.886	.01293	.06173	3.73991	33.36585	32.83600	29.98357
47.000	480.783	.01264	.06168	3.75494	33.38459	32.83915	29.94700
47.333	480.680	.01235	.06163	3.76998	33.40333	32.84229	29.91042
47.667	480.577	.01207	.06159	3.78502	33.42207	32.84543	29.87382
48.000	480.475	.01179	.06154	3.80006	33.44081	32.84857	29.83722
48.333	480.372	.01153	.06150	3.81510	33.45956	32.85171	29.80061
48.667	480.270	.01126	.06145	3.83015	33.47831	32.85484	29.76398
49.000	480.167	.01101	.06141	3.84519	33.49706	32.85798	29.72735
49.333	480.065	.01076	.06136	3.86024	33.51581	32.86111	29.69071
49.667	479.962	.01052	.06132	3.87529	33.53457	32.86425	29.65406
50.000	479.860	.01028	.06128	3.89034	33.55333	32.86738	29.61740
50.333	479.758	.01005	.06124	3.90540	33.57209	32.87051	29.58073
50.667	479.655	.00982	.06119	3.92045	33.59085	32.87364	29.54405
51.000	479.553	.00960	.06115	3.93551	33.60961	32.87677	29.50736
51.333	479.451	.00939	.06111	3.95056	33.62838	32.87990	29.47066
51.667	479.349	.00918	.06107	3.96562	33.64715	32.88302	29.43395
52.000	479.247	.00897	.06103	3.98069	33.66593	32.88615	29.39723
52.333	479.145	.00877	.06099	3.99575	33.68470	32.88928	29.36051
52.667	479.043	.00857	.06096	4.01081	33.70348	32.89240	29.32377
53.000	478.941	.00838	.06092	4.02588	33.72226	32.89553	29.28703
53.333	478.839	.00820	.06088	4.04095	33.74105	32.89865	29.25027
53.667	478.737	.00802	.06084	4.05602	33.75984	32.90177	29.21351
54.000	478.635	.00784	.06081	4.07109	33.77863	32.90490	29.17674
54.333	478.533	.00766	.06077	4.08617	33.79742	32.90802	29.13996
54.667	478.431	.00749	.06074	4.10124	33.81622	32.91114	29.10317
55.000	478.330	.00733	.06070	4.11632	33.83502	32.91426	29.06637
55.333	478.228	.00717	.06067	4.13140	33.85382	32.91738	29.02956
55.667	478.126	.00701	.06063	4.14648	33.87263	32.92051	28.99274
56.000	478.025	.00686	.06060	4.16156	33.89144	32.92363	28.95592
56.333	477.923	.00671	.06057	4.17665	33.91025	32.92675	28.91908
56.667	477.822	.00656	.06053	4.19173	33.92907	32.92987	28.88224
57.000	477.720	.00641	.06050	4.20682	33.94789	32.93299	28.84539
57.333	477.619	.00627	.06047	4.22191	33.96671	32.93611	28.80853
57.667	477.517	.00614	.06044	4.23700	33.98554	32.93923	28.77166
58.000	477.416	.00600	.06041	4.25210	34.00437	32.94235	28.73478
58.333	477.314	.00587	.06037	4.26719	34.02320	32.94546	28.69789
58.667	477.213	.00575	.06034	4.28229	34.04204	32.94858	28.66100
59.000	477.112	.00562	.06031	4.29739	34.06088	32.95170	28.62409
59.333	477.010	.00550	.06029	4.31249	34.07973	32.95482	28.58718
59.667	476.909	.00538	.06026	4.32759	34.09857	32.95794	28.55026
60.000	476.808	.00526	.06023	4.34269	34.11742	32.96106	28.51333
60.333	476.707	.00515	.06020	4.35780	34.13628	32.96418	28.47639
60.667	476.605	.00504	.06017	4.37291	34.15514	32.96730	28.43945
61.000	476.504	.00493	.06014	4.38802	34.17400	32.97042	28.40249
61.333	476.403	.00483	.06012	4.40313	34.19286	32.97354	28.36553
61.667	476.302	.00472	.06009	4.41824	34.21173	32.97666	28.32856
62.000	476.201	.00462	.06006	4.43335	34.23061	32.97978	28.29158
62.333	476.100	.00452	.06004	4.44847	34.24948	32.98290	28.25459
62.667	475.999	.00443	.06001	4.46359	34.26836	32.98602	28.21759
63.000	475.898	.00433	.05999	4.47871	34.28725	32.98914	28.18059
63.333	475.797	.00424	.05996	4.49383	34.30613	32.99226	28.14357
63.667	475.696	.00415	.05994	4.50895	34.32503	32.99538	28.10655
64.000	475.595	.00406	.05991	4.52408	34.34392	32.99851	28.06952
64.333	475.494	.00398	.05989	4.53921	34.36282	33.00163	28.03248
64.667	475.394	.00389	.05986	4.55433	34.38172	33.00475	27.99543
65.000	475.293	.00381	.05984	4.56946	34.40063	33.00787	27.95838
65.333	475.192	.00373	.05982	4.58460	34.41954	33.01100	27.92132
65.667	475.091	.00365	.05980	4.59973	34.43846	33.01412	27.88425
66.000	474.990	.00357	.05977	4.61487	34.45738	33.01724	27.84717
66.333	474.890	.00350	.05975	4.63000	34.47630	33.02037	27.81008
66.667	474.789	.00343	.05973	4.64514	34.49523	33.02349	27.77298
67.000	474.688	.00336	.05971	4.66028	34.51416	33.02662	27.73588
67.333	474.588	.00329	.05969	4.67543	34.53309	33.02974	27.69877
67.667	474.487	.00322	.05967	4.69057	34.55203	33.03287	27.66165
68.000	474.386	.00315	.05965	4.70572	34.57097	33.03600	27.62452

68.333	474.286	.00308	.05963	4.72087	34.58992	33.03912	27.58738
68.667	474.185	.00302	.05961	4.73602	34.60887	33.04225	27.55024
69.000	474.085	.00296	.05959	4.75117	34.62783	33.04538	27.51308
69.333	473.984	.00290	.05957	4.76632	34.64679	33.04851	27.47592
69.667	473.884	.00284	.05955	4.78148	34.66575	33.05164	27.43875
70.000	473.783	.00278	.05953	4.79663	34.68472	33.05477	27.40158
70.333	473.683	.00272	.05951	4.81179	34.70369	33.05790	27.36439
70.667	473.583	.00267	.05949	4.82695	34.72266	33.06103	27.32720
71.000	473.482	.00261	.05947	4.84212	34.74164	33.06416	27.29000
71.333	473.382	.00256	.05946	4.85728	34.76063	33.06729	27.25279
71.667	473.281	.00251	.05944	4.87245	34.77962	33.07042	27.21557
72.000	473.181	.00246	.05942	4.88761	34.79861	33.07356	27.17834
72.333	473.081	.00241	.05940	4.90278	34.81761	33.07669	27.14111
72.667	472.981	.00236	.05939	4.91795	34.83661	33.07983	27.10387
73.000	472.880	.00231	.05937	4.93313	34.85561	33.08296	27.06662
73.333	472.780	.00226	.05935	4.94830	34.87462	33.08610	27.02936
73.667	472.680	.00222	.05934	4.96348	34.89363	33.08924	26.99210
74.000	472.580	.00217	.05932	4.97866	34.91265	33.09237	26.95482
74.333	472.479	.00213	.05931	4.99383	34.93167	33.09551	26.91754
74.667	472.379	.00209	.05929	5.00902	34.95070	33.09865	26.88025
75.000	472.279	.00205	.05928	5.02420	34.96973	33.10179	26.84296
75.333	472.179	.00200	.05926	5.03938	34.98877	33.10493	26.80565
75.667	472.079	.00196	.05925	5.05457	35.00781	33.10807	26.76834
76.000	471.979	.00193	.05923	5.06976	35.02685	33.11122	26.73102
76.333	471.879	.00189	.05922	5.08495	35.04590	33.11436	26.69369
76.667	471.779	.00185	.05921	5.10014	35.06495	33.11750	26.65635
77.000	471.679	.00181	.05919	5.11534	35.08401	33.12065	26.61901
77.333	471.579	.00178	.05918	5.13053	35.10307	33.12379	26.58165
77.667	471.479	.00174	.05916	5.14573	35.12213	33.12694	26.54429
78.000	471.379	.00171	.05915	5.16093	35.14120	33.13009	26.50692
78.333	471.279	.00168	.05914	5.17613	35.16028	33.13323	26.46955
78.667	471.179	.00164	.05913	5.19133	35.17935	33.13638	26.43216
79.000	471.079	.00161	.05911	5.20654	35.19844	33.13953	26.39477
79.333	470.979	.00158	.05910	5.22174	35.21752	33.14268	26.35737
79.667	470.879	.00155	.05909	5.23695	35.23662	33.14583	26.31996
80.000	470.779	.00152	.05908	5.25216	35.25571	33.14899	26.28254
80.333	470.680	.00149	.05907	5.26737	35.27481	33.15214	26.24512
80.667	470.580	.00146	.05905	5.28258	35.29392	33.15529	26.20769
81.000	470.480	.00143	.05904	5.29780	35.31303	33.15845	26.17025
81.333	470.380	.00141	.05903	5.31301	35.33214	33.16160	26.13280
81.667	470.280	.00138	.05902	5.32823	35.35126	33.16476	26.09535
82.000	470.181	.00135	.05901	5.34345	35.37038	33.16792	26.05788
82.333	470.081	.00133	.05900	5.35867	35.38951	33.17108	26.02041
82.667	469.981	.00130	.05899	5.37390	35.40864	33.17424	25.98293
83.000	469.881	.00128	.05898	5.38912	35.42778	33.17740	25.94545
83.333	469.782	.00125	.05897	5.40435	35.44692	33.18056	25.90795
83.667	469.682	.00123	.05896	5.41958	35.46607	33.18372	25.87045
84.000	469.582	.00121	.05895	5.43481	35.48522	33.18688	25.83294
84.333	469.483	.00118	.05894	5.45004	35.50437	33.19005	25.79542
84.667	469.383	.00116	.05893	5.46527	35.52353	33.19321	25.75789
85.000	469.284	.00114	.05892	5.48051	35.54269	33.19638	25.72036
85.333	469.184	.00112	.05891	5.49575	35.56186	33.19954	25.68282
85.667	469.085	.00110	.05890	5.51098	35.58104	33.20271	25.64527
86.000	468.985	.00108	.05889	5.52623	35.60021	33.20588	25.60771
86.333	468.885	.00106	.05888	5.54147	35.61939	33.20905	25.57014
86.667	468.786	.00104	.05888	5.55671	35.63858	33.21222	25.53257
87.000	468.686	.00102	.05887	5.57196	35.65777	33.21539	25.49499
87.333	468.587	.00100	.05886	5.58720	35.67697	33.21857	25.45740
87.667	468.488	.00098	.05885	5.60245	35.69617	33.22174	25.41980
88.000	468.388	.00096	.05884	5.61770	35.71537	33.22492	25.38220
88.333	468.289	.00095	.05883	5.63296	35.73458	33.22809	25.34459
88.667	468.189	.00093	.05883	5.64821	35.75380	33.23127	25.30697
89.000	468.090	.00091	.05882	5.66347	35.77302	33.23445	25.26934
89.333	467.990	.00090	.05881	5.67872	35.79224	33.23763	25.23170
89.667	467.891	.00088	.05880	5.69398	35.81147	33.24081	25.19406
90.000	467.792	.00086	.05880	5.70924	35.83070	33.24399	25.15641
90.333	467.692	.00085	.05879	5.72451	35.84994	33.24717	25.11875
90.667	467.593	.00083	.05878	5.73977	35.86918	33.25035	25.08108
91.000	467.494	.00082	.05878	5.75504	35.88843	33.25354	25.04341
91.333	467.395	.00081	.05877	5.77030	35.90768	33.25672	25.00572
91.667	467.295	.00079	.05876	5.78557	35.92693	33.25991	24.96803
92.000	467.196	.00078	.05876	5.80084	35.94619	33.26309	24.93034
92.333	467.097	.00076	.05875	5.81612	35.96546	33.26628	24.89263
92.667	466.998	.00075	.05874	5.83139	35.98473	33.26947	24.85492
93.000	466.898	.00074	.05874	5.84667	36.00400	33.27266	24.81719
93.333	466.799	.00072	.05873	5.86194	36.02328	33.27585	24.77946
93.667	466.700	.00071	.05872	5.87722	36.04257	33.27905	24.74173
94.000	466.601	.00070	.05872	5.89251	36.06185	33.28224	24.70398
94.333	466.502	.00069	.05871	5.90779	36.08115	33.28544	24.66623
94.667	466.403	.00068	.05871	5.92307	36.10045	33.28863	24.62847
95.000	466.303	.00066	.05870	5.93836	36.11975	33.29183	24.59070
95.333	466.204	.00065	.05870	5.95365	36.13906	33.29503	24.55292
95.667	466.105	.00064	.05869	5.96894	36.15837	33.29822	24.51514
96.000	466.006	.00063	.05869	5.98423	36.17769	33.30142	24.47735
96.333	465.907	.00062	.05868	5.99952	36.19701	33.30463	24.43955
96.667	465.808	.00061	.05868	6.01481	36.21633	33.30783	24.40174
97.000	465.709	.00060	.05867	6.03011	36.23567	33.31103	24.36392
97.333	465.610	.00059	.05867	6.04541	36.25500	33.31424	24.32610
97.667	465.511	.00058	.05866	6.06071	36.27434	33.31744	24.28827
98.000	465.412	.00057	.05866	6.07601	36.29369	33.32065	24.25043
98.333	465.313	.00056	.05865	6.09131	36.31304	33.32386	24.21258
98.667	465.214	.00055	.05865	6.10661	36.33239	33.32707	24.17473
99.000	465.115	.00054	.05864	6.12192	36.35175	33.33028	24.13687
99.333	465.016	.00053	.05864	6.13723	36.37112	33.33349	24.09900
99.667	464.917	.00052	.05863	6.15254	36.39049	33.33670	24.06112
100.000	464.818	.00052	.05863	6.16785	36.40986	33.33991	24.02324
100.333	464.720	.00051	.05862	6.18316	36.42924	33.34313	23.98534
100.667	464.621	.00050	.05862	6.19848	36.44862	33.34634	23.94744
101.000	464.522	.00049	.05862	6.21379	36.46801	33.34956	23.90953
101.333	464.423	.00048	.05861	6.22911	36.48740	33.35278	23.87162
101.667	464.324	.00048	.05861	6.24443	36.50680	33.35600	23.83369
102.000	464.225	.00047	.05860	6.25975	36.52620	33.35922	23.79576
102.333	464.127	.00046	.05860	6.27507	36.54561	33.36244	23.75782

102.667	464.028	.00045	.05860	6.29039	36.56502	33.36566	23.71987
103.000	463.929	.00045	.05859	6.30572	36.58444	33.36888	23.68192
103.333	463.830	.00044	.05859	6.32105	36.60386	33.37211	23.64395
103.667	463.732	.00043	.05859	6.33638	36.62329	33.37533	23.60598
104.000	463.633	.00043	.05858	6.35171	36.64272	33.37856	23.56801
104.333	463.534	.00042	.05858	6.36704	36.66216	33.38179	23.53002
104.667	463.435	.00041	.05858	6.38237	36.68160	33.38502	23.49203
105.000	463.337	.00041	.05857	6.39771	36.70105	33.38825	23.45402
105.333	463.238	.00040	.05857	6.41304	36.72050	33.39148	23.41601
105.667	463.139	.00039	.05857	6.42838	36.73995	33.39471	23.37800
106.000	463.041	.00039	.05856	6.44372	36.75941	33.39794	23.33997
106.333	462.942	.00038	.05856	6.45906	36.77888	33.40118	23.30194
106.667	462.843	.00038	.05856	6.47441	36.79835	33.40441	23.26390
107.000	462.745	.00037	.05855	6.48975	36.81782	33.40765	23.22585
107.333	462.646	.00037	.05855	6.50510	36.83730	33.41089	23.18780
107.667	462.548	.00036	.05855	6.52045	36.85679	33.41412	23.14973
108.000	462.449	.00035	.05854	6.53580	36.87628	33.41736	23.11166
108.333	462.351	.00035	.05854	6.55115	36.89577	33.42061	23.07358
108.667	462.252	.00034	.05854	6.56650	36.91527	33.42385	23.03550
109.000	462.154	.00034	.05854	6.58185	36.93478	33.42709	22.99740
109.333	462.055	.00033	.05853	6.59721	36.95429	33.43033	22.95930
109.667	461.956	.00033	.05853	6.61257	36.97380	33.43358	22.92119
110.000	461.858	.00032	.05853	6.62793	36.99332	33.43683	22.88307
110.333	461.760	.00032	.05853	6.64329	37.01284	33.44007	22.84495
110.667	461.661	.00031	.05852	6.65865	37.03237	33.44332	22.80682
111.000	461.563	.00031	.05852	6.67401	37.05191	33.44657	22.76868
111.333	461.464	.00031	.05852	6.68938	37.07144	33.44982	22.73053
111.667	461.366	.00030	.05852	6.70475	37.09099	33.45307	22.69237
112.000	461.267	.00030	.05851	6.72012	37.11054	33.45633	22.65421
112.333	461.169	.00029	.05851	6.73549	37.13009	33.45958	22.61604
112.667	461.071	.00029	.05851	6.75086	37.14965	33.46283	22.57786
113.000	460.972	.00028	.05851	6.76623	37.16921	33.46609	22.53968
113.333	460.874	.00028	.05850	6.78161	37.18878	33.46935	22.50148
113.667	460.775	.00028	.05850	6.79698	37.20835	33.47260	22.46328
114.000	460.677	.00027	.05850	6.81236	37.22793	33.47586	22.42507
114.333	460.579	.00027	.05850	6.82774	37.24751	33.47912	22.38686
114.667	460.481	.00027	.05850	6.84312	37.26710	33.48238	22.34863
115.000	460.382	.00026	.05849	6.85850	37.28669	33.48565	22.31040
115.333	460.284	.00026	.05849	6.87389	37.30629	33.48891	22.27216
115.667	460.186	.00025	.05849	6.88927	37.32589	33.49217	22.23392
116.000	460.087	.00025	.05849	6.90466	37.34550	33.49544	22.19566
116.333	459.989	.00025	.05849	6.92005	37.36511	33.49870	22.15740
116.667	459.891	.00024	.05848	6.93544	37.38473	33.50197	22.11913
117.000	459.793	.00024	.05848	6.95083	37.40435	33.50524	22.08086
117.333	459.695	.00024	.05848	6.96623	37.42398	33.50851	22.04257
117.667	459.596	.00024	.05848	6.98162	37.44361	33.51178	22.00428
118.000	459.498	.00023	.05848	6.99702	37.46325	33.51505	21.96598
118.333	459.400	.00023	.05847	7.01241	37.48289	33.51832	21.92768
118.667	459.302	.00023	.05847	7.02781	37.50253	33.52159	21.88936
119.000	459.204	.00022	.05847	7.04322	37.52219	33.52486	21.85104
119.333	459.106	.00022	.05847	7.05862	37.54184	33.52814	21.81271
119.667	459.007	.00022	.05847	7.07402	37.56150	33.53141	21.77438
120.000	458.909	.00021	.05847	7.08943	37.58117	33.53469	21.73604
120.333	458.811	.00021	.05846	7.10483	37.60084	33.53796	21.69768
120.667	458.713	.00021	.05846	7.12024	37.62052	33.54124	21.65933
121.000	458.615	.00021	.05846	7.13565	37.64020	33.54452	21.62096
121.333	458.517	.00020	.05846	7.15107	37.65989	33.54780	21.58259
121.667	458.419	.00020	.05846	7.16648	37.67958	33.55108	21.54421
122.000	458.321	.00020	.05845	7.18189	37.69927	33.55436	21.50582
122.333	458.223	.00020	.05845	7.19731	37.71897	33.55764	21.46743
122.667	458.125	.00019	.05845	7.21273	37.73868	33.56092	21.42903
123.000	458.027	.00019	.05845	7.22815	37.75839	33.56421	21.39062
123.333	457.929	.00019	.05845	7.24357	37.77811	33.56749	21.35220
123.667	457.831	.00019	.05845	7.25899	37.79783	33.57077	21.31378
124.000	457.733	.00018	.05844	7.27441	37.81755	33.57406	21.27535
124.333	457.635	.00018	.05844	7.28984	37.83728	33.57734	21.23691
124.667	457.537	.00018	.05844	7.30526	37.85702	33.58063	21.19847
125.000	457.439	.00018	.05844	7.32069	37.87676	33.58392	21.16001
125.333	457.341	.00018	.05844	7.33612	37.89651	33.58721	21.12155
125.667	457.243	.00017	.05844	7.35155	37.91626	33.59049	21.08309
126.000	457.145	.00017	.05843	7.36699	37.93601	33.59378	21.04461
126.333	457.048	.00017	.05843	7.38242	37.95577	33.59707	21.00613
126.667	456.950	.00017	.05843	7.39785	37.97554	33.60036	20.96765
127.000	456.852	.00017	.05843	7.41329	37.99531	33.60365	20.92915
127.333	456.754	.00016	.05843	7.42873	38.01508	33.60694	20.89065
127.667	456.656	.00016	.05843	7.44417	38.03486	33.61023	20.85214
128.000	456.558	.00016	.05842	7.45961	38.05465	33.61353	20.81363
128.333	456.460	.00016	.05842	7.47505	38.07444	33.61682	20.77511
128.667	456.363	.00016	.05842	7.49050	38.09424	33.62011	20.73658
129.000	456.265	.00015	.05842	7.50594	38.11404	33.62341	20.69804
129.333	456.167	.00015	.05842	7.52139	38.13384	33.62670	20.65950
129.667	456.069	.00015	.05841	7.53684	38.15365	33.62999	20.62095
130.000	455.972	.00015	.05841	7.55229	38.17347	33.63329	20.58240
130.333	455.874	.00015	.05841	7.56774	38.19329	33.63658	20.54383
130.667	455.776	.00015	.05841	7.58319	38.21311	33.63988	20.50526
131.000	455.678	.00014	.05841	7.59865	38.23294	33.64317	20.46669
131.333	455.581	.00014	.05841	7.61410	38.25278	33.64647	20.42810
131.667	455.483	.00014	.05840	7.62956	38.27262	33.64976	20.38951
132.000	455.385	.00014	.05840	7.64502	38.29246	33.65306	20.35092
132.333	455.288	.00014	.05840	7.66048	38.31231	33.65635	20.31232
132.667	455.190	.00014	.05840	7.67594	38.33217	33.65965	20.27371
133.000	455.092	.00013	.05840	7.69140	38.35203	33.66295	20.23509
133.333	454.995	.00013	.05839	7.70687	38.37189	33.66624	20.19647
133.667	454.897	.00013	.05839	7.72233	38.39176	33.66954	20.15784
134.000	454.799	.00013	.05839	7.73780	38.41164	33.67283	20.11921
134.333	454.702	.00013	.05839	7.75327	38.43152	33.67613	20.08057
134.667	454.604	.00013	.05839	7.76874	38.45140	33.67943	20.04192
135.000	454.507	.00013	.05839	7.78421	38.47129	33.68272	20.00327
135.333	454.409	.00012	.05838	7.79968	38.49118	33.68602	19.96461
135.667	454.311	.00012	.05838	7.81516	38.51108	33.68931	19.92594
136.000	454.214	.00012	.05838	7.83063	38.53099	33.69261	19.88727
136.333	454.116	.00012	.05838	7.84611	38.55090	33.69591	19.84859
136.667	454.019	.00012	.05838	7.86159	38.57081	33.69920	19.80990

137.000	453.921	.00012	.05837	7.87707	38.59073	33.70249	19.77121
137.333	453.824	.00012	.05837	7.89255	38.61066	33.70579	19.73252
137.667	453.726	.00012	.05837	7.90803	38.63058	33.70908	19.69382
138.000	453.629	.00011	.05837	7.92351	38.65052	33.71238	19.65511
138.333	453.531	.00011	.05837	7.93900	38.67046	33.71567	19.61639
138.667	453.434	.00011	.05836	7.95449	38.69040	33.71896	19.57767
139.000	453.336	.00011	.05836	7.96997	38.71035	33.72225	19.53895
139.333	453.239	.00011	.05836	7.98546	38.73030	33.72554	19.50022
139.667	453.141	.00011	.05836	8.00095	38.75026	33.72883	19.46148
140.000	453.044	.00011	.05835	8.01645	38.77023	33.73212	19.42274
140.333	452.947	.00011	.05835	8.03194	38.79020	33.73541	19.38399
140.667	452.849	.00011	.05835	8.04744	38.81017	33.73870	19.34524
141.000	452.752	.00010	.05835	8.06293	38.83015	33.74199	19.30648
141.333	452.654	.00010	.05835	8.07843	38.85013	33.74528	19.26771
141.667	452.557	.00010	.05834	8.09393	38.87012	33.74856	19.22895
142.000	452.460	.00010	.05834	8.10943	38.89011	33.75185	19.19017
142.333	452.362	.00010	.05834	8.12493	38.91011	33.75513	19.15139
142.667	452.265	.00010	.05834	8.14043	38.93011	33.75841	19.11261
143.000	452.168	.00010	.05833	8.15594	38.95012	33.76169	19.07381
143.333	452.070	.00010	.05833	8.17144	38.97013	33.76497	19.03502
143.667	451.973	.00010	.05833	8.18695	38.99015	33.76825	18.99622
144.000	451.876	.00010	.05833	8.20246	39.01017	33.77153	18.95741
144.333	451.778	.00010	.05832	8.21797	39.03020	33.77481	18.91860
144.667	451.681	.00009	.05832	8.23348	39.05023	33.77808	18.87979
145.000	451.584	.00009	.05832	8.24899	39.07027	33.78136	18.84097
145.333	451.487	.00009	.05832	8.26450	39.09031	33.78463	18.80214
145.667	451.389	.00009	.05831	8.28002	39.11036	33.78790	18.76332
146.000	451.292	.00009	.05831	8.29553	39.13041	33.79117	18.72448
146.333	451.195	.00009	.05831	8.31105	39.15047	33.79443	18.68564
146.667	451.098	.00009	.05831	8.32657	39.17053	33.79770	18.64680
147.000	451.000	.00009	.05830	8.34209	39.19060	33.80096	18.60796
147.333	450.903	.00009	.05830	8.35761	39.21067	33.80423	18.56910
147.667	450.806	.00009	.05830	8.37314	39.23075	33.80748	18.53025
148.000	450.709	.00009	.05830	8.38866	39.25083	33.81074	18.49139
148.333	450.612	.00009	.05829	8.40418	39.27091	33.81400	18.45253
148.667	450.515	.00008	.05829	8.41971	39.29100	33.81725	18.41366
149.000	450.417	.00008	.05829	8.43524	39.31110	33.82050	18.37479
149.333	450.320	.00008	.05828	8.45077	39.33120	33.82375	18.33591
149.667	450.223	.00008	.05828	8.46630	39.35130	33.82700	18.29704
150.000	450.126	.00008	.05828	8.48183	39.37141	33.83024	18.25815
150.333	450.029	.00008	.05828	8.49736	39.39153	33.83348	18.21927
150.667	449.932	.00008	.05827	8.51290	39.41165	33.83672	18.18038
151.000	449.835	.00008	.05827	8.52843	39.43177	33.83996	18.14149
151.333	449.738	.00008	.05827	8.54397	39.45190	33.84319	18.10259
151.667	449.641	.00008	.05826	8.55951	39.47204	33.84642	18.06369
152.000	449.543	.00008	.05826	8.57505	39.49218	33.84965	18.02479
152.333	449.446	.00008	.05826	8.59059	39.51232	33.85288	17.98588
152.667	449.349	.00008	.05825	8.60613	39.53247	33.85610	17.94697
153.000	449.252	.00008	.05825	8.62167	39.55262	33.85932	17.90806
153.333	449.155	.00007	.05825	8.63722	39.57278	33.86253	17.86915
153.667	449.058	.00007	.05824	8.65276	39.59294	33.86574	17.83023
154.000	448.961	.00007	.05824	8.66831	39.61311	33.86895	17.79131
154.333	448.864	.00007	.05824	8.68386	39.63328	33.87216	17.75239
154.667	448.767	.00007	.05823	8.69941	39.65346	33.87536	17.71347
155.000	448.670	.00007	.05823	8.71496	39.67364	33.87856	17.67454
155.333	448.573	.00007	.05823	8.73051	39.69383	33.88175	17.63561
155.667	448.476	.00007	.05822	8.74606	39.71402	33.88494	17.59668
156.000	448.379	.00007	.05822	8.76162	39.73422	33.88813	17.55775
156.333	448.283	.00007	.05822	8.77717	39.75442	33.89131	17.51882
156.667	448.186	.00007	.05821	8.79273	39.77462	33.89449	17.47988
157.000	448.089	.00007	.05821	8.80829	39.79483	33.89766	17.44094
157.333	447.992	.00007	.05821	8.82385	39.81505	33.90083	17.40200
157.667	447.895	.00007	.05820	8.83941	39.83527	33.90400	17.36306
158.000	447.798	.00007	.05820	8.85497	39.85549	33.90716	17.32412
158.333	447.701	.00007	.05819	8.87053	39.87572	33.91032	17.28517
158.667	447.604	.00007	.05819	8.88610	39.89595	33.91347	17.24623
159.000	447.507	.00006	.05819	8.90166	39.91619	33.91661	17.20728
159.333	447.410	.00006	.05818	8.91723	39.93643	33.91975	17.16834
159.667	447.314	.00006	.05818	8.93279	39.95668	33.92289	17.12939
160.000	447.217	.00006	.05818	8.94836	39.97693	33.92602	17.09044
160.333	447.120	.00006	.05817	8.96393	39.99719	33.92915	17.05149
160.667	447.023	.00006	.05817	8.97950	40.01745	33.93227	17.01254
161.000	446.926	.00006	.05816	8.99508	40.03772	33.93539	16.97359
161.333	446.830	.00006	.05816	9.01065	40.05799	33.93850	16.93464
161.667	446.733	.00006	.05815	9.02623	40.07826	33.94160	16.89570
162.000	446.636	.00006	.05815	9.04180	40.09854	33.94470	16.85675
162.333	446.539	.00006	.05815	9.05738	40.11883	33.94779	16.81780
162.667	446.442	.00006	.05814	9.07296	40.13912	33.95088	16.77885
163.000	446.346	.00006	.05814	9.08854	40.15941	33.95396	16.73990
163.333	446.249	.00006	.05813	9.10412	40.17971	33.95703	16.70095
163.667	446.152	.00006	.05813	9.11970	40.20001	33.96010	16.66200
164.000	446.055	.00006	.05813	9.13528	40.22032	33.96316	16.62306
164.333	445.959	.00006	.05812	9.15086	40.24063	33.96621	16.58411
164.667	445.862	.00006	.05812	9.16645	40.26095	33.96926	16.54517
165.000	445.765	.00006	.05811	9.18204	40.28127	33.97230	16.50623
165.333	445.669	.00006	.05811	9.19762	40.30159	33.97534	16.46728
165.667	445.572	.00006	.05810	9.21321	40.32192	33.97836	16.42834
166.000	445.475	.00005	.05810	9.22880	40.34226	33.98138	16.38941
166.333	445.379	.00005	.05809	9.24439	40.36260	33.98439	16.35047
166.667	445.282	.00005	.05809	9.25998	40.38294	33.98740	16.31154
167.000	445.185	.00005	.05808	9.27558	40.40329	33.99040	16.27260
167.333	445.089	.00005	.05808	9.29117	40.42364	33.99338	16.23367
167.667	444.992	.00005	.05808	9.30677	40.44399	33.99636	16.19475
168.000	444.895	.00005	.05807	9.32236	40.46436	33.99934	16.15582
168.333	444.799	.00005	.05807	9.33796	40.48472	34.00230	16.11690
168.667	444.702	.00005	.05806	9.35356	40.50509	34.00526	16.07798
169.000	444.606	.00005	.05806	9.36916	40.52547	34.00820	16.03906
169.333	444.509	.00005	.05805	9.38476	40.54584	34.01114	16.00015
169.667	444.412	.00005	.05805	9.40036	40.56623	34.01407	15.96124
170.000	444.316	.00005	.05804	9.41596	40.58661	34.01699	15.92234
170.333	444.219	.00005	.05804	9.43157	40.60701	34.01991	15.88343
170.667	444.123	.00005	.05803	9.44717	40.62740	34.02281	15.84454
171.000	444.026	.00005	.05803	9.46278	40.64780	34.02570	15.80564

171.333	443.930	.00005	.05802	9.47839	40.66821	34.02858	15.76675
171.667	443.833	.00005	.05802	9.49400	40.68862	34.03146	15.72787
172.000	443.736	.00005	.05801	9.50960	40.70903	34.03432	15.68898
172.333	443.640	.00005	.05801	9.52522	40.72945	34.03718	15.65011
172.667	443.543	.00005	.05800	9.54083	40.74987	34.04002	15.61124
173.000	443.447	.00005	.05800	9.55644	40.77030	34.04285	15.57237
173.333	443.350	.00005	.05799	9.57205	40.79073	34.04568	15.53351
173.667	443.254	.00005	.05798	9.58767	40.81116	34.04849	15.49465
174.000	443.157	.00005	.05798	9.60328	40.83160	34.05129	15.45580
174.333	443.061	.00005	.05797	9.61890	40.85204	34.05408	15.41696
174.667	442.965	.00005	.05797	9.63452	40.87249	34.05686	15.37812
175.000	442.868	.00004	.05796	9.65014	40.89294	34.05962	15.33929
175.333	442.772	.00004	.05796	9.66576	40.91340	34.06238	15.30046
175.667	442.675	.00004	.05795	9.68138	40.93386	34.06513	15.26164
176.000	442.579	.00004	.05795	9.69700	40.95432	34.06786	15.22283
176.333	442.482	.00004	.05794	9.71262	40.97479	34.07058	15.18402
176.667	442.386	.00004	.05793	9.72825	40.99526	34.07329	15.14523
177.000	442.290	.00004	.05793	9.74387	41.01574	34.07598	15.10643
177.333	442.193	.00004	.05792	9.75950	41.03622	34.07866	15.06765
177.667	442.097	.00004	.05792	9.77513	41.05671	34.08134	15.02887
178.000	442.000	.00004	.05791	9.79075	41.07719	34.08399	14.99011
178.333	441.904	.00004	.05791	9.80638	41.09769	34.08664	14.95134
178.667	441.808	.00004	.05790	9.82201	41.11818	34.08927	14.91259
179.000	441.711	.00004	.05789	9.83764	41.13869	34.09189	14.87385
179.333	441.615	.00004	.05789	9.85328	41.15919	34.09449	14.83511
179.667	441.519	.00004	.05788	9.86891	41.17970	34.09708	14.79639
180.000	441.422	.00004	.05788	9.88454	41.20021	34.09965	14.75767
180.333	441.326	.00004	.05787	9.90018	41.22073	34.10222	14.71896
180.667	441.230	.00004	.05786	9.91582	41.24125	34.10476	14.68027
181.000	441.133	.00004	.05786	9.93145	41.26178	34.10730	14.64158
181.333	441.037	.00004	.05785	9.94709	41.28231	34.10981	14.60290
181.667	440.941	.00004	.05785	9.96273	41.30284	34.11232	14.56423
182.000	440.844	.00004	.05784	9.97837	41.32338	34.11480	14.52557
182.333	440.748	.00004	.05783	9.99401	41.34392	34.11728	14.48692
182.667	440.652	.00004	.05783	10.00965	41.36446	34.11973	14.44829
183.000	440.556	.00004	.05782	10.02529	41.38501	34.12217	14.40966
183.333	440.459	.00004	.05782	10.04094	41.40556	34.12460	14.37105
183.667	440.363	.00004	.05781	10.05658	41.42612	34.12700	14.33245
184.000	440.267	.00004	.05780	10.07223	41.44668	34.12940	14.29385
184.333	440.171	.00004	.05780	10.08788	41.46725	34.13177	14.25527
184.667	440.074	.00004	.05779	10.10352	41.48781	34.13413	14.21671
185.000	439.978	.00004	.05778	10.11917	41.50839	34.13647	14.17815
185.333	439.882	.00004	.05778	10.13482	41.52896	34.13879	14.13961
185.667	439.786	.00004	.05777	10.15047	41.54954	34.14110	14.10108
186.000	439.689	.00004	.05776	10.16612	41.57012	34.14339	14.06256
186.333	439.593	.00004	.05776	10.18177	41.59071	34.14566	14.02406
186.667	439.497	.00004	.05775	10.19743	41.61130	34.14791	13.98557
187.000	439.401	.00004	.05774	10.21308	41.63190	34.15015	13.94710
187.333	439.305	.00004	.05774	10.22874	41.65250	34.15236	13.90863
187.667	439.209	.00003	.05773	10.24439	41.67310	34.15456	13.87019
188.000	439.112	.00003	.05772	10.26005	41.69370	34.15674	13.83175
188.333	439.016	.00003	.05772	10.27571	41.71431	34.15890	13.79333
188.667	438.920	.00003	.05771	10.29136	41.73493	34.16103	13.75493
189.000	438.824	.00003	.05770	10.30702	41.75554	34.16315	13.71654
189.333	438.728	.00003	.05770	10.32268	41.77616	34.16525	13.67817
189.667	438.632	.00003	.05769	10.33835	41.79679	34.16733	13.63981
190.000	438.536	.00003	.05768	10.35401	41.81741	34.16939	13.60147
190.333	438.439	.00003	.05768	10.36967	41.83804	34.17143	13.56315
190.667	438.343	.00003	.05767	10.38533	41.85868	34.17345	13.52484
191.000	438.247	.00003	.05766	10.40100	41.87932	34.17544	13.48654
191.333	438.151	.00003	.05766	10.41666	41.89996	34.17742	13.44827
191.667	438.055	.00003	.05765	10.43233	41.92061	34.17937	13.41001
192.000	437.959	.00003	.05764	10.44800	41.94125	34.18130	13.37177
192.333	437.863	.00003	.05764	10.46366	41.96191	34.18321	13.33355
192.667	437.767	.00003	.05763	10.47933	41.98256	34.18510	13.29534
193.000	437.671	.00003	.05762	10.49500	42.00322	34.18697	13.25716
193.333	437.575	.00003	.05761	10.51067	42.02388	34.18881	13.21899
193.667	437.479	.00003	.05761	10.52634	42.04455	34.19063	13.18084
194.000	437.383	.00003	.05760	10.54202	42.06522	34.19242	13.14271
194.333	437.287	.00003	.05759	10.55769	42.08589	34.19420	13.10460
194.667	437.191	.00003	.05759	10.57336	42.10657	34.19594	13.06651
195.000	437.095	.00003	.05758	10.58904	42.12725	34.19767	13.02843
195.333	436.999	.00003	.05757	10.60471	42.14793	34.19937	12.99038
195.667	436.903	.00003	.05757	10.62039	42.16862	34.20105	12.95235
196.000	436.806	.00003	.05756	10.63607	42.18931	34.20270	12.91434
196.333	436.711	.00003	.05755	10.65174	42.21000	34.20432	12.87635
196.667	436.615	.00003	.05754	10.66742	42.23070	34.20593	12.83838
197.000	436.519	.00003	.05754	10.68310	42.25140	34.20750	12.80043
197.333	436.423	.00003	.05753	10.69878	42.27210	34.20905	12.76251
197.667	436.327	.00003	.05752	10.71446	42.29281	34.21058	12.72460
198.000	436.231	.00003	.05751	10.73014	42.31352	34.21207	12.68672
198.333	436.135	.00003	.05751	10.74583	42.33423	34.21355	12.64886
198.667	436.039	.00003	.05750	10.76151	42.35495	34.21499	12.61103
199.000	435.943	.00003	.05749	10.77719	42.37566	34.21641	12.57321
199.333	435.847	.00003	.05749	10.79288	42.39639	34.21780	12.53542
199.667	435.751	.00003	.05748	10.80856	42.41711	34.21916	12.49766
200.000	435.655	.00003	.05747	10.82425	42.43784	34.22050	12.45991
200.333	435.559	.00003	.05746	10.83994	42.45857	34.22180	12.42219
200.667	435.463	.00003	.05746	10.85563	42.47931	34.22308	12.38450
201.000	435.367	.00003	.05745	10.87131	42.50004	34.22433	12.34683
201.333	435.271	.00003	.05744	10.88700	42.52079	34.22556	12.30919
201.667	435.175	.00003	.05743	10.90269	42.54153	34.22675	12.27157
202.000	435.080	.00003	.05743	10.91838	42.56228	34.22791	12.23398
202.333	434.984	.00003	.05742	10.93407	42.58303	34.22904	12.19641
202.667	434.888	.00003	.05741	10.94977	42.60378	34.23015	12.15887
203.000	434.792	.00003	.05740	10.96546	42.62454	34.23122	12.12135
203.333	434.696	.00003	.05740	10.98115	42.64530	34.23226	12.08386
203.667	434.600	.00003	.05739	10.99685	42.66606	34.23328	12.04640
204.000	434.504	.00003	.05738	11.01254	42.68682	34.23426	12.00897
204.333	434.408	.00003	.05737	11.02824	42.70759	34.23521	11.97156
204.667	434.313	.00003	.05737	11.04393	42.72836	34.23613	11.93419
205.000	434.217	.00003	.05736	11.05963	42.74913	34.23701	11.89684
205.333	434.121	.00003	.05735	11.07533	42.76991	34.23787	11.85952

205.667	434.025	.00003	.05735	11.09103	42.79069	34.23869	11.82222
206.000	433.929	.00003	.05734	11.10672	42.81147	34.23948	11.78496
206.333	433.833	.00003	.05733	11.12242	42.83226	34.24024	11.74773
206.667	433.738	.00002	.05732	11.13812	42.85305	34.24096	11.71052
207.000	433.642	.00002	.05732	11.15383	42.87384	34.24165	11.67335
207.333	433.546	.00002	.05731	11.16953	42.89463	34.24231	11.63620
207.667	433.450	.00002	.05730	11.18523	42.91543	34.24293	11.59909
208.000	433.354	.00002	.05729	11.20093	42.93623	34.24352	11.56201
208.333	433.259	.00002	.05729	11.21664	42.95703	34.24407	11.52495
208.667	433.163	.00002	.05728	11.23234	42.97783	34.24459	11.48793
209.000	433.067	.00002	.05727	11.24804	42.99864	34.24508	11.45095
209.333	432.971	.00002	.05726	11.26375	43.01945	34.24552	11.41399
209.667	432.876	.00002	.05726	11.27946	43.04026	34.24594	11.37707
210.000	432.780	.00002	.05725	11.29516	43.06108	34.24631	11.34017
210.333	432.684	.00002	.05724	11.31087	43.08189	34.24665	11.30332
210.667	432.588	.00002	.05723	11.32658	43.10271	34.24696	11.26649
211.000	432.493	.00002	.05723	11.34229	43.12354	34.24723	11.22970
211.333	432.397	.00002	.05722	11.35799	43.14436	34.24746	11.19294
211.667	432.301	.00002	.05721	11.37370	43.16519	34.24765	11.15622
212.000	432.205	.00002	.05721	11.38941	43.18602	34.24780	11.11953
212.333	432.110	.00002	.05720	11.40513	43.20685	34.24792	11.08288
212.667	432.014	.00002	.05719	11.42084	43.22769	34.24800	11.04626
213.000	431.918	.00002	.05718	11.43655	43.24853	34.24804	11.00967
213.333	431.822	.00002	.05718	11.45226	43.26937	34.24804	10.97313
213.667	431.727	.00002	.05717	11.46797	43.29021	34.24801	10.93661
214.000	431.631	.00002	.05716	11.48369	43.31106	34.24793	10.90014
214.333	431.535	.00002	.05716	11.49940	43.33191	34.24781	10.86370
214.667	431.440	.00002	.05715	11.51512	43.35276	34.24766	10.82730
215.000	431.344	.00002	.05714	11.53083	43.37361	34.24746	10.79093
215.333	431.248	.00002	.05713	11.54655	43.39447	34.24723	10.75461
215.667	431.153	.00002	.05713	11.56226	43.41532	34.24695	10.71832
216.000	431.057	.00002	.05712	11.57798	43.43618	34.24663	10.68207
216.333	430.961	.00002	.05711	11.59370	43.45705	34.24627	10.64585
216.667	430.866	.00002	.05711	11.60942	43.47791	34.24587	10.60968
217.000	430.770	.00002	.05710	11.62513	43.49878	34.24542	10.57354
217.333	430.674	.00002	.05709	11.64085	43.51965	34.24494	10.53745
217.667	430.579	.00002	.05709	11.65657	43.54052	34.24441	10.50139
218.000	430.483	.00002	.05708	11.67229	43.56139	34.24384	10.46538
218.333	430.387	.00002	.05707	11.68801	43.58227	34.24323	10.42940
218.667	430.292	.00002	.05706	11.70373	43.60315	34.24257	10.39346
219.000	430.196	.00002	.05706	11.71945	43.62403	34.24187	10.35757
219.333	430.100	.00002	.05705	11.73518	43.64491	34.24112	10.32172
219.667	430.005	.00002	.05704	11.75090	43.66580	34.24033	10.28591
220.000	429.909	.00002	.05704	11.76662	43.68668	34.23950	10.25014
220.333	429.814	.00002	.05703	11.78234	43.70757	34.23862	10.21441
220.667	429.718	.00002	.05702	11.79807	43.72847	34.23770	10.17872
221.000	429.622	.00002	.05702	11.81379	43.74936	34.23673	10.14308
221.333	429.527	.00002	.05701	11.82952	43.77026	34.23571	10.10748
221.667	429.431	.00002	.05701	11.84524	43.79115	34.23465	10.07193
222.000	429.336	.00002	.05700	11.86097	43.81205	34.23355	10.03641
222.333	429.240	.00002	.05699	11.87669	43.83296	34.23239	10.00095
222.667	429.144	.00002	.05699	11.89242	43.85386	34.23119	9.96552
223.000	429.049	.00002	.05698	11.90815	43.87477	34.22995	9.93014
223.333	428.953	.00002	.05697	11.92387	43.89567	34.22865	9.89481
223.667	428.858	.00002	.05697	11.93960	43.91658	34.22731	9.85952
224.000	428.762	.00002	.05696	11.95533	43.93750	34.22592	9.82427
224.333	428.667	.00002	.05696	11.97106	43.95841	34.22448	9.78907
224.667	428.571	.00002	.05695	11.98679	43.97933	34.22299	9.75392
225.000	428.475	.00002	.05694	12.00252	44.00025	34.22146	9.71882
225.333	428.380	.00002	.05694	12.01825	44.02117	34.21987	9.68376
225.667	428.284	.00002	.05693	12.03398	44.04209	34.21824	9.64875
226.000	428.189	.00002	.05693	12.04971	44.06301	34.21656	9.61378
226.333	428.093	.00002	.05692	12.06544	44.08394	34.21482	9.57886
226.667	427.998	.00002	.05692	12.08117	44.10487	34.21304	9.54399
227.000	427.902	.00002	.05691	12.09690	44.12579	34.21121	9.50917
227.333	427.807	.00002	.05690	12.11263	44.14673	34.20932	9.47440
227.667	427.711	.00002	.05690	12.12836	44.16766	34.20739	9.43968
228.000	427.616	.00002	.05689	12.14410	44.18859	34.20540	9.40500
228.333	427.520	.00002	.05689	12.15983	44.20953	34.20336	9.37037
228.667	427.425	.00002	.05688	12.17556	44.23047	34.20127	9.33580
229.000	427.329	.00002	.05688	12.19129	44.25141	34.19913	9.30127
229.333	427.234	.00002	.05687	12.20703	44.27235	34.19693	9.26680
229.667	427.138	.00002	.05687	12.22276	44.29330	34.19468	9.23237
230.000	427.043	.00002	.05686	12.23850	44.31424	34.19238	9.19800
230.333	426.947	.00002	.05686	12.25423	44.33519	34.19003	9.16367
230.667	426.852	.00002	.05685	12.26997	44.35614	34.18762	9.12940
231.000	426.756	.00002	.05685	12.28570	44.37709	34.18516	9.09518
231.333	426.661	.00002	.05684	12.30144	44.39804	34.18264	9.06101
231.667	426.565	.00002	.05684	12.31717	44.41900	34.18007	9.02690
232.000	426.470	.00002	.05684	12.33291	44.43995	34.17745	8.99284
232.333	426.374	.00002	.05683	12.34865	44.46091	34.17477	8.95883
232.667	426.279	.00002	.05683	12.36438	44.48187	34.17204	8.92487
233.000	426.183	.00002	.05682	12.38012	44.50283	34.16925	8.89096
233.333	426.088	.00002	.05682	12.39586	44.52379	34.16640	8.85711
233.667	425.992	.00002	.05681	12.41159	44.54476	34.16350	8.82332
234.000	425.897	.00002	.05681	12.42733	44.56572	34.16054	8.78958
234.333	425.801	.00002	.05681	12.44307	44.58669	34.15753	8.75589
234.667	425.706	.00002	.05680	12.45881	44.60766	34.15445	8.72226
235.000	425.610	.00002	.05680	12.47455	44.62863	34.15133	8.68868
235.333	425.515	.00002	.05680	12.49029	44.64960	34.14814	8.65516
235.667	425.420	.00002	.05679	12.50602	44.67058	34.14490	8.62169
236.000	425.324	.00002	.05679	12.52176	44.69155	34.14160	8.58828
236.333	425.229	.00002	.05679	12.53750	44.71253	34.13824	8.55493
236.667	425.133	.00002	.05678	12.55324	44.73350	34.13482	8.52163
237.000	425.038	.00002	.05678	12.56898	44.75448	34.13135	8.48839
237.333	424.942	.00002	.05678	12.58472	44.77546	34.12781	8.45521
237.667	424.847	.00002	.05677	12.60046	44.79645	34.12422	8.42208
238.000	424.752	.00002	.05677	12.61620	44.81743	34.12056	8.38901
238.333	424.656	.00002	.05677	12.63194	44.83842	34.11685	8.35600
238.667	424.561	.00002	.05677	12.64768	44.85940	34.11308	8.32305
239.000	424.465	.00002	.05677	12.66342	44.88039	34.10925	8.29016
239.333	424.370	.00002	.05676	12.67916	44.90138	34.10535	8.25732
239.667	424.274	.00002	.05676	12.69491	44.92237	34.10140	8.22455

240.000	424.179	.00002	.05676	12.71065	44.94336	34.09739	8.19183
240.333	424.084	.00002	.05676	12.72639	44.96436	34.09331	8.15917
240.667	423.988	.00002	.05676	12.74213	44.98535	34.08917	8.12657
241.000	423.893	.00002	.05675	12.75787	45.00635	34.08497	8.09404
241.333	423.797	.00002	.05675	12.77361	45.02735	34.08071	8.06156
241.667	423.702	.00002	.05675	12.78935	45.04835	34.07639	8.02914
242.000	423.607	.00002	.05675	12.80510	45.06935	34.07201	7.99679
242.333	423.511	.00002	.05675	12.82084	45.09035	34.06756	7.96449
242.667	423.416	.00002	.05675	12.83658	45.11135	34.06305	7.93226
243.000	423.320	.00002	.05675	12.85232	45.13235	34.05847	7.90009
243.333	423.225	.00001	.05675	12.86806	45.15336	34.05384	7.86798
243.667	423.130	.00001	.05675	12.88381	45.17437	34.04914	7.83593
244.000	423.034	.00001	.05675	12.89955	45.19537	34.04437	7.80394
244.333	422.939	.00001	.05675	12.91529	45.21638	34.03954	7.77202
244.667	422.844	.00001	.05675	12.93103	45.23739	34.03465	7.74016
245.000	422.748	.00001	.05675	12.94678	45.25841	34.02969	7.70836
245.333	422.653	.00001	.05675	12.96252	45.27942	34.02467	7.67663
245.667	422.557	.00001	.05675	12.97826	45.30043	34.01959	7.64495
246.000	422.462	.00001	.05675	12.99400	45.32145	34.01443	7.61335
246.333	422.367	.00001	.05675	13.00975	45.34247	34.00922	7.58180
246.667	422.271	.00001	.05675	13.02549	45.36348	34.00393	7.55033
247.000	422.176	.00001	.05675	13.04123	45.38450	33.99859	7.51891
247.333	422.081	.00001	.05675	13.05698	45.40552	33.99317	7.48756
247.667	421.985	.00001	.05676	13.07272	45.42654	33.98769	7.45628
248.000	421.890	.00001	.05676	13.08846	45.44757	33.98214	7.42506
248.333	421.795	.00001	.05676	13.10420	45.46859	33.97653	7.39390
248.667	421.699	.00001	.05676	13.11995	45.48961	33.97085	7.36281
249.000	421.604	.00001	.05676	13.13569	45.51064	33.96510	7.33179
249.333	421.509	.00001	.05677	13.15143	45.53167	33.95928	7.30084
249.667	421.413	.00001	.05677	13.16717	45.55269	33.95340	7.26995
250.000	421.318	.00001	.05677	13.18292	45.57372	33.94745	7.23912
250.333	421.222	.00001	.05678	13.19866	45.59475	33.94143	7.20836
250.667	421.127	.00001	.05678	13.21440	45.61579	33.93534	7.17767
251.000	421.032	.00001	.05678	13.23014	45.63682	33.92919	7.14705
251.333	420.936	.00001	.05679	13.24589	45.65785	33.92296	7.11650
251.667	420.841	.00001	.05679	13.26163	45.67889	33.91667	7.08601
252.000	420.746	.00001	.05680	13.27737	45.69992	33.91031	7.05559
252.333	420.650	.00001	.05680	13.29311	45.72096	33.90388	7.02524
252.667	420.555	.00001	.05680	13.30886	45.74200	33.89738	6.99495
253.000	420.460	.00001	.05681	13.32460	45.76304	33.89081	6.96474
253.333	420.364	.00001	.05681	13.34034	45.78408	33.88417	6.93459
253.667	420.269	.00001	.05682	13.35608	45.80512	33.87746	6.90451
254.000	420.174	.00001	.05682	13.37182	45.82616	33.87068	6.87450
254.333	420.078	.00001	.05683	13.38756	45.84720	33.86383	6.84456
254.667	419.983	.00001	.05684	13.40331	45.86825	33.85691	6.81469
255.000	419.888	.00001	.05684	13.41905	45.88929	33.84992	6.78489
255.333	419.793	.00001	.05685	13.43479	45.91034	33.84285	6.75516
255.667	419.697	.00001	.05686	13.45053	45.93138	33.83572	6.72550
256.000	419.602	.00001	.05686	13.46627	45.95243	33.82851	6.69591
256.333	419.507	.00001	.05687	13.48201	45.97348	33.82124	6.66639
256.667	419.411	.00001	.05688	13.49775	45.99453	33.81389	6.63694
257.000	419.316	.00001	.05688	13.51349	46.01558	33.80647	6.60756
257.333	419.221	.00001	.05689	13.52923	46.03663	33.79898	6.57825
257.667	419.125	.00001	.05690	13.54497	46.05769	33.79141	6.54902
258.000	419.030	.00001	.05691	13.56071	46.07874	33.78378	6.51985
258.333	418.935	.00001	.05692	13.57645	46.09979	33.77607	6.49076
258.667	418.839	.00001	.05693	13.59219	46.12085	33.76829	6.46173
259.000	418.744	.00001	.05694	13.60793	46.14191	33.76043	6.43278
259.333	418.649	.00001	.05694	13.62367	46.16297	33.75251	6.40390
259.667	418.553	.00001	.05695	13.63941	46.18402	33.74450	6.37510
260.000	418.458	.00001	.05696	13.65515	46.20508	33.73643	6.34636
260.333	418.363	.00001	.05697	13.67088	46.22614	33.72828	6.31770
260.667	418.267	.00001	.05698	13.68662	46.24721	33.72006	6.28911
261.000	418.172	.00001	.05700	13.70236	46.26827	33.71177	6.26060
261.333	418.077	.00001	.05701	13.71810	46.28933	33.70340	6.23215
261.667	417.982	.00001	.05702	13.73383	46.31040	33.69496	6.20378
262.000	417.886	.00001	.05703	13.74957	46.33146	33.68644	6.17549
262.333	417.791	.00001	.05704	13.76531	46.35253	33.67785	6.14726
262.667	417.696	.00001	.05705	13.78104	46.37359	33.66918	6.11911
263.000	417.600	.00001	.05707	13.79678	46.39466	33.66044	6.09104
263.333	417.505	.00001	.05708	13.81252	46.41573	33.65163	6.06304
263.667	417.410	.00001	.05709	13.82825	46.43680	33.64274	6.03511
264.000	417.314	.00001	.05711	13.84399	46.45787	33.63377	6.00725
264.333	417.219	.00001	.05712	13.85972	46.47894	33.62473	5.97947
264.667	417.124	.00001	.05713	13.87546	46.50002	33.61561	5.95177
265.000	417.029	.00001	.05715	13.89119	46.52109	33.60642	5.92414
265.333	416.933	.00001	.05716	13.90692	46.54216	33.59716	5.89658
265.667	416.838	.00001	.05718	13.92266	46.56324	33.58781	5.86910
266.000	416.743	.00001	.05719	13.93839	46.58431	33.57839	5.84169
266.333	416.647	.00001	.05721	13.95412	46.60539	33.56890	5.81436
266.667	416.552	.00001	.05723	13.96986	46.62647	33.55933	5.78711
267.000	416.457	.00001	.05724	13.98559	46.64755	33.54968	5.75993
267.333	416.361	.00001	.05726	14.00132	46.66863	33.53996	5.73282
267.667	416.266	.00001	.05728	14.01705	46.68971	33.53016	5.70579
268.000	416.171	.00001	.05729	14.03278	46.71079	33.52028	5.67884
268.333	416.075	.00001	.05731	14.04851	46.73187	33.51033	5.65196
268.667	415.980	.00001	.05733	14.06424	46.75296	33.50030	5.62516
269.000	415.885	.00001	.05735	14.07997	46.77404	33.49019	5.59843
269.333	415.790	.00001	.05737	14.09570	46.79512	33.48001	5.57179
269.667	415.694	.00001	.05739	14.11143	46.81621	33.46975	5.54521
270.000	415.599	.00001	.05741	14.12716	46.83730	33.45941	5.51872
270.333	415.504	.00001	.05743	14.14289	46.85838	33.44900	5.49230
270.667	415.408	.00001	.05745	14.15861	46.87947	33.43850	5.46595
271.000	415.313	.00001	.05747	14.17434	46.90056	33.42793	5.43968
271.333	415.218	.00001	.05749	14.19007	46.92165	33.41728	5.41349
271.667	415.122	.00001	.05751	14.20579	46.94274	33.40656	5.38738
272.000	415.027	.00001	.05753	14.22152	46.96384	33.39575	5.36134
272.333	414.932	.00001	.05756	14.23725	46.98493	33.38487	5.33539
272.667	414.837	.00001	.05758	14.25297	47.00602	33.37391	5.30950
273.000	414.741	.00001	.05760	14.26869	47.02712	33.36288	5.28370
273.333	414.646	.00001	.05762	14.28442	47.04821	33.35176	5.25797
273.667	414.551	.00001	.05765	14.30014	47.06931	33.34057	5.23232
274.000	414.455	.00001	.05767	14.31586	47.09041	33.32929	5.20675

274.333	414.360	.00001	.05770	14.33159	47.11151	33.31794	5.18125
274.667	414.265	.00001	.05772	14.34731	47.13261	33.30651	5.15584
275.000	414.169	.00001	.05775	14.36303	47.15371	33.29501	5.13050
275.333	414.074	.00001	.05778	14.37875	47.17481	33.28342	5.10524
275.667	413.979	.00001	.05780	14.39447	47.19591	33.27176	5.08005
276.000	413.883	.00001	.05783	14.41019	47.21701	33.26001	5.05495
276.333	413.788	.00001	.05786	14.42591	47.23812	33.24819	5.02992
276.667	413.693	.00001	.05788	14.44163	47.25922	33.23629	5.00497
277.000	413.597	.00001	.05791	14.45735	47.28033	33.22431	4.98010
277.333	413.502	.00001	.05794	14.47306	47.30143	33.21225	4.95530
277.667	413.407	.00001	.05797	14.48878	47.32254	33.20011	4.93059
278.000	413.312	.00001	.05800	14.50450	47.34365	33.18789	4.90595
278.333	413.216	.00001	.05803	14.52021	47.36476	33.17560	4.88139
278.667	413.121	.00001	.05806	14.53593	47.38587	33.16322	4.85691
279.000	413.026	.00001	.05809	14.55164	47.40698	33.15077	4.83251
279.333	412.930	.00001	.05813	14.56735	47.42809	33.13823	4.80819
279.667	412.835	.00001	.05816	14.58307	47.44920	33.12562	4.78394
280.000	412.740	.00001	.05819	14.59878	47.47032	33.11292	4.75978
280.333	412.644	.00001	.05822	14.61449	47.49143	33.10015	4.73569
280.667	412.549	.00001	.05826	14.63020	47.51255	33.08730	4.71168
281.000	412.454	.00001	.05829	14.64591	47.53367	33.07437	4.68775
281.333	412.358	.00001	.05833	14.66162	47.55478	33.06136	4.66390
281.667	412.263	.00001	.05836	14.67733	47.57590	33.04827	4.64013
282.000	412.168	.00001	.05840	14.69304	47.59702	33.03510	4.61643
282.333	412.072	.00001	.05843	14.70875	47.61814	33.02185	4.59282
282.667	411.977	.00001	.05847	14.72445	47.63927	33.00852	4.56928
283.000	411.882	.00001	.05851	14.74016	47.66039	32.99511	4.54583
283.333	411.786	.00001	.05855	14.75587	47.68151	32.98162	4.52245
283.667	411.691	.00001	.05858	14.77157	47.70264	32.96805	4.49915
284.000	411.596	.00001	.05862	14.78728	47.72376	32.95440	4.47593
284.333	411.500	.00001	.05866	14.80298	47.74489	32.94067	4.45279
284.667	411.405	.00001	.05870	14.81868	47.76602	32.92686	4.42973
285.000	411.310	.00001	.05874	14.83438	47.78714	32.91297	4.40674
285.333	411.214	.00001	.05879	14.85009	47.80827	32.89901	4.38384
285.667	411.119	.00001	.05883	14.86579	47.82941	32.88496	4.36101
286.000	411.024	.00001	.05887	14.88149	47.85054	32.87083	4.33827
286.333	410.928	.00001	.05891	14.89719	47.87167	32.85662	4.31560
286.667	410.833	.00001	.05896	14.91288	47.89280	32.84233	4.29301
287.000	410.737	.00001	.05900	14.92858	47.91394	32.82797	4.27050
287.333	410.642	.00001	.05905	14.94428	47.93507	32.81352	4.24807
287.667	410.547	.00001	.05909	14.95997	47.95621	32.79899	4.22572
288.000	410.451	.00001	.05914	14.97567	47.97735	32.78438	4.20345
288.333	410.356	.00001	.05918	14.99136	47.99849	32.76970	4.18126
288.667	410.261	.00001	.05923	15.00706	48.01963	32.75493	4.15914
289.000	410.165	.00001	.05928	15.02275	48.04077	32.74008	4.13711
289.333	410.070	.00001	.05933	15.03844	48.06191	32.72516	4.11515
289.667	409.974	.00001	.05938	15.05413	48.08305	32.71015	4.09328
290.000	409.879	.00001	.05943	15.06982	48.10420	32.69506	4.07148
290.333	409.784	.00001	.05948	15.08551	48.12534	32.67990	4.04976
290.667	409.688	.00001	.05953	15.10120	48.14649	32.66465	4.02812
291.000	409.593	.00001	.05958	15.11689	48.16764	32.64933	4.00656
291.333	409.498	.00001	.05963	15.13258	48.18879	32.63392	3.98508
291.667	409.402	.00001	.05968	15.14826	48.20994	32.61843	3.96367
292.000	409.307	.00001	.05974	15.16395	48.23109	32.60287	3.94235
292.333	409.211	.00001	.05979	15.17963	48.25224	32.58723	3.92110
292.667	409.116	.00001	.05985	15.19531	48.27339	32.57150	3.89994
293.000	409.021	.00001	.05990	15.21100	48.29455	32.55570	3.87885
293.333	408.925	.00001	.05996	15.22668	48.31570	32.53981	3.85784
293.667	408.830	.00001	.06002	15.24236	48.33686	32.52385	3.83691
294.000	408.734	.00001	.06007	15.25804	48.35802	32.50781	3.81606
294.333	408.639	.00001	.06013	15.27372	48.37917	32.49168	3.79528
294.667	408.544	.00001	.06019	15.28940	48.40034	32.47548	3.77459
295.000	408.448	.00001	.06025	15.30507	48.42150	32.45920	3.75397
295.333	408.353	.00001	.06031	15.32075	48.44266	32.44284	3.73343
295.667	408.257	.00001	.06037	15.33642	48.46382	32.42640	3.71297
296.000	408.162	.00001	.06043	15.35210	48.48499	32.40988	3.69259
296.333	408.066	.00001	.06050	15.36777	48.50615	32.39328	3.67229
296.667	407.971	.00001	.06056	15.38344	48.52732	32.37660	3.65206
297.000	407.876	.00001	.06063	15.39912	48.54849	32.35985	3.63191
297.333	407.780	.00001	.06069	15.41479	48.56966	32.34301	3.61184
297.667	407.685	.00001	.06076	15.43045	48.59083	32.32610	3.59185
298.000	407.589	.00001	.06082	15.44612	48.61200	32.30910	3.57194
298.333	407.494	.00001	.06089	15.46179	48.63318	32.29203	3.55211
298.667	407.398	.00001	.06096	15.47746	48.65435	32.27488	3.53235
299.000	407.303	.00001	.06103	15.49312	48.67553	32.25764	3.51267
299.333	407.207	.00001	.06110	15.50879	48.69670	32.24033	3.49307
299.667	407.112	.00001	.06117	15.52445	48.71788	32.22295	3.47354
300.000	407.017	.00001	.06124	15.54011	48.73906	32.20548	3.45410
300.333	406.921	.00001	.06131	15.55577	48.76024	32.18793	3.43473

OUTPUT File = 4MS.OUT

TITLE = Attritiion test : MMD=1764 microns,Velocity=4 m/s,Temp.=70 F

DATA INPUT

		Minimum	Maximum	Mean (um)	Weight (%)
Particle Dia.(1)	=	400.000	595.000	497.500	.920
Particle Dia.(2)	=	595.000	841.000	718.000	.040
Particle Dia.(3)	=	841.000	1008.000	924.500	.100
Particle Dia.(4)	=	1008.000	1190.000	1099.000	4.000
Particle Dia.(5)	=	1190.000	2000.000	1595.000	61.330
Particle Dia.(6)	=	2000.000	2380.000	2190.000	33.610

Density of Particle	=	2.100	(g/cm3)
Density of Gas	=	.102E-02	(g/cm3)
Viscosity	=	.178E-03	(g/cm/sec)
Gravitational Constant	=	980.660	(cm/sec2)
Bed Diameter	=	7.620	(cm)
Bed Height	=	250.000	(cm)
Efficiency of 1st cyclone	=	.000	(%)
Gas Velocity	=	400.000	(cm/sec)
Attrition Rate Constant	=	.00009090	(/sec)
Size Interval	=	10.000	(microns)
Time Interval	=	20.000	(sec)
Number of Iteration	=	900	

MINIMUM FLUIDIZATION VELOCITY AND TERMINAL VELOCITY

Particle Diameter (microns)	Minimum Fluidization Velocity (m/sec)		Terminal Velocity (m/sec)	
	Yen	Babu	Re #	Ut
497.500	.162	.313	106.098	3.705
718.000	.304	.535	220.988	5.347
924.500	.443	.723	366.381	6.885
1099.000	.556	.864	523.356	8.273
1595.000	.834	1.195	915.044	9.967
2190.000	1.099	1.504	1472.201	11.679

Changes in size distributions of solids in a bed as a function of time

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Time(min)	Tot-Wt(g)	MMD = 498.	MMD = 718.	MMD = 925.	MMD =1099.	MMD =1595.	MMD =2190.
.000	500.000	.92000	.04000	.10000	4.00000	61.33000	33.61000
.333	500.321	.85330	.03874	.32300	3.97605	61.29758	33.51132
.667	499.721	.77454	.03853	.33101	4.00339	61.37814	33.47439
1.000	499.169	.70525	.03832	.33899	4.03038	61.45291	33.43415
1.333	498.659	.64407	.03811	.34695	4.05709	61.52271	33.39106
1.667	498.184	.58986	.03791	.35489	4.08355	61.58826	33.34553
2.000	497.740	.54164	.03771	.36282	4.10979	61.65014	33.29790
2.333	497.323	.49860	.03751	.37073	4.13585	61.70886	33.24845
2.667	496.928	.46006	.03731	.37862	4.16175	61.76484	33.19743
3.000	496.553	.42541	.03712	.38650	4.18751	61.81843	33.14502
3.333	496.196	.39418	.03693	.39437	4.21315	61.86995	33.09141
3.667	495.853	.36594	.03674	.40223	4.23869	61.91966	33.03675
4.000	495.524	.34031	.03656	.41008	4.26414	61.96776	32.98115
4.333	495.206	.31700	.03638	.41792	4.28950	62.01447	32.92473
4.667	494.899	.29574	.03620	.42575	4.31480	62.05993	32.86758
5.000	494.602	.27630	.03603	.43357	4.34004	62.10429	32.80978
5.333	494.312	.25847	.03586	.44139	4.36522	62.14767	32.75139
5.667	494.030	.24209	.03569	.44919	4.39035	62.19019	32.69248
6.000	493.754	.22701	.03553	.45699	4.41544	62.23192	32.63310
6.333	493.484	.21309	.03537	.46478	4.44050	62.27296	32.57330
6.667	493.219	.20023	.03521	.47257	4.46552	62.31336	32.51310
7.000	492.960	.18831	.03506	.48035	4.49052	62.35320	32.45256
7.333	492.704	.17726	.03491	.48812	4.51549	62.39253	32.39169
7.667	492.453	.16698	.03477	.49589	4.54043	62.43140	32.33053
8.000	492.205	.15743	.03462	.50365	4.56536	62.46985	32.26910
8.333	491.961	.14852	.03449	.51140	4.59027	62.50791	32.20742
8.667	491.719	.14020	.03435	.51915	4.61516	62.54563	32.14551
9.000	491.480	.13244	.03422	.52690	4.64004	62.58302	32.08339
9.333	491.244	.12518	.03409	.53463	4.66490	62.62013	32.02107
9.667	491.011	.11837	.03396	.54237	4.68976	62.65698	31.95856
10.000	490.779	.11200	.03383	.55010	4.71461	62.69357	31.89589
10.333	490.549	.10602	.03371	.55782	4.73945	62.72995	31.83305
10.667	490.322	.10040	.03359	.56554	4.76428	62.76612	31.77007
11.000	490.096	.09512	.03348	.57325	4.78911	62.80210	31.70694
11.333	489.871	.09016	.03336	.58096	4.81393	62.83791	31.64368
11.667	489.649	.08549	.03325	.58866	4.83874	62.87356	31.58030
12.000	489.427	.08108	.03315	.59636	4.86356	62.90906	31.51680
12.333	489.207	.07694	.03304	.60405	4.88837	62.94442	31.45318
12.667	488.988	.07302	.03294	.61174	4.91318	62.97966	31.38947
13.000	488.770	.06933	.03284	.61942	4.93799	63.01478	31.32565
13.333	488.554	.06584	.03274	.62710	4.96279	63.04979	31.26173
13.667	488.338	.06255	.03264	.63478	4.98760	63.08471	31.19772
14.000	488.123	.05943	.03255	.64245	5.01241	63.11953	31.13363
14.333	487.909	.05649	.03246	.65011	5.03721	63.15428	31.06945
14.667	487.696	.05370	.03237	.65777	5.06202	63.18894	31.00520
15.000	487.484	.05106	.03228	.66543	5.08683	63.22353	30.94087
15.333	487.272	.04856	.03220	.67308	5.11164	63.25805	30.87646
15.667	487.062	.04620	.03211	.68072	5.13646	63.29252	30.81199
16.000	486.851	.04395	.03203	.68837	5.16127	63.32693	30.74745
16.333	486.642	.04183	.03195	.69600	5.18609	63.36128	30.68284
16.667	486.433	.03981	.03188	.70364	5.21091	63.39559	30.61817
17.000	486.224	.03790	.03180	.71127	5.23574	63.42986	30.55344
17.333	486.016	.03609	.03173	.71889	5.26057	63.46408	30.48865
17.667	485.809	.03436	.03166	.72651	5.28540	63.49827	30.42380
18.000	485.602	.03273	.03159	.73412	5.31023	63.53243	30.35890
18.333	485.396	.03118	.03152	.74173	5.33507	63.56656	30.29394
18.667	485.190	.02970	.03146	.74934	5.35992	63.60066	30.22893
19.000	484.984	.02830	.03139	.75694	5.38476	63.63473	30.16388
19.333	484.779	.02697	.03133	.76454	5.40962	63.66878	30.09877
19.667	484.574	.02570	.03127	.77213	5.43447	63.70282	30.03361
20.000	484.369	.02449	.03121	.77972	5.45934	63.73683	29.96841
20.333	484.165	.02335	.03115	.78730	5.48420	63.77084	29.90316
20.667	483.961	.02226	.03109	.79488	5.50907	63.80482	29.83787
21.000	483.758	.02122	.03104	.80245	5.53395	63.83880	29.77253
21.333	483.554	.02024	.03098	.81002	5.55883	63.87277	29.70715
21.667	483.351	.01930	.03093	.81759	5.58372	63.90673	29.64173
22.000	483.148	.01841	.03088	.82515	5.60862	63.94068	29.57627
22.333	482.946	.01756	.03083	.83271	5.63351	63.97462	29.51077
22.667	482.744	.01675	.03078	.84026	5.65842	64.00857	29.44523
23.000	482.542	.01598	.03074	.84780	5.68333	64.04251	29.37964
23.333	482.340	.01524	.03069	.85535	5.70824	64.07645	29.31402
23.667	482.138	.01454	.03065	.86289	5.73317	64.11039	29.24837
24.000	481.937	.01388	.03060	.87042	5.75810	64.14433	29.18267
24.333	481.735	.01324	.03056	.87795	5.78303	64.17828	29.11694
24.667	481.534	.01264	.03052	.88547	5.80797	64.21223	29.05117
25.000	481.333	.01206	.03048	.89299	5.83292	64.24618	28.98537
25.333	481.133	.01151	.03044	.90051	5.85787	64.28014	28.91953
25.667	480.932	.01099	.03040	.90802	5.88283	64.31410	28.85366
26.000	480.732	.01049	.03037	.91553	5.90779	64.34807	28.78775
26.333	480.531	.01001	.03033	.92303	5.93277	64.38205	28.72181
26.667	480.331	.00956	.03030	.93053	5.95774	64.41604	28.65583
27.000	480.131	.00913	.03026	.93802	5.98273	64.45004	28.58982
27.333	479.931	.00871	.03023	.94551	6.00772	64.48404	28.52378
27.667	479.732	.00832	.03020	.95299	6.03272	64.51806	28.45771
28.000	479.532	.00794	.03017	.96047	6.05772	64.55209	28.39160
28.333	479.333	.00759	.03014	.96795	6.08274	64.58613	28.32546
28.667	479.133	.00724	.03011	.97542	6.10775	64.62019	28.25929
29.000	478.934	.00692	.03008	.98288	6.13278	64.65425	28.19308
29.333	478.735	.00661	.03006	.99035	6.15781	64.68833	28.12685
29.667	478.536	.00631	.03003	.99780	6.18285	64.72243	28.06058
30.000	478.337	.00603	.03000	1.00525	6.20789	64.75653	27.99429
30.333	478.138	.00576	.02998	1.01270	6.23295	64.79066	27.92796
30.667	477.939	.00550	.02995	1.02014	6.25801	64.82479	27.86160
31.000	477.740	.00525	.02993	1.02758	6.28307	64.85895	27.79521
31.333	477.542	.00502	.02991	1.03502	6.30815	64.89312	27.72879
31.667	477.343	.00480	.02989	1.04244	6.33323	64.92731	27.66234
32.000	477.145	.00458	.02986	1.04987	6.35831	64.96151	27.59586
32.333	476.946	.00438	.02984	1.05729	6.38341	64.99573	27.52935
32.667	476.748	.00418	.02982	1.06470	6.40851	65.02997	27.46281
33.000	476.550	.00400	.02980	1.07211	6.43362	65.06423	27.39624

33.333	476.352	.00382	.02979	1.07952	6.45873	65.09850	27.32964
33.667	476.154	.00365	.02977	1.08692	6.48386	65.13279	27.26301
34.000	475.956	.00349	.02975	1.09431	6.50899	65.16710	27.19636
34.333	475.758	.00333	.02973	1.10171	6.53412	65.20144	27.12967
34.667	475.560	.00319	.02972	1.10909	6.55927	65.23579	27.06295
35.000	475.362	.00305	.02970	1.11647	6.58442	65.27016	26.99620
35.333	475.164	.00291	.02969	1.12385	6.60958	65.30454	26.92943
35.667	474.967	.00278	.02967	1.13122	6.63474	65.33895	26.86263
36.000	474.769	.00266	.02966	1.13859	6.65992	65.37338	26.79579
36.333	474.571	.00254	.02964	1.14595	6.68510	65.40783	26.72893
36.667	474.374	.00243	.02963	1.15331	6.71028	65.44230	26.66204
37.000	474.176	.00232	.02962	1.16066	6.73548	65.47679	26.59512
37.333	473.979	.00222	.02961	1.16801	6.76068	65.51131	26.52817
37.667	473.781	.00212	.02959	1.17536	6.78589	65.54584	26.46119
38.000	473.584	.00203	.02958	1.18269	6.81111	65.58040	26.39419
38.333	473.387	.00194	.02957	1.19003	6.83633	65.61497	26.32715
38.667	473.190	.00186	.02956	1.19736	6.86156	65.64957	26.26009
39.000	472.992	.00178	.02955	1.20468	6.88680	65.68419	26.19300
39.333	472.795	.00170	.02954	1.21200	6.91205	65.71883	26.12588
39.667	472.598	.00163	.02953	1.21931	6.93730	65.75350	26.05873
40.000	472.401	.00155	.02952	1.22662	6.96256	65.78818	25.99155
40.333	472.204	.00149	.02952	1.23393	6.98783	65.82289	25.92435
40.667	472.007	.00142	.02951	1.24123	7.01311	65.85763	25.85711
41.000	471.810	.00136	.02950	1.24852	7.03839	65.89238	25.78985
41.333	471.613	.00130	.02949	1.25581	7.06368	65.92716	25.72256
41.667	471.416	.00125	.02949	1.26309	7.08898	65.96196	25.65524
42.000	471.219	.00119	.02948	1.27037	7.11428	65.99678	25.58789
42.333	471.023	.00114	.02947	1.27765	7.13959	66.03163	25.52052
42.667	470.826	.00109	.02947	1.28492	7.16491	66.06650	25.45311
43.000	470.629	.00104	.02946	1.29218	7.19024	66.10139	25.38568
43.333	470.432	.00100	.02946	1.29944	7.21557	66.13631	25.31822
43.667	470.236	.00096	.02945	1.30670	7.24092	66.17125	25.25073
44.000	470.039	.00092	.02944	1.31395	7.26627	66.20622	25.18321
44.333	469.842	.00088	.02944	1.32119	7.29162	66.24121	25.11566
44.667	469.646	.00084	.02944	1.32843	7.31699	66.27622	25.04809
45.000	469.449	.00080	.02943	1.33566	7.34236	66.31126	24.98049
45.333	469.253	.00077	.02943	1.34289	7.36774	66.34632	24.91286
45.667	469.056	.00074	.02942	1.35012	7.39312	66.38140	24.84520
46.000	468.860	.00071	.02942	1.35734	7.41852	66.41651	24.77751
46.333	468.663	.00068	.02942	1.36455	7.44392	66.45165	24.70979
46.667	468.467	.00065	.02941	1.37176	7.46933	66.48681	24.64205
47.000	468.271	.00062	.02941	1.37896	7.49474	66.52199	24.57427
47.333	468.074	.00059	.02941	1.38616	7.52017	66.55720	24.50647
47.667	467.878	.00057	.02941	1.39335	7.54560	66.59243	24.43864
48.000	467.682	.00054	.02940	1.40054	7.57103	66.62769	24.37078
48.333	467.485	.00052	.02940	1.40773	7.59648	66.66297	24.30290
48.667	467.289	.00050	.02940	1.41490	7.62193	66.69828	24.23498
49.000	467.093	.00048	.02940	1.42208	7.64739	66.73361	24.16704
49.333	466.897	.00046	.02940	1.42924	7.67286	66.76897	24.09906
49.667	466.701	.00044	.02940	1.43641	7.69834	66.80436	24.03106
50.000	466.504	.00042	.02940	1.44356	7.72382	66.83977	23.96303
50.333	466.308	.00040	.02940	1.45071	7.74931	66.87520	23.89498
50.667	466.112	.00039	.02939	1.45786	7.77480	66.91066	23.82689
51.000	465.916	.00037	.02939	1.46500	7.80031	66.94615	23.75877
51.333	465.720	.00036	.02939	1.47214	7.82582	66.98166	23.69063
51.667	465.524	.00034	.02939	1.47927	7.85134	67.01720	23.62246
52.000	465.328	.00033	.02939	1.48640	7.87686	67.05276	23.55426
52.333	465.132	.00032	.02939	1.49352	7.90240	67.08835	23.48603
52.667	464.936	.00030	.02940	1.50063	7.92794	67.12396	23.41777
53.000	464.740	.00029	.02940	1.50774	7.95349	67.15961	23.34948
53.333	464.544	.00028	.02940	1.51485	7.97904	67.19527	23.28117
53.667	464.348	.00027	.02940	1.52195	8.00460	67.23097	23.21282
54.000	464.152	.00026	.02940	1.52904	8.03017	67.26669	23.14445
54.333	463.956	.00025	.02940	1.53613	8.05575	67.30243	23.07605
54.667	463.761	.00024	.02940	1.54321	8.08133	67.33820	23.00761
55.000	463.565	.00023	.02940	1.55029	8.10692	67.37400	22.93915
55.333	463.369	.00022	.02941	1.55736	8.13252	67.40983	22.87067
55.667	463.173	.00021	.02941	1.56443	8.15812	67.44568	22.80215
56.000	462.977	.00020	.02941	1.57149	8.18374	67.48156	22.73360
56.333	462.782	.00019	.02941	1.57855	8.20936	67.51746	22.66503
56.667	462.586	.00019	.02941	1.58560	8.23498	67.55339	22.59642
57.000	462.390	.00018	.02942	1.59265	8.26061	67.58935	22.52779
57.333	462.194	.00017	.02942	1.59969	8.28625	67.62534	22.45912
57.667	461.999	.00017	.02942	1.60673	8.31190	67.66135	22.39043
58.000	461.803	.00016	.02943	1.61376	8.33755	67.69739	22.32171
58.333	461.607	.00015	.02943	1.62079	8.36321	67.73345	22.25296
58.667	461.412	.00015	.02943	1.62781	8.38888	67.76955	22.18418
59.000	461.216	.00014	.02944	1.63482	8.41455	67.80567	22.11537
59.333	461.021	.00014	.02944	1.64183	8.44023	67.84182	22.04654
59.667	460.825	.00013	.02945	1.64884	8.46592	67.87799	21.97767
60.000	460.629	.00013	.02945	1.65584	8.49162	67.91419	21.90877
60.333	460.434	.00012	.02946	1.66284	8.51732	67.95042	21.83985
60.667	460.238	.00012	.02946	1.66983	8.54302	67.98668	21.77089
61.000	460.043	.00011	.02947	1.67681	8.56874	68.02296	21.70191
61.333	459.847	.00011	.02947	1.68379	8.59445	68.05928	21.63289
61.667	459.652	.00011	.02948	1.69077	8.62018	68.09562	21.56385
62.000	459.456	.00010	.02948	1.69774	8.64591	68.13198	21.49478
62.333	459.261	.00010	.02949	1.70470	8.67165	68.16838	21.42568
62.667	459.065	.00009	.02950	1.71166	8.69740	68.20480	21.35655
63.000	458.870	.00009	.02951	1.71862	8.72315	68.24125	21.28738
63.333	458.675	.00009	.02951	1.72557	8.74890	68.27773	21.21819
63.667	458.479	.00009	.02952	1.73252	8.77466	68.31424	21.14897
64.000	458.284	.00008	.02953	1.73946	8.80043	68.35077	21.07972
64.333	458.088	.00008	.02954	1.74640	8.82621	68.38734	21.01044
64.667	457.893	.00008	.02955	1.75333	8.85199	68.42393	20.94114
65.000	457.698	.00007	.02956	1.76025	8.87777	68.46055	20.87180
65.333	457.502	.00007	.02957	1.76718	8.90356	68.49720	20.80243
65.667	457.307	.00007	.02958	1.77410	8.92936	68.53387	20.73303
66.000	457.111	.00007	.02959	1.78101	8.95516	68.57058	20.66360
66.333	456.916	.00006	.02960	1.78792	8.98097	68.60731	20.59414
66.667	456.721	.00006	.02961	1.79482	9.00678	68.64407	20.52465
67.000	456.526	.00006	.02962	1.80172	9.03260	68.68086	20.45514
67.333	456.330	.00006	.02963	1.80862	9.05842	68.71768	20.38559

67.667	456.135	.00006	.02965	1.81551	9.08425	68.75453	20.31601
68.000	455.940	.00005	.02966	1.82240	9.11008	68.79140	20.24640
68.333	455.744	.00005	.02967	1.82929	9.13592	68.82831	20.17676
68.667	455.549	.00005	.02969	1.83617	9.16176	68.86524	20.10709
69.000	455.354	.00005	.02970	1.84304	9.18760	68.90220	20.03740
69.333	455.159	.00005	.02972	1.84992	9.21345	68.93920	19.96767
69.667	454.963	.00005	.02974	1.85679	9.23931	68.97622	19.89791
70.000	454.768	.00005	.02976	1.86365	9.26516	69.01327	19.82812
70.333	454.573	.00004	.02977	1.87051	9.29102	69.05034	19.75830
70.667	454.378	.00004	.02979	1.87737	9.31689	69.08745	19.68845
71.000	454.183	.00004	.02981	1.88423	9.34276	69.12459	19.61857
71.333	453.988	.00004	.02983	1.89108	9.36863	69.16176	19.54866
71.667	453.792	.00004	.02985	1.89793	9.39451	69.19895	19.47872
72.000	453.597	.00004	.02988	1.90477	9.42039	69.23618	19.40875
72.333	453.402	.00004	.02990	1.91162	9.44627	69.27343	19.33875
72.667	453.207	.00004	.02992	1.91846	9.47215	69.31072	19.26872
73.000	453.012	.00003	.02995	1.92529	9.49804	69.34803	19.19866
73.333	452.817	.00003	.02997	1.93213	9.52393	69.38537	19.12856
73.667	452.621	.00003	.03000	1.93896	9.54982	69.42275	19.05844
74.000	452.426	.00003	.03003	1.94579	9.57571	69.46015	18.98829
74.333	452.231	.00003	.03006	1.95262	9.60161	69.49758	18.91810
74.667	452.036	.00003	.03009	1.95944	9.62751	69.53504	18.84789
75.000	451.841	.00003	.03012	1.96627	9.65341	69.57253	18.77765
75.333	451.646	.00003	.03015	1.97309	9.67931	69.61006	18.70737
75.667	451.451	.00003	.03018	1.97991	9.70521	69.64761	18.63706
76.000	451.256	.00003	.03022	1.98673	9.73111	69.68519	18.56673
76.333	451.061	.00003	.03025	1.99355	9.75701	69.72280	18.49636
76.667	450.866	.00003	.03029	2.00036	9.78292	69.76044	18.42596
77.000	450.670	.00003	.03033	2.00718	9.80882	69.79811	18.35554
77.333	450.475	.00002	.03037	2.01399	9.83473	69.83581	18.28508
77.667	450.280	.00002	.03041	2.02081	9.86063	69.87354	18.21459
78.000	450.085	.00002	.03045	2.02762	9.88653	69.91130	18.14407
78.333	449.890	.00002	.03049	2.03444	9.91243	69.94910	18.07352
78.667	449.695	.00002	.03054	2.04125	9.93834	69.98692	18.00294
79.000	449.500	.00002	.03059	2.04806	9.96423	70.02477	17.93232
79.333	449.305	.00002	.03064	2.05488	9.99013	70.06265	17.86168
79.667	449.110	.00002	.03069	2.06169	10.01603	70.10056	17.79101
80.000	448.915	.00002	.03074	2.06851	10.04192	70.13850	17.72031
80.333	448.720	.00002	.03079	2.07532	10.06782	70.17648	17.64957
80.667	448.525	.00002	.03085	2.08214	10.09371	70.21448	17.57881
81.000	448.330	.00002	.03091	2.08896	10.11959	70.25251	17.50801
81.333	448.135	.00002	.03097	2.09578	10.14548	70.29057	17.43719
81.667	447.940	.00002	.03103	2.10260	10.17136	70.32866	17.36633
82.000	447.745	.00002	.03109	2.10942	10.19723	70.36679	17.29545
82.333	447.550	.00002	.03116	2.11625	10.22310	70.40494	17.22453
82.667	447.355	.00002	.03122	2.12308	10.24897	70.44312	17.15358
83.000	447.160	.00002	.03129	2.12991	10.27483	70.48133	17.08261
83.333	446.965	.00002	.03137	2.13675	10.30069	70.51958	17.01160
83.667	446.770	.00002	.03144	2.14358	10.32654	70.55785	16.94057
84.000	446.575	.00002	.03152	2.15042	10.35239	70.59615	16.86950
84.333	446.380	.00001	.03160	2.15727	10.37823	70.63448	16.79841
84.667	446.185	.00001	.03168	2.16412	10.40407	70.67284	16.72728
85.000	445.990	.00001	.03176	2.17097	10.42989	70.71123	16.65612
85.333	445.795	.00001	.03185	2.17783	10.45571	70.74965	16.58494
85.667	445.599	.00001	.03194	2.18469	10.48152	70.78810	16.51373
86.000	445.404	.00001	.03203	2.19156	10.50733	70.82658	16.44248
86.333	445.209	.00001	.03212	2.19844	10.53312	70.86509	16.37121
86.667	445.014	.00001	.03222	2.20531	10.55891	70.90363	16.29991
87.000	444.819	.00001	.03232	2.21220	10.58469	70.94220	16.22858
87.333	444.624	.00001	.03242	2.21909	10.61046	70.98079	16.15722
87.667	444.429	.00001	.03253	2.22599	10.63622	71.01941	16.08583
88.000	444.234	.00001	.03264	2.23290	10.66197	71.05807	16.01442
88.333	444.039	.00001	.03275	2.23981	10.68770	71.09675	15.94298
88.667	443.844	.00001	.03287	2.24673	10.71343	71.13546	15.87150
89.000	443.649	.00001	.03299	2.25366	10.73915	71.17419	15.80000
89.333	443.454	.00001	.03311	2.26060	10.76485	71.21296	15.72848
89.667	443.259	.00001	.03323	2.26754	10.79054	71.25175	15.65692
90.000	443.064	.00001	.03336	2.27450	10.81622	71.29057	15.58534
90.333	442.869	.00001	.03349	2.28146	10.84188	71.32942	15.51374
90.667	442.674	.00001	.03363	2.28843	10.86754	71.36829	15.44210
91.000	442.479	.00001	.03377	2.29542	10.89317	71.40719	15.37044
91.333	442.284	.00001	.03391	2.30241	10.91880	71.44612	15.29876
91.667	442.089	.00001	.03406	2.30942	10.94440	71.48507	15.22705
92.000	441.894	.00001	.03421	2.31643	10.97000	71.52405	15.15531
92.333	441.699	.00001	.03436	2.32346	10.99557	71.56305	15.08355
92.667	441.503	.00001	.03452	2.33050	11.02113	71.60208	15.01176
93.000	441.308	.00001	.03468	2.33755	11.04667	71.64113	14.93995
93.333	441.113	.00001	.03485	2.34461	11.07220	71.68021	14.86812
93.667	440.918	.00001	.03502	2.35169	11.09771	71.71931	14.79626
94.000	440.723	.00001	.03519	2.35878	11.12320	71.75844	14.72438
94.333	440.528	.00001	.03537	2.36589	11.14867	71.79758	14.65248
94.667	440.333	.00001	.03556	2.37301	11.17412	71.83675	14.58056
95.000	440.138	.00001	.03574	2.38014	11.19955	71.87595	14.50861
95.333	439.943	.00001	.03594	2.38729	11.22496	71.91516	14.43665
95.667	439.747	.00001	.03613	2.39445	11.25035	71.95440	14.36466
96.000	439.552	.00001	.03634	2.40163	11.27572	71.99365	14.29266
96.333	439.357	.00001	.03654	2.40883	11.30106	72.03293	14.22063
96.667	439.162	.00001	.03675	2.41604	11.32639	72.07222	14.14859
97.000	438.967	.00001	.03697	2.42327	11.35169	72.11154	14.07653
97.333	438.772	.00001	.03719	2.43052	11.37696	72.15087	14.00445
97.667	438.576	.00001	.03742	2.43779	11.40222	72.19022	13.93235
98.000	438.381	.00001	.03765	2.44507	11.42745	72.22959	13.86024
98.333	438.186	.00001	.03788	2.45237	11.45265	72.26897	13.78812
98.667	437.991	.00001	.03813	2.45970	11.47783	72.30837	13.71597
99.000	437.796	.00001	.03837	2.46704	11.50298	72.34778	13.64382
99.333	437.600	.00001	.03863	2.47440	11.52810	72.38721	13.57165
99.667	437.405	.00001	.03888	2.48178	11.55320	72.42665	13.49948
100.000	437.210	.00001	.03915	2.48919	11.57827	72.46610	13.42729
100.333	437.015	.00001	.03942	2.49661	11.60331	72.50556	13.35509
100.667	436.819	.00001	.03969	2.50406	11.62833	72.54504	13.28288
101.000	436.624	.00001	.03997	2.51153	11.65331	72.58452	13.21066
101.333	436.429	.00001	.04026	2.51902	11.67826	72.62401	13.13843
101.667	436.233	.00001	.04055	2.52654	11.70319	72.66351	13.06620

102.000	436.038	.00001	.04085	2.53408	11.72808	72.70302	12.99397
102.333	435.843	.00001	.04116	2.54164	11.75294	72.74253	12.92173
102.667	435.647	.00001	.04147	2.54923	11.77777	72.78205	12.84948
103.000	435.452	.00001	.04178	2.55685	11.80256	72.82157	12.77724
103.333	435.257	.00001	.04211	2.56449	11.82732	72.86109	12.70499
103.667	435.061	.00001	.04244	2.57215	11.85205	72.90061	12.63274
104.000	434.866	.00001	.04277	2.57985	11.87674	72.94014	12.56050
104.333	434.671	.00001	.04312	2.58757	11.90140	72.97966	12.48826
104.667	434.475	.00001	.04347	2.59531	11.92602	73.01918	12.41602
105.000	434.280	.00001	.04382	2.60309	11.95061	73.05869	12.34379
105.333	434.084	.00000	.04418	2.61089	11.97515	73.09820	12.27156
105.667	433.889	.00000	.04455	2.61872	11.99967	73.13770	12.19935
106.000	433.693	.00000	.04493	2.62659	12.02414	73.17720	12.12714
106.333	433.498	.00000	.04532	2.63448	12.04857	73.21668	12.05494
106.667	433.302	.00000	.04571	2.64240	12.07297	73.25616	11.98276
107.000	433.107	.00000	.04610	2.65035	12.09733	73.29562	11.91059
107.333	432.911	.00000	.04651	2.65834	12.12164	73.33506	11.83844
107.667	432.716	.00000	.04692	2.66636	12.14592	73.37449	11.76631
108.000	432.520	.00000	.04734	2.67440	12.17015	73.41391	11.69419
108.333	432.325	.00000	.04777	2.68249	12.19434	73.45330	11.62210
108.667	432.129	.00000	.04820	2.69060	12.21849	73.49267	11.55003
109.000	431.934	.00000	.04865	2.69875	12.24260	73.53202	11.47798
109.333	431.738	.00000	.04910	2.70693	12.26666	73.57135	11.40596
109.667	431.542	.00000	.04955	2.71515	12.29068	73.61065	11.33397
110.000	431.347	.00000	.05002	2.72340	12.31465	73.64992	11.26201
110.333	431.151	.00000	.05049	2.73169	12.33858	73.68916	11.19008
110.667	430.955	.00000	.05097	2.74001	12.36246	73.72837	11.11818
111.000	430.760	.00000	.05146	2.74837	12.38630	73.76754	11.04632
111.333	430.564	.00000	.05196	2.75677	12.41009	73.80668	10.97450
111.667	430.368	.00000	.05246	2.76520	12.43383	73.84578	10.90272
112.000	430.173	.00000	.05298	2.77367	12.45752	73.88484	10.83098
112.333	429.977	.00000	.05350	2.78218	12.48117	73.92386	10.75929
112.667	429.781	.00000	.05403	2.79073	12.50476	73.96283	10.68764
113.000	429.585	.00000	.05457	2.79932	12.52831	74.00176	10.61604
113.333	429.389	.00000	.05511	2.80795	12.55180	74.04064	10.54450
113.667	429.194	.00000	.05567	2.81662	12.57525	74.07946	10.47300
114.000	428.998	.00000	.05623	2.82532	12.59864	74.11823	10.40157
114.333	428.802	.00000	.05680	2.83407	12.62198	74.15695	10.33019
114.667	428.606	.00000	.05738	2.84286	12.64527	74.19560	10.25887
115.000	428.410	.00000	.05797	2.85170	12.66851	74.23420	10.18762
115.333	428.214	.00000	.05857	2.86057	12.69169	74.27273	10.11643
115.667	428.018	.00000	.05918	2.86949	12.71482	74.31120	10.04531
116.000	427.822	.00000	.05979	2.87845	12.73789	74.34959	9.97427
116.333	427.626	.00000	.06042	2.88745	12.76091	74.38792	9.90329
116.667	427.430	.00000	.06105	2.89650	12.78388	74.42617	9.83240
117.000	427.234	.00000	.06169	2.90560	12.80679	74.46434	9.76158
117.333	427.038	.00000	.06235	2.91473	12.82964	74.50244	9.69084
117.667	426.842	.00000	.06301	2.92392	12.85243	74.54045	9.62019
118.000	426.646	.00000	.06368	2.93314	12.87517	74.57837	9.54963
118.333	426.450	.00000	.06436	2.94242	12.89785	74.61621	9.47916
118.667	426.254	.00000	.06504	2.95174	12.92047	74.65396	9.40878
119.000	426.058	.00000	.06574	2.96111	12.94304	74.69162	9.33849
119.333	425.862	.00000	.06645	2.97052	12.96554	74.72918	9.26831
119.667	425.665	.00000	.06717	2.97999	12.98798	74.76664	9.19823
120.000	425.469	.00000	.06789	2.98950	13.01037	74.80399	9.12825
120.333	425.273	.00000	.06863	2.99905	13.03269	74.84124	9.05838
120.667	425.077	.00000	.06937	3.00866	13.05495	74.87838	8.98863
121.000	424.880	.00000	.07013	3.01832	13.07715	74.91542	8.91898
121.333	424.684	.00000	.07089	3.02802	13.09929	74.95233	8.84946
121.667	424.488	.00000	.07166	3.03778	13.12137	74.98913	8.78005
122.000	424.291	.00000	.07245	3.04759	13.14338	75.02581	8.71077
122.333	424.095	.00000	.07324	3.05744	13.16533	75.06236	8.64162
122.667	423.899	.00000	.07404	3.06735	13.18722	75.09879	8.57260
123.000	423.702	.00000	.07485	3.07731	13.20905	75.13508	8.50371
123.333	423.506	.00000	.07568	3.08732	13.23080	75.17124	8.43495
123.667	423.309	.00000	.07651	3.09738	13.25250	75.20727	8.36634
124.000	423.113	.00000	.07735	3.10750	13.27413	75.24315	8.29787
124.333	422.916	.00000	.07820	3.11766	13.29569	75.27889	8.22955
124.667	422.720	.00000	.07906	3.12788	13.31719	75.31448	8.16138
125.000	422.523	.00000	.07994	3.13816	13.33862	75.34992	8.09336
125.333	422.327	.00000	.08082	3.14848	13.35999	75.38521	8.02550
125.667	422.130	.00000	.08171	3.15886	13.38129	75.42034	7.95779
126.000	421.933	.00000	.08261	3.16930	13.40252	75.45532	7.89026
126.333	421.737	.00000	.08352	3.17978	13.42368	75.49012	7.82289
126.667	421.540	.00000	.08444	3.19033	13.44478	75.52476	7.75569
127.000	421.343	.00000	.08537	3.20092	13.46581	75.55923	7.68866
127.333	421.146	.00000	.08632	3.21158	13.48677	75.59353	7.62181
127.667	420.950	.00000	.08727	3.22229	13.50766	75.62764	7.55514
128.000	420.753	.00000	.08823	3.23305	13.52848	75.66158	7.48866
128.333	420.556	.00000	.08920	3.24387	13.54923	75.69533	7.42236
128.667	420.359	.00000	.09018	3.25474	13.56992	75.72890	7.35626
129.000	420.162	.00000	.09117	3.26568	13.59053	75.76227	7.29035
129.333	419.965	.00000	.09218	3.27666	13.61108	75.79545	7.22464
129.667	419.768	.00000	.09319	3.28771	13.63155	75.82843	7.15913
130.000	419.571	.00000	.09421	3.29881	13.65195	75.86120	7.09382
130.333	419.374	.00000	.09524	3.30997	13.67228	75.89378	7.02873
130.667	419.177	.00000	.09628	3.32119	13.69254	75.92614	6.96384
131.000	418.980	.00000	.09734	3.33246	13.71273	75.95829	6.89917
131.333	418.783	.00000	.09840	3.34380	13.73285	75.99023	6.83472
131.667	418.586	.00000	.09947	3.35519	13.75290	76.02195	6.77050
132.000	418.389	.00000	.10056	3.36663	13.77287	76.05344	6.70650
132.333	418.192	.00000	.10165	3.37814	13.79277	76.08471	6.64273
132.667	417.994	.00000	.10275	3.38971	13.81260	76.11575	6.57919
133.000	417.797	.00000	.10386	3.40133	13.83236	76.14656	6.51589
133.333	417.600	.00000	.10499	3.41301	13.85204	76.17713	6.45282
133.667	417.403	.00000	.10612	3.42475	13.87166	76.20746	6.39000
134.000	417.205	.00000	.10727	3.43656	13.89119	76.23755	6.32743
134.333	417.008	.00000	.10842	3.44842	13.91066	76.26740	6.26511
134.667	416.811	.00000	.10958	3.46034	13.93005	76.29699	6.20304
135.000	416.613	.00000	.11076	3.47231	13.94937	76.32633	6.14122
135.333	416.416	.00000	.11194	3.48435	13.96862	76.35542	6.07967
135.667	416.218	.00000	.11313	3.49645	13.98779	76.38425	6.01838
136.000	416.021	.00000	.11434	3.50861	14.00689	76.41281	5.95735

136.333	415.823	.00000	.11555	3.52083	14.02591	76.44111	5.89659
136.667	415.625	.00000	.11677	3.53310	14.04487	76.46914	5.83611
137.000	415.428	.00000	.11801	3.54544	14.06374	76.49690	5.77590
137.333	415.230	.00000	.11925	3.55784	14.08255	76.52439	5.71597
137.667	415.033	.00000	.12051	3.57030	14.10127	76.55159	5.65633
138.000	414.835	.00000	.12177	3.58282	14.11993	76.57852	5.59696
138.333	414.637	.00000	.12304	3.59540	14.13851	76.60516	5.53789
138.667	414.439	.00000	.12432	3.60803	14.15702	76.63152	5.47910
139.000	414.241	.00000	.12562	3.62073	14.17545	76.65759	5.42061
139.333	414.044	.00000	.12692	3.63349	14.19381	76.68336	5.36242
139.667	413.846	.00000	.12823	3.64631	14.21209	76.70884	5.30453
140.000	413.648	.00000	.12955	3.65919	14.23030	76.73402	5.24693
140.333	413.450	.00000	.13088	3.67214	14.24844	76.75890	5.18965
140.667	413.252	.00000	.13222	3.68514	14.26650	76.78347	5.13267
141.000	413.054	.00000	.13357	3.69820	14.28448	76.80774	5.07600
141.333	412.856	.00000	.13493	3.71132	14.30240	76.83170	5.01965
141.667	412.658	.00000	.13630	3.72450	14.32023	76.85535	4.96361
142.000	412.459	.00000	.13768	3.73775	14.33800	76.87868	4.90789
142.333	412.261	.00000	.13907	3.75105	14.35569	76.90170	4.85249
142.667	412.063	.00000	.14047	3.76442	14.37330	76.92440	4.79741
143.000	411.865	.00000	.14188	3.77784	14.39084	76.94678	4.74266
143.333	411.667	.00000	.14329	3.79132	14.40831	76.96883	4.68824
143.667	411.468	.00000	.14472	3.80487	14.42571	76.99056	4.63415
144.000	411.270	.00000	.14615	3.81847	14.44303	77.01196	4.58039
144.333	411.071	.00000	.14759	3.83214	14.46027	77.03303	4.52697
144.667	410.873	.00000	.14905	3.84587	14.47745	77.05376	4.47388
145.000	410.675	.00000	.15051	3.85965	14.49454	77.07416	4.42113
145.333	410.476	.00000	.15198	3.87350	14.51157	77.09423	4.36873
145.667	410.278	.00000	.15346	3.88740	14.52852	77.11395	4.31667
146.000	410.079	.00000	.15495	3.90137	14.54540	77.13334	4.26495
146.333	409.880	.00000	.15644	3.91539	14.56221	77.15238	4.21358
146.667	409.682	.00000	.15795	3.92947	14.57894	77.17107	4.16256
147.000	409.483	.00000	.15946	3.94362	14.59560	77.18943	4.11189
147.333	409.284	.00000	.16099	3.95782	14.61219	77.20743	4.06157
147.667	409.085	.00000	.16252	3.97208	14.62871	77.22508	4.01161
148.000	408.887	.00000	.16406	3.98640	14.64515	77.24239	3.96200
148.333	408.688	.00000	.16561	4.00078	14.66152	77.25934	3.91275
148.667	408.489	.00000	.16716	4.01522	14.67782	77.27593	3.86386
149.000	408.290	.00000	.16873	4.02972	14.69405	77.29217	3.81533
149.333	408.091	.00000	.17030	4.04427	14.71020	77.30806	3.76716
149.667	407.892	.00000	.17188	4.05889	14.72629	77.32358	3.71936
150.000	407.693	.00000	.17347	4.07356	14.74230	77.33875	3.67191
150.333	407.494	.00000	.17507	4.08829	14.75824	77.35355	3.62484
150.667	407.295	.00000	.17668	4.10308	14.77412	77.36800	3.57813
151.000	407.096	.00000	.17829	4.11793	14.78992	77.38208	3.53178
151.333	406.896	.00000	.17991	4.13283	14.80565	77.39580	3.48581
151.667	406.697	.00000	.18154	4.14779	14.82131	77.40915	3.44020
152.000	406.498	.00000	.18318	4.16281	14.83690	77.42214	3.39497
152.333	406.298	.00000	.18482	4.17788	14.85242	77.43477	3.35010
152.667	406.099	.00000	.18648	4.19301	14.86787	77.44702	3.30561
153.000	405.900	.00000	.18814	4.20820	14.88326	77.45891	3.26149
153.333	405.700	.00000	.18980	4.22344	14.89857	77.47043	3.21775
153.667	405.501	.00000	.19148	4.23875	14.91382	77.48159	3.17437
154.000	405.301	.00000	.19316	4.25410	14.92899	77.49237	3.13137
154.333	405.102	.00000	.19485	4.26951	14.94410	77.50279	3.08875
154.667	404.902	.00000	.19654	4.28498	14.95915	77.51283	3.04650
155.000	404.702	.00000	.19825	4.30050	14.97412	77.52251	3.00462
155.333	404.503	.00000	.19996	4.31608	14.98903	77.53181	2.96312
155.667	404.303	.00000	.20168	4.33171	15.00387	77.54075	2.92200
156.000	404.103	.00000	.20340	4.34740	15.01864	77.54931	2.88125
156.333	403.903	.00000	.20513	4.36314	15.03335	77.55750	2.84087
156.667	403.703	.00000	.20687	4.37894	15.04799	77.56533	2.80088
157.000	403.503	.00000	.20861	4.39478	15.06257	77.57278	2.76125
157.333	403.303	.00000	.21036	4.41069	15.07708	77.57987	2.72201
157.667	403.103	.00000	.21212	4.42664	15.09152	77.58658	2.68313
158.000	402.903	.00000	.21388	4.44265	15.10591	77.59293	2.64464
158.333	402.703	.00000	.21565	4.45871	15.12022	77.59890	2.60651
158.667	402.503	.00000	.21742	4.47482	15.13448	77.60451	2.56877
159.000	402.303	.00000	.21921	4.49099	15.14867	77.60975	2.53139
159.333	402.102	.00000	.22099	4.50721	15.16279	77.61462	2.49439
159.667	401.902	.00000	.22279	4.52348	15.17685	77.61912	2.45776
160.000	401.702	.00000	.22459	4.53980	15.19086	77.62326	2.42150
160.333	401.501	.00000	.22639	4.55617	15.20479	77.62703	2.38562
160.667	401.301	.00000	.22820	4.57259	15.21867	77.63043	2.35010
161.000	401.100	.00000	.23002	4.58906	15.23248	77.63347	2.31496
161.333	400.900	.00000	.23184	4.60559	15.24624	77.63615	2.28018
161.667	400.699	.00000	.23367	4.62216	15.25993	77.63847	2.24578
162.000	400.499	.00000	.23550	4.63878	15.27356	77.64042	2.21173
162.333	400.298	.00000	.23734	4.65545	15.28714	77.64201	2.17806
162.667	400.097	.00000	.23918	4.67217	15.30065	77.64325	2.14475
163.000	399.897	.00000	.24103	4.68894	15.31410	77.64412	2.11181
163.333	399.696	.00000	.24288	4.70576	15.32750	77.64464	2.07922
163.667	399.495	.00000	.24474	4.72262	15.34083	77.64480	2.04700
164.000	399.294	.00000	.24660	4.73953	15.35411	77.64461	2.01514
164.333	399.093	.00000	.24847	4.75649	15.36733	77.64407	1.98364
164.667	398.892	.00000	.25034	4.77350	15.38050	77.64317	1.95250
165.000	398.691	.00000	.25221	4.79055	15.39360	77.64192	1.92171
165.333	398.490	.00000	.25409	4.80765	15.40665	77.64032	1.89128
165.667	398.289	.00000	.25598	4.82480	15.41964	77.63838	1.86120
166.000	398.088	.00000	.25787	4.84199	15.43258	77.63608	1.83147
166.333	397.886	.00000	.25976	4.85923	15.44546	77.63345	1.80210
166.667	397.685	.00000	.26166	4.87651	15.45829	77.63047	1.77307
167.000	397.484	.00000	.26356	4.89384	15.47106	77.62715	1.74439
167.333	397.282	.00000	.26547	4.91121	15.48378	77.62349	1.71605
167.667	397.081	.00000	.26738	4.92862	15.49645	77.61949	1.68806
168.000	396.879	.00000	.26929	4.94608	15.50906	77.61516	1.66041
168.333	396.678	.00000	.27121	4.96358	15.52162	77.61049	1.63310
168.667	396.476	.00000	.27313	4.98112	15.53413	77.60549	1.60613
169.000	396.275	.00000	.27505	4.99871	15.54658	77.60016	1.57950
169.333	396.073	.00000	.27698	5.01634	15.55898	77.59450	1.55320
169.667	395.871	.00000	.27891	5.03401	15.57133	77.58852	1.52723
170.000	395.669	.00000	.28084	5.05172	15.58364	77.58221	1.50159
170.333	395.467	.00000	.28278	5.06948	15.59589	77.57557	1.47628

170.667	395.265	.00000	.28472	5.08727	15.60809	77.56862	1.45130
171.000	395.064	.00000	.28666	5.10511	15.62024	77.56135	1.42664
171.333	394.862	.00000	.28861	5.12298	15.63234	77.55376	1.40231
171.667	394.659	.00000	.29056	5.14090	15.64439	77.54586	1.37829
172.000	394.457	.00000	.29251	5.15885	15.65640	77.53765	1.35459
172.333	394.255	.00000	.29446	5.17684	15.66836	77.52913	1.33121
172.667	394.053	.00000	.29642	5.19487	15.68027	77.52030	1.30814
173.000	393.851	.00000	.29838	5.21294	15.69213	77.51117	1.28538
173.333	393.648	.00000	.30034	5.23105	15.70395	77.50173	1.26293
173.667	393.446	.00000	.30230	5.24920	15.71572	77.49199	1.24079
174.000	393.244	.00000	.30427	5.26738	15.72744	77.48196	1.21895
174.333	393.041	.00000	.30624	5.28560	15.73912	77.47163	1.19741
174.667	392.839	.00000	.30821	5.30385	15.75076	77.46101	1.17618
175.000	392.636	.00000	.31018	5.32215	15.76235	77.45009	1.15524
175.333	392.433	.00000	.31215	5.34047	15.77390	77.43889	1.13459
175.667	392.231	.00000	.31413	5.35884	15.78540	77.42740	1.11424
176.000	392.028	.00000	.31610	5.37723	15.79686	77.41562	1.09418
176.333	391.825	.00000	.31808	5.39567	15.80828	77.40357	1.07440
176.667	391.622	.00000	.32006	5.41413	15.81966	77.39124	1.05491
177.000	391.419	.00000	.32205	5.43263	15.83099	77.37863	1.03570
177.333	391.216	.00000	.32403	5.45117	15.84228	77.36575	1.01677
177.667	391.013	.00000	.32601	5.46973	15.85354	77.35259	.99812
178.000	390.810	.00000	.32800	5.48833	15.86475	77.33917	.97975
178.333	390.607	.00000	.32999	5.50696	15.87592	77.32548	.96165
178.667	390.404	.00000	.33197	5.52563	15.88705	77.31153	.94381
179.000	390.201	.00000	.33396	5.54432	15.89815	77.29732	.92625
179.333	389.997	.00000	.33595	5.56305	15.90920	77.28285	.90895
179.667	389.794	.00000	.33794	5.58181	15.92022	77.26812	.89191
180.000	389.591	.00000	.33994	5.60060	15.93120	77.25314	.87513
180.333	389.387	.00000	.34193	5.61941	15.94214	77.23791	.85861
180.667	389.184	.00000	.34392	5.63826	15.95304	77.22243	.84234
181.000	388.980	.00000	.34591	5.65714	15.96391	77.20671	.82632
181.333	388.776	.00000	.34791	5.67605	15.97474	77.19074	.81056
181.667	388.573	.00000	.34990	5.69498	15.98554	77.17454	.79504
182.000	388.369	.00000	.35190	5.71395	15.99630	77.15809	.77976
182.333	388.165	.00000	.35389	5.73294	16.00703	77.14141	.76473
182.667	387.961	.00000	.35589	5.75196	16.01772	77.12450	.74994
183.000	387.757	.00000	.35788	5.77100	16.02838	77.10736	.73538
183.333	387.553	.00000	.35988	5.79008	16.03900	77.08999	.72105
183.667	387.349	.00000	.36187	5.80917	16.04959	77.07240	.70696
184.000	387.145	.00000	.36387	5.82830	16.06015	77.05458	.69309
184.333	386.941	.00000	.36587	5.84745	16.07068	77.03655	.67946
184.667	386.737	.00000	.36786	5.86663	16.08117	77.01830	.66604
185.000	386.533	.00000	.36985	5.88583	16.09164	76.99983	.65285
185.333	386.328	.00000	.37185	5.90506	16.10207	76.98116	.63987
185.667	386.124	.00000	.37384	5.92431	16.11247	76.96227	.62711
186.000	385.919	.00000	.37584	5.94358	16.12284	76.94318	.61456
186.333	385.715	.00000	.37783	5.96288	16.13318	76.92388	.60223
186.667	385.510	.00000	.37982	5.98220	16.14350	76.90438	.59010
187.000	385.306	.00000	.38181	6.00154	16.15378	76.88469	.57817
187.333	385.101	.00000	.38381	6.02091	16.16403	76.86480	.56645
187.667	384.896	.00000	.38580	6.04030	16.17426	76.84471	.55493
188.000	384.692	.00000	.38779	6.05971	16.18446	76.82443	.54361
188.333	384.487	.00000	.38977	6.07914	16.19463	76.80397	.53249
188.667	384.282	.00000	.39176	6.09859	16.20478	76.78332	.52155
189.000	384.077	.00000	.39375	6.11806	16.21489	76.76248	.51081
189.333	383.872	.00000	.39573	6.13756	16.22499	76.74147	.50026
189.667	383.667	.00000	.39772	6.15707	16.23505	76.72027	.48989
190.000	383.461	.00000	.39970	6.17660	16.24509	76.69890	.47970
190.333	383.256	.00000	.40169	6.19616	16.25511	76.67736	.46969
190.667	383.051	.00000	.40367	6.21573	16.26510	76.65564	.45987
191.000	382.846	.00000	.40565	6.23532	16.27507	76.63376	.45021
191.333	382.640	.00000	.40763	6.25492	16.28501	76.61170	.44074
191.667	382.435	.00000	.40960	6.27455	16.29493	76.58949	.43143
192.000	382.229	.00000	.41158	6.29419	16.30483	76.56711	.42229
192.333	382.024	.00000	.41355	6.31385	16.31470	76.54457	.41332
192.667	381.818	.00000	.41553	6.33353	16.32455	76.52188	.40451
193.000	381.612	.00000	.41750	6.35322	16.33438	76.49903	.39586
193.333	381.407	.00000	.41947	6.37293	16.34419	76.47603	.38738
193.667	381.201	.00000	.42144	6.39266	16.35398	76.45288	.37905
194.000	380.995	.00000	.42340	6.41240	16.36374	76.42958	.37087
194.333	380.789	.00000	.42537	6.43215	16.37349	76.40614	.36285
194.667	380.583	.00000	.42733	6.45192	16.38322	76.38255	.35498
195.000	380.377	.00000	.42929	6.47171	16.39292	76.35882	.34725
195.333	380.171	.00000	.43125	6.49151	16.40261	76.33496	.33968
195.667	379.964	.00000	.43321	6.51132	16.41228	76.31095	.33224
196.000	379.758	.00000	.43516	6.53115	16.42193	76.28681	.32495
196.333	379.552	.00000	.43712	6.55099	16.43156	76.26254	.31779
196.667	379.345	.00000	.43907	6.57084	16.44117	76.23814	.31078
197.000	379.139	.00000	.44102	6.59070	16.45077	76.21361	.30390
197.333	378.932	.00000	.44297	6.61058	16.46035	76.18896	.29715
197.667	378.726	.00000	.44491	6.63047	16.46991	76.16418	.29053
198.000	378.519	.00000	.44686	6.65037	16.47945	76.13928	.28405
198.333	378.312	.00000	.44880	6.67028	16.48898	76.11426	.27769
198.667	378.106	.00000	.45074	6.69020	16.49849	76.08912	.27145
199.000	377.899	.00000	.45268	6.71013	16.50799	76.06386	.26534
199.333	377.692	.00000	.45461	6.73007	16.51747	76.03850	.25935
199.667	377.485	.00000	.45655	6.75002	16.52694	76.01302	.25347
200.000	377.278	.00000	.45848	6.76998	16.53640	75.98743	.24772
200.333	377.071	.00000	.46041	6.78996	16.54583	75.96173	.24208
200.667	376.864	.00000	.46233	6.80993	16.55526	75.93592	.23655
201.000	376.656	.00000	.46426	6.82992	16.56467	75.91002	.23113
201.333	376.449	.00000	.46618	6.84992	16.57407	75.88400	.22583
201.667	376.242	.00000	.46810	6.86992	16.58346	75.85789	.22063
202.000	376.034	.00000	.47002	6.88993	16.59283	75.83168	.21554
202.333	375.827	.00000	.47193	6.90995	16.60219	75.80538	.21055
202.667	375.619	.00000	.47384	6.92998	16.61154	75.77897	.20567
203.000	375.412	.00000	.47575	6.95001	16.62088	75.75248	.20088
203.333	375.204	.00000	.47766	6.97005	16.63020	75.72589	.19620
203.667	374.996	.00000	.47957	6.99009	16.63952	75.69921	.19161
204.000	374.788	.00000	.48147	7.01015	16.64882	75.67245	.18711
204.333	374.580	.00000	.48337	7.03020	16.65811	75.64560	.18271
204.667	374.372	.00000	.48527	7.05026	16.66740	75.61866	.17841

205.000	374.164	.00000	.48717	7.07033	16.67667	75.59164	.17419
205.333	373.956	.00000	.48906	7.09040	16.68594	75.56454	.17006
205.667	373.748	.00000	.49095	7.11047	16.69519	75.53736	.16602
206.000	373.540	.00000	.49284	7.13055	16.70444	75.51010	.16207
206.333	373.332	.00000	.49473	7.15063	16.71368	75.48276	.15820
206.667	373.123	.00000	.49661	7.17072	16.72291	75.45535	.15441
207.000	372.915	.00000	.49850	7.19081	16.73213	75.42786	.15071
207.333	372.706	.00000	.50038	7.21090	16.74134	75.40030	.14708
207.667	372.498	.00000	.50225	7.23100	16.75055	75.37267	.14354
208.000	372.289	.00000	.50413	7.25109	16.75975	75.34497	.14007
208.333	372.081	.00000	.50600	7.27119	16.76894	75.31720	.13667
208.667	371.872	.00000	.50787	7.29129	16.77812	75.28937	.13335
209.000	371.663	.00000	.50974	7.31139	16.78730	75.26147	.13010
209.333	371.454	.00000	.51161	7.33149	16.79648	75.23350	.12692
209.667	371.245	.00000	.51347	7.35160	16.80564	75.20548	.12382
210.000	371.036	.00000	.51533	7.37170	16.81480	75.17739	.12078
210.333	370.827	.00000	.51719	7.39180	16.82396	75.14924	.11781
210.667	370.618	.00000	.51905	7.41191	16.83311	75.12103	.11490
211.000	370.409	.00000	.52090	7.43201	16.84226	75.09277	.11206
211.333	370.199	.00000	.52275	7.45211	16.85140	75.06445	.10929
211.667	369.990	.00000	.52460	7.47221	16.86054	75.03608	.10657
212.000	369.780	.00000	.52645	7.49231	16.86967	75.00765	.10392
212.333	369.571	.00000	.52829	7.51241	16.87880	74.97917	.10133
212.667	369.361	.00000	.53014	7.53251	16.88792	74.95063	.09879
213.000	369.152	.00000	.53198	7.55260	16.89705	74.92205	.09632
213.333	368.942	.00000	.53382	7.57270	16.90617	74.89342	.09390
213.667	368.732	.00000	.53566	7.59279	16.91528	74.86474	.09153
214.000	368.522	.00000	.53749	7.61287	16.92440	74.83602	.08922
214.333	368.312	.00000	.53932	7.63296	16.93351	74.80724	.08696
214.667	368.102	.00000	.54115	7.65304	16.94262	74.77843	.08476
215.000	367.892	.00000	.54298	7.67312	16.95173	74.74957	.08260
215.333	367.682	.00000	.54481	7.69319	16.96083	74.72067	.08050
215.667	367.472	.00000	.54664	7.71326	16.96994	74.69172	.07844
216.000	367.262	.00000	.54846	7.73333	16.97904	74.66274	.07644
216.333	367.051	.00000	.55028	7.75339	16.98814	74.63371	.07447
216.667	366.841	.00000	.55210	7.77344	16.99724	74.60465	.07256
217.000	366.630	.00000	.55392	7.79349	17.00635	74.57555	.07069
217.333	366.420	.00000	.55573	7.81354	17.01545	74.54642	.06886
217.667	366.209	.00000	.55755	7.83358	17.02455	74.51724	.06708
218.000	365.999	.00000	.55936	7.85361	17.03365	74.48804	.06534
218.333	365.788	.00000	.56117	7.87364	17.04275	74.45880	.06364
218.667	365.577	.00000	.56298	7.89366	17.05185	74.42952	.06199
219.000	365.366	.00000	.56479	7.91367	17.06095	74.40022	.06037
219.333	365.155	.00000	.56660	7.93368	17.07006	74.37088	.05879
219.667	364.944	.00000	.56840	7.95368	17.07916	74.34151	.05725
220.000	364.733	.00000	.57020	7.97367	17.08827	74.31211	.05574
220.333	364.522	.00000	.57201	7.99366	17.09738	74.28269	.05427
220.667	364.310	.00000	.57381	8.01363	17.10648	74.25323	.05284
221.000	364.099	.00000	.57561	8.03360	17.11560	74.22375	.05144
221.333	363.888	.00000	.57741	8.05356	17.12471	74.19424	.05008
221.667	363.676	.00000	.57920	8.07351	17.13382	74.16471	.04875
222.000	363.465	.00000	.58100	8.09345	17.14294	74.13515	.04745
222.333	363.253	.00000	.58279	8.11339	17.15206	74.10557	.04619
222.667	363.041	.00000	.58459	8.13331	17.16119	74.07596	.04495
223.000	362.830	.00000	.58638	8.15323	17.17031	74.04633	.04375
223.333	362.618	.00000	.58817	8.17313	17.17944	74.01668	.04257
223.667	362.406	.00000	.58996	8.19303	17.18858	73.98700	.04143
224.000	362.194	.00000	.59175	8.21291	17.19771	73.95731	.04031
224.333	361.982	.00000	.59354	8.23278	17.20686	73.92759	.03922
224.667	361.770	.00000	.59533	8.25265	17.21600	73.89786	.03816
225.000	361.557	.00000	.59712	8.27250	17.22515	73.86810	.03713
225.333	361.345	.00000	.59891	8.29234	17.23430	73.83833	.03612
225.667	361.133	.00000	.60069	8.31217	17.24346	73.80854	.03514
226.000	360.920	.00000	.60248	8.33199	17.25262	73.77873	.03418
226.333	360.708	.00000	.60426	8.35179	17.26179	73.74891	.03324
226.667	360.495	.00000	.60605	8.37158	17.27096	73.71907	.03233
227.000	360.283	.00000	.60784	8.39137	17.28014	73.68921	.03145
227.333	360.070	.00000	.60962	8.41113	17.28933	73.65934	.03058
227.667	359.857	.00000	.61140	8.43089	17.29851	73.62945	.02974
228.000	359.644	.00000	.61319	8.45063	17.30771	73.59955	.02892
228.333	359.431	.00000	.61497	8.47036	17.31691	73.56964	.02812
228.667	359.218	.00000	.61676	8.49008	17.32612	73.53971	.02734
229.000	359.005	.00000	.61854	8.50978	17.33533	73.50977	.02658
229.333	358.792	.00000	.62033	8.52947	17.34455	73.47982	.02584
229.667	358.579	.00000	.62211	8.54914	17.35377	73.44986	.02512
230.000	358.366	.00000	.62390	8.56880	17.36300	73.41988	.02442
230.333	358.152	.00000	.62568	8.58844	17.37224	73.38990	.02373
230.667	357.939	.00000	.62747	8.60807	17.38149	73.35990	.02307
231.000	357.725	.00000	.62925	8.62769	17.39074	73.32990	.02242
231.333	357.512	.00000	.63104	8.64729	17.40000	73.29988	.02179
231.667	357.298	.00000	.63283	8.66687	17.40927	73.26986	.02118
232.000	357.084	.00000	.63462	8.68644	17.41854	73.23982	.02058
232.333	356.870	.00000	.63641	8.70600	17.42782	73.20978	.01999
232.667	356.656	.00000	.63820	8.72553	17.43711	73.17973	.01943
233.000	356.442	.00000	.63999	8.74505	17.44641	73.14967	.01888
233.333	356.228	.00000	.64178	8.76456	17.45572	73.11961	.01834
233.667	356.014	.00000	.64357	8.78404	17.46503	73.08954	.01782
234.000	355.800	.00000	.64536	8.80352	17.47435	73.05946	.01731
234.333	355.586	.00000	.64716	8.82297	17.48368	73.02938	.01681
234.667	355.371	.00000	.64895	8.84240	17.49302	72.99929	.01633
235.000	355.157	.00000	.65075	8.86182	17.50237	72.96919	.01586
235.333	354.943	.00000	.65255	8.88122	17.51173	72.93909	.01540
235.667	354.728	.00000	.65435	8.90061	17.52109	72.90899	.01496
236.000	354.513	.00000	.65615	8.91997	17.53047	72.87888	.01453
236.333	354.299	.00000	.65795	8.93932	17.53985	72.84876	.01411
236.667	354.084	.00000	.65976	8.95865	17.54925	72.81865	.01370
237.000	353.869	.00000	.66157	8.97796	17.55865	72.78853	.01330
237.333	353.654	.00000	.66337	8.99725	17.56806	72.75840	.01291
237.667	353.439	.00000	.66519	9.01652	17.57748	72.72827	.01254
238.000	353.224	.00000	.66700	9.03577	17.58692	72.69814	.01217
238.333	353.009	.00000	.66881	9.05501	17.59636	72.66801	.01182
238.667	352.793	.00000	.67063	9.07422	17.60581	72.63787	.01147
239.000	352.578	.00000	.67245	9.09341	17.61527	72.60773	.01113

239.333	352.363	.00000	.67427	9.11259	17.62475	72.57759	.01081
239.667	352.147	.00000	.67609	9.13174	17.63423	72.54745	.01049
240.000	351.932	.00000	.67792	9.15087	17.64372	72.51731	.01018
240.333	351.716	.00000	.67975	9.16998	17.65323	72.48716	.00988
240.667	351.500	.00000	.68158	9.18908	17.66274	72.45702	.00959
241.000	351.285	.00000	.68341	9.20815	17.67227	72.42687	.00930
241.333	351.069	.00000	.68525	9.22720	17.68181	72.39672	.00903
241.667	350.853	.00000	.68709	9.24622	17.69136	72.36657	.00876
242.000	350.637	.00000	.68893	9.26523	17.70091	72.33643	.00850
242.333	350.421	.00000	.69078	9.28421	17.71049	72.30628	.00824
242.667	350.204	.00000	.69263	9.30318	17.72007	72.27613	.00800
243.000	349.988	.00000	.69448	9.32212	17.72966	72.24598	.00776
243.333	349.772	.00000	.69633	9.34104	17.73927	72.21584	.00753
243.667	349.556	.00000	.69819	9.35993	17.74888	72.18569	.00730
244.000	349.339	.00000	.70005	9.37881	17.75851	72.15554	.00708
244.333	349.123	.00000	.70192	9.39766	17.76815	72.12540	.00687
244.667	348.906	.00000	.70379	9.41649	17.77781	72.09526	.00666
245.000	348.689	.00000	.70566	9.43529	17.78747	72.06512	.00646
245.333	348.472	.00000	.70754	9.45408	17.79715	72.03498	.00626
245.667	348.256	.00000	.70942	9.47283	17.80684	72.00484	.00607
246.000	348.039	.00000	.71130	9.49157	17.81654	71.97470	.00589
246.333	347.822	.00000	.71319	9.51028	17.82625	71.94456	.00571
246.667	347.605	.00000	.71508	9.52897	17.83598	71.91443	.00553
247.000	347.387	.00000	.71698	9.54763	17.84572	71.88430	.00537
247.333	347.170	.00000	.71888	9.56627	17.85547	71.85417	.00520
247.667	346.953	.00000	.72078	9.58489	17.86524	71.82405	.00504
248.000	346.735	.00000	.72269	9.60348	17.87502	71.79392	.00489
248.333	346.518	.00000	.72461	9.62204	17.88481	71.76380	.00474
248.667	346.300	.00000	.72653	9.64058	17.89461	71.73368	.00459
249.000	346.083	.00000	.72845	9.65910	17.90443	71.70357	.00445
249.333	345.865	.00000	.73038	9.67759	17.91426	71.67346	.00431
249.667	345.647	.00000	.73231	9.69605	17.92411	71.64335	.00418
250.000	345.429	.00000	.73425	9.71449	17.93397	71.61324	.00405
250.333	345.211	.00000	.73619	9.73291	17.94384	71.58314	.00392
250.667	344.993	.00000	.73814	9.75130	17.95373	71.55304	.00380
251.000	344.775	.00000	.74009	9.76966	17.96362	71.52294	.00368
251.333	344.557	.00000	.74205	9.78799	17.97354	71.49285	.00357
251.667	344.339	.00000	.74401	9.80630	17.98347	71.46276	.00346
252.000	344.121	.00000	.74598	9.82459	17.99341	71.43268	.00335
252.333	343.902	.00000	.74795	9.84285	18.00336	71.40260	.00325
252.667	343.684	.00000	.74993	9.86108	18.01333	71.37252	.00314
253.000	343.465	.00000	.75191	9.87928	18.02332	71.34245	.00305
253.333	343.247	.00000	.75390	9.89746	18.03331	71.31238	.00295
253.667	343.028	.00000	.75590	9.91561	18.04333	71.28231	.00286
254.000	342.809	.00000	.75790	9.93373	18.05335	71.25225	.00277
254.333	342.590	.00000	.75991	9.95182	18.06340	71.22219	.00268
254.667	342.371	.00000	.76192	9.96989	18.07345	71.19214	.00259
255.000	342.152	.00000	.76394	9.98793	18.08352	71.16209	.00251
255.333	341.933	.00000	.76597	10.00594	18.09361	71.13205	.00243
255.667	341.714	.00000	.76800	10.02393	18.10371	71.10201	.00236
256.000	341.495	.00000	.77004	10.04188	18.11383	71.07198	.00228
256.333	341.275	.00000	.77208	10.05981	18.12396	71.04195	.00221
256.667	341.056	.00000	.77413	10.07771	18.13410	71.01192	.00214
257.000	340.836	.00000	.77619	10.09558	18.14426	70.98190	.00207
257.333	340.617	.00000	.77825	10.11342	18.15444	70.95188	.00200
257.667	340.397	.00000	.78032	10.13124	18.16463	70.92187	.00194
258.000	340.177	.00000	.78240	10.14902	18.17484	70.89187	.00188
258.333	339.958	.00000	.78448	10.16678	18.18506	70.86187	.00182
258.667	339.738	.00000	.78657	10.18450	18.19530	70.83187	.00176
259.000	339.518	.00000	.78866	10.20220	18.20556	70.80188	.00170
259.333	339.298	.00000	.79077	10.21987	18.21583	70.77189	.00165
259.667	339.078	.00000	.79288	10.23751	18.22611	70.74191	.00159
260.000	338.857	.00000	.79500	10.25512	18.23641	70.71193	.00154
260.333	338.637	.00000	.79712	10.27270	18.24673	70.68196	.00149
260.667	338.417	.00000	.79925	10.29025	18.25706	70.65199	.00144
261.000	338.196	.00000	.80139	10.30777	18.26741	70.62203	.00140
261.333	337.976	.00000	.80354	10.32526	18.27778	70.59208	.00135
261.667	337.755	.00000	.80569	10.34271	18.28816	70.56213	.00131
262.000	337.535	.00000	.80785	10.36014	18.29856	70.53218	.00126
262.333	337.314	.00000	.81002	10.37754	18.30897	70.50224	.00122
262.667	337.093	.00000	.81219	10.39491	18.31940	70.47230	.00118
263.000	336.872	.00000	.81438	10.41225	18.32985	70.44238	.00114
263.333	336.651	.00000	.81657	10.42956	18.34032	70.41245	.00111
263.667	336.430	.00000	.81877	10.44683	18.35080	70.38253	.00107
264.000	336.209	.00000	.82097	10.46408	18.36129	70.35262	.00104
264.333	335.988	.00000	.82319	10.48129	18.37181	70.32271	.00100
264.667	335.766	.00000	.82541	10.49848	18.38234	70.29281	.00097
265.000	335.545	.00000	.82764	10.51563	18.39288	70.26291	.00094
265.333	335.324	.00000	.82988	10.53275	18.40345	70.23301	.00091
265.667	335.102	.00000	.83212	10.54984	18.41403	70.20313	.00088
266.000	334.880	.00000	.83438	10.56690	18.42463	70.17325	.00085
266.333	334.659	.00000	.83664	10.58393	18.43524	70.14337	.00082
266.667	334.437	.00000	.83891	10.60092	18.44588	70.11350	.00079
267.000	334.215	.00000	.84119	10.61789	18.45653	70.08363	.00076
267.333	333.993	.00000	.84347	10.63482	18.46719	70.05377	.00074
267.667	333.771	.00000	.84577	10.65172	18.47788	70.02392	.00071
268.000	333.549	.00000	.84807	10.66859	18.48858	69.99407	.00069
268.333	333.327	.00000	.85038	10.68542	18.49930	69.96423	.00067
268.667	333.105	.00000	.85270	10.70223	18.51004	69.93439	.00065
269.000	332.882	.00000	.85503	10.71900	18.52079	69.90456	.00062
269.333	332.660	.00000	.85737	10.73574	18.53156	69.87473	.00060
269.667	332.438	.00000	.85971	10.75245	18.54235	69.84491	.00058
270.000	332.215	.00000	.86207	10.76912	18.55316	69.81509	.00056
270.333	331.992	.00000	.86443	10.78576	18.56399	69.78528	.00054
270.667	331.770	.00000	.86680	10.80237	18.57483	69.75547	.00053
271.000	331.547	.00000	.86918	10.81895	18.58569	69.72567	.00051
271.333	331.324	.00000	.87157	10.83549	18.59657	69.69588	.00049
271.667	331.101	.00000	.87396	10.85200	18.60747	69.66609	.00047
272.000	330.878	.00000	.87637	10.86848	18.61838	69.63631	.00046
272.333	330.655	.00000	.87878	10.88493	18.62932	69.60653	.00044
272.667	330.432	.00000	.88121	10.90134	18.64027	69.57675	.00043
273.000	330.209	.00000	.88364	10.91772	18.65124	69.54699	.00041
273.333	329.985	.00000	.88608	10.93407	18.66223	69.51722	.00040

273.667	329.762	.00000	.88853	10.95038	18.67324	69.48747	.00039
274.000	329.538	.00000	.89099	10.96666	18.68426	69.45772	.00037
274.333	329.315	.00000	.89346	10.98290	18.69531	69.42797	.00036
274.667	329.091	.00000	.89594	10.99912	18.70637	69.39823	.00035
275.000	328.867	.00000	.89842	11.01530	18.71745	69.36849	.00034
275.333	328.644	.00000	.90092	11.03144	18.72855	69.33876	.00032
275.667	328.420	.00000	.90342	11.04756	18.73967	69.30904	.00031
276.000	328.196	.00000	.90594	11.06364	18.75081	69.27932	.00030
276.333	327.972	.00000	.90846	11.07968	18.76196	69.24960	.00029
276.667	327.747	.00000	.91099	11.09569	18.77314	69.21990	.00028
277.000	327.523	.00000	.91353	11.11167	18.78433	69.19019	.00027
277.333	327.299	.00000	.91608	11.12762	18.79555	69.16049	.00026
277.667	327.075	.00000	.91864	11.14353	18.80678	69.13080	.00025
278.000	326.850	.00000	.92121	11.15940	18.81803	69.10111	.00024
278.333	326.626	.00000	.92379	11.17525	18.82930	69.07143	.00024
278.667	326.401	.00000	.92637	11.19106	18.84059	69.04175	.00023
279.000	326.176	.00000	.92897	11.20683	18.85190	69.01208	.00022
279.333	325.952	.00000	.93157	11.22257	18.86323	68.98241	.00021
279.667	325.727	.00000	.93419	11.23828	18.87458	68.95275	.00020
280.000	325.502	.00000	.93681	11.25395	18.88595	68.92309	.00020
280.333	325.277	.00000	.93944	11.26959	18.89733	68.89344	.00019
280.667	325.052	.00000	.94209	11.28520	18.90874	68.86379	.00018
281.000	324.827	.00000	.94474	11.30077	18.92017	68.83415	.00018
281.333	324.602	.00000	.94740	11.31631	18.93161	68.80451	.00017
281.667	324.376	.00000	.95007	11.33181	18.94308	68.77488	.00017
282.000	324.151	.00000	.95275	11.34728	18.95457	68.74525	.00016
282.333	323.926	.00000	.95543	11.36271	18.96607	68.71563	.00015
282.667	323.700	.00000	.95813	11.37811	18.97760	68.68601	.00015
283.000	323.474	.00000	.96084	11.39348	18.98914	68.65640	.00014
283.333	323.249	.00000	.96356	11.40881	19.00071	68.62679	.00014
283.667	323.023	.00000	.96628	11.42411	19.01229	68.59718	.00013
284.000	322.797	.00000	.96902	11.43937	19.02390	68.56758	.00013
284.333	322.571	.00000	.97176	11.45460	19.03552	68.53799	.00012
284.667	322.345	.00000	.97451	11.46980	19.04717	68.50840	.00012
285.000	322.119	.00000	.97727	11.48496	19.05884	68.47882	.00012
285.333	321.893	.00000	.98004	11.50008	19.07052	68.44924	.00011
285.667	321.667	.00000	.98283	11.51518	19.08223	68.41966	.00011
286.000	321.441	.00000	.98561	11.53023	19.09396	68.39009	.00010
286.333	321.214	.00000	.98841	11.54526	19.10570	68.36052	.00010
286.667	320.988	.00000	.99122	11.56025	19.11747	68.33096	.00010
287.000	320.761	.00000	.99404	11.57520	19.12926	68.30141	.00009
287.333	320.535	.00000	.99686	11.59012	19.14107	68.27185	.00009
287.667	320.308	.00000	.99970	11.60501	19.15290	68.24230	.00009
288.000	320.081	.00000	1.00254	11.61986	19.16475	68.21276	.00008
288.333	319.854	.00000	1.00540	11.63468	19.17662	68.18322	.00008
288.667	319.627	.00000	1.00826	11.64946	19.18852	68.15369	.00008
289.000	319.400	.00000	1.01113	11.66421	19.20043	68.12415	.00007
289.333	319.173	.00000	1.01401	11.67893	19.21236	68.09463	.00007
289.667	318.946	.00000	1.01690	11.69361	19.22432	68.06511	.00007
290.000	318.719	.00000	1.01980	11.70825	19.23630	68.03559	.00007
290.333	318.492	.00000	1.02270	11.72287	19.24829	68.00607	.00006
290.667	318.264	.00000	1.02562	11.73744	19.26031	67.97656	.00006
291.000	318.037	.00000	1.02854	11.75199	19.27235	67.94706	.00006
291.333	317.809	.00000	1.03147	11.76650	19.28441	67.91756	.00006
291.667	317.582	.00000	1.03442	11.78097	19.29650	67.88806	.00006
292.000	317.354	.00000	1.03737	11.79542	19.30860	67.85856	.00005
292.333	317.126	.00000	1.04032	11.80982	19.32073	67.82907	.00005
292.667	316.899	.00000	1.04329	11.82420	19.33287	67.79959	.00005
293.000	316.671	.00000	1.04627	11.83854	19.34504	67.77010	.00005
293.333	316.443	.00000	1.04925	11.85284	19.35723	67.74063	.00005
293.667	316.215	.00000	1.05225	11.86712	19.36944	67.71115	.00004
294.000	315.987	.00000	1.05525	11.88135	19.38168	67.68168	.00004
294.333	315.758	.00000	1.05826	11.89556	19.39393	67.65221	.00004
294.667	315.530	.00000	1.06127	11.90973	19.40621	67.62275	.00004
295.000	315.302	.00000	1.06430	11.92386	19.41851	67.59329	.00004
295.333	315.073	.00000	1.06734	11.93797	19.43083	67.56383	.00004
295.667	314.845	.00000	1.07038	11.95204	19.44317	67.53438	.00004
296.000	314.616	.00000	1.07343	11.96607	19.45553	67.50493	.00003
296.333	314.388	.00000	1.07649	11.98007	19.46792	67.47548	.00003
296.667	314.159	.00000	1.07955	11.99404	19.48033	67.44604	.00003
297.000	313.930	.00000	1.08263	12.00798	19.49276	67.41660	.00003
297.333	313.701	.00000	1.08571	12.02188	19.50521	67.38717	.00003
297.667	313.472	.00000	1.08880	12.03575	19.51769	67.35773	.00003
298.000	313.243	.00000	1.09190	12.04958	19.53018	67.32830	.00003
298.333	313.014	.00000	1.09501	12.06338	19.54270	67.29888	.00003
298.667	312.785	.00000	1.09812	12.07715	19.55524	67.26946	.00003
299.000	312.556	.00000	1.10124	12.09089	19.56781	67.24003	.00002
299.333	312.326	.00000	1.10437	12.10459	19.58040	67.21062	.00002
299.667	312.097	.00000	1.10751	12.11826	19.59301	67.18120	.00002
300.000	311.867	.00000	1.11065	12.13189	19.60564	67.15179	.00002
300.333	311.638	.00000	1.11381	12.14550	19.61829	67.12238	.00002

C.4 INPUT DATA and OUTPUT for Figure 3.24 - 3.25

Input File = A2MS.DAT

```
Attritiion test : Arbitary data of lime, Velocity = 2 m/s,Temp.= 70 F
9,                                         Number of size interval
300.0,500.0,400.0,1.0,
500.0,700.0,600.0,4.0,
700.0,900.0,800.0,11.0,                    Lower, Upper, Mean, Weight(%)
900.0,1100.0,1000.0,21.0,
1100.0,1300.0,1200.0,25.5,
1300.0,1500.0,1400.0,21.0,
1500.0,1700.0,1600.0,11.0,
1700.0,1900.0,1800.0,4.0,
1900.0,2100.0,2000.0,1.0,
2.100,                                     Particle density (g/cm3)
1.0246E-03,                                Gas density (g/cm3)
1.78E-04,                                  Viscosity (g/cm/sec)
980.660,                                   Gravitational constant (cm/sec2)
7.620,                                     Diameter of bed (cm)
250.000,                                   Height of bed (cm)
0.000,                                     Collection efficiency of cyclone (%)
200.000,                                   Gas velocity (cm/sec)
4.82e-5,                                   Attrition rate constant (/sec)
10.000,                                    Size increments (microns)
10.000,                                    Time increments (sec)
1801,                                      Number of iteration based on time
Y                                          Data check - O.K. (Y or N)
Y                                          Use of Wen's equation for Umf(Y/N)
Y                                          Write minimum fluidization and
                                           terminal velocity (Y or N)
```

INPUT File = A4MS.DAT

```
Attritiion test : Arbitary data of lime, Velocity = 4 m/s,Temp.= 70 F
9,                                          Number of size interval
300.0,500.0,400.0,1.0,
500.0,700.0,600.0,4.0,
700.0,900.0,800.0,11.0,                     Lower, Upper, Mean, Weight(%)
900.0,1100.0,1000.0,21.0,
1100.0,1300.0,1200.0,25.5,
1300.0,1500.0,1400.0,21.0,
1500.0,1700.0,1600.0,11.0,
1700.0,1900.0,1800.0,4.0,
1900.0,2100.0,2000.0,1.0,
2.100,                                      Particle density (g/cm3)
1.0246E-03,                                 Gas density (g/cm3)
1.78E-04,                                   Viscosity (g/cm/sec)
980.660,                                    Gravitational constant (cm/sec2)
7.620,                                      Diameter of bed (cm)
250.000,                                    Height of bed (cm)
0.000,                                      Collection efficiency of cyclone (%)
400.000,                                    Gas velocity (cm/sec)
9.09e-5,                                    Attrition rate constant (/sec)
10.000,                                     Size increments (microns)
10.000,                                     Time increments (sec)
1801,                                       Number of iteration based on time
Y                                           Data check - O.K. (Y or N)
Y                                           Use of Wen's equation for Umf(Y/N)
Y                                           Write minimum fluidization and
                                            terminal velocity (Y or N)
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OUTPUT File = A2MS.OUT

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     TITLE = Attritiion test : Arbitary data of lime, Velocity = 2 m/s,Temp
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     DATA INPUT
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                             Minimum     Maximum    Mean (um)   Weight (%)
     Particle Dia.( 1)   =   300.000     500.000     400.000       1.000
     Particle Dia.( 2)   =   500.000     700.000     600.000       4.000
     Particle Dia.( 3)   =   700.000     900.000     800.000      11.000
     Particle Dia.( 4)   =   900.000    1100.000    1000.000      21.000
     Particle Dia.( 5)   =  1100.000    1300.000    1200.000      25.500
     Particle Dia.( 6)   =  1300.000    1500.000    1400.000      21.000
     Particle Dia.( 7)   =  1500.000    1700.000    1600.000      11.000
     Particle Dia.( 8)   =  1700.000    1900.000    1800.000       4.000
     Particle Dia.( 9)   =  1900.000    2100.000    2000.000       1.000

     Density of Particle       =        2.100     (g/cm3)
     Density of Gas            =      .102E-02    (g/cm3)
     Viscosity                 =      .178E-03    (g/cm/sec)
     Gravitational Constant    =      980.660     (cm/sec2)
     Bed Diameter              =        7.620     (cm)
     Bed Height                =      250.000     (cm)
     Efficiency of 1st cyclone =         .000     (%)
     Gas Velocity              =      200.000     (cm/sec)
     Attrition Rate Constant   =     .00004820    (/sec)
     Size Interval             =       10.000     (microns)
     Time Interval             =       10.000     (sec)
     Number of Iteration       =     1801

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     MINIMUM FLUIDIZATION VELOCITY AND TERMINAL VELOCITY
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Particle Diameter (microns)	Minimum Fluidization Velocity (m/sec)		Terminal Velocity (m/sec)	
	Yen	Babu	Re #	Ut
400.000	.108	.217	68.587	2.979
600.000	.226	.417	154.320	4.468
800.000	.360	.612	274.346	5.958
1000.000	.493	.786	428.666	7.447
1200.000	.617	.939	597.135	8.645
1400.000	.732	1.076	752.477	9.337
1600.000	.836	1.198	919.350	9.982

1800.000	.932	1.310	1097.008	10.588
2000.000	1.021	1.413	1284.831	11.160

Changes in size distributions of solids in a bed as a function of time

Time(min)	Tot-Wt(g)	MMD = 400.	MMD = 600.	MMD = 800.	MMD =1000.	MMD =1200.	MMD =1400.	MMD =1600.	MMD =1800.	MMD =2000.
.000	500.000	1.00000	4.00000	11.00000	21.00000	25.50000	21.00000	11.00000	4.00000	1.00000
30.000	487.343	.95658	4.51674	12.07491	21.96739	25.62383	20.20061	10.22396	3.59655	.83942
60.000	477.658	.96554	5.02354	13.10973	22.83525	25.60417	19.26328	9.36773	3.16122	.66954
90.000	468.362	1.01913	5.54018	14.16031	23.71120	25.57258	18.29706	8.48865	2.71496	.49593
120.000	459.324	1.09291	6.06732	15.22952	24.60061	25.53446	17.30449	7.58751	2.25922	.32396
150.000	450.484	1.17566	6.60528	16.31922	25.50521	25.48156	16.26980	6.66260	1.80562	.17505
180.000	441.806	1.26137	7.15435	17.43154	26.41994	25.37052	15.15797	5.73762	1.39154	.07514
210.000	433.270	1.34639	7.71542	18.57080	27.32456	25.11988	13.96344	4.87926	1.05475	.02551
240.000	424.861	1.42830	8.29137	19.74515	28.18039	24.66074	12.74587	4.14539	.79580	.00697
270.000	416.567	1.50563	8.88943	20.96512	28.94159	23.98962	11.58298	3.53509	.58895	.00157
300.000	408.379	1.57786	9.52297	22.23760	29.57419	23.16078	10.50686	3.00552	.41394	.00030

Time (min)	.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0
Total Wt(g)	496.0	487.3	477.7	468.4	459.3	450.5	441.8	433.3	424.9	416.6	408.4

Fractional weight (g) as a function of time

400.000	1.00000	.95658	.96554	1.01913	1.09291	1.17566	1.26137	1.34639	1.42830	1.50563	1.57786
600.000	4.00000	4.51674	5.02354	5.54018	6.06732	6.60528	7.15435	7.71542	8.29137	8.88943	9.52297
800.000	11.00000	12.07491	13.10973	14.16031	15.22952	16.31922	17.43154	18.57080	19.74515	20.96512	22.23760
1000.000	21.00000	21.96739	22.83525	23.71120	24.60061	25.50521	26.41994	27.32456	28.18039	28.94159	29.57419
1200.000	25.50000	25.62383	25.60417	25.57258	25.53446	25.48156	25.37052	25.11988	24.66074	23.98962	23.16078
1400.000	21.00000	20.20061	19.26328	18.29706	17.30449	16.26980	15.15797	13.96344	12.74587	11.58298	10.50686
1600.000	11.00000	10.22396	9.36773	8.48865	7.58751	6.66260	5.73762	4.87926	4.14539	3.53509	3.00552
1800.000	4.00000	3.59655	3.16122	2.71496	2.25922	1.80562	1.39154	1.05475	.79580	.58895	.41394
2000.000	1.00000	.83942	.66954	.49593	.32396	.17505	.07514	.02551	.00697	.00157	.00030

OUTPUT File = A4MS.OUT

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     TITLE = Attritiion test : Arbitary data of lime, Velocity=4 m/s,Temp
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     DATA INPUT
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                                  Minimum     Maximum    Mean (um)   Weight (%)
     Particle Dia.( 1)      =     300.000     500.000     400.000       1.000
     Particle Dia.( 2)      =     500.000     700.000     600.000       4.000
     Particle Dia.( 3)      =     700.000     900.000     800.000      11.000
     Particle Dia.( 4)      =     900.000    1100.000    1000.000      21.000
     Particle Dia.( 5)      =    1100.000    1300.000    1200.000      25.500
     Particle Dia.( 6)      =    1300.000    1500.000    1400.000      21.000
     Particle Dia.( 7)      =    1500.000    1700.000    1600.000      11.000
     Particle Dia.( 8)      =    1700.000    1900.000    1800.000       4.000
     Particle Dia.( 9)      =    1900.000    2100.000    2000.000       1.000

     Density of Particle         =         2.100     (g/cm3)
     Density of Gas              =       .102E-02    (g/cm3)
     Viscosity                   =       .178E-03    (g/cm/sec)
     Gravitational Constant      =       980.660     (cm/sec2)
     Bed Diameter                =         7.620     (cm)
     Bed Height                  =       250.000     (cm)
     Efficiency of 1st cyclone   =          .000     (%)
     Gas Velocity                =       400.000     (cm/sec)
     Attrition Rate Constant     =     .00009090     (/sec)
     Size Interval               =        10.000     (microns)
     Time Interval               =        10.000     (sec)
     Number of Iteration         =      1801

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     MINIMUM FLUIDIZATION VELOCITY AND TERMINAL VELOCITY
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Particle Diameter (microns)	Minimum Fluidization Velocity (m/sec)		Terminal Velocity (m/sec)	
	Yen	Babu	Re #	Ut
400.000	.108	.217	68.587	2.979
600.000	.226	.417	154.320	4.468
800.000	.360	.612	274.346	5.958
1000.000	.493	.786	428.666	7.447
1200.000	.617	.939	597.135	8.645
1400.000	.732	1.076	752.477	9.337
1600.000	.836	1.198	919.350	9.982

1800.000	.932	1.310	1097.008	10.588
2000.000	1.021	1.413	1284.831	11.160

Changes in size distributions of solids in a bed as a function of time

Time(min)	Tot-Wt(g)	MMD = 400.	MMD = 600.	MMD = 800.	MMD =1000.	MMD =1200.	MMD =1400.	MMD =1600.	MMD =1800.	MMD =2000.
.000	500.000	1.00000	4.00000	11.00000	21.00000	25.50000	21.00000	11.00000	4.00000	1.00000
30.000	430.944	.00030	.96899	10.46509	24.11184	28.18264	21.44045	10.50016	3.56521	.76533
60.000	389.767	.00000	.45579	10.27633	26.55662	29.68758	20.60215	9.19852	2.79428	.42873
90.000	353.298	.00000	.22238	10.35858	29.27027	31.15232	19.36346	7.58376	1.91855	.13068
120.000	318.916	.00000	.11282	10.46423	32.28217	32.30824	17.62973	5.96876	1.21620	.01785
150.000	285.554	.00000	.06259	10.55122	35.37287	32.73538	15.79785	4.74198	.73691	.00121
180.000	252.852	.00000	.03929	10.70195	38.35576	32.70218	14.14801	3.69319	.35957	.00005
210.000	220.754	.00000	.02605	10.94370	41.34654	32.48015	12.41543	2.66605	.12207	.00000
240.000	189.296	.00000	.01582	11.16653	44.49299	31.92360	10.58116	1.79207	.02784	.00000
270.000	158.585	.00000	.00803	11.17545	47.68789	31.05950	8.93885	1.12589	.00439	.00000
300.000	128.875	.00000	.00325	10.76349	50.74974	30.30148	7.55438	.62716	.00050	.00000

Time (min)	.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0
Total Wt(g)	496.0	430.9	389.8	353.3	318.9	285.6	252.9	220.8	189.3	158.6	128.9

Fractional weight (g) as a function of time

400.000	1.00000	.00030	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
600.000	4.00000	.96899	.45579	.22238	.11282	.06259	.03929	.02605	.01582	.00803	.00325
800.000	11.00000	10.46509	10.27633	10.35858	10.46423	10.55122	10.70195	10.94370	11.16653	11.17545	10.76349
1000.000	21.00000	24.11184	26.55662	29.27027	32.28217	35.37287	38.35576	41.34654	44.49299	47.68789	50.74974
1200.000	25.50000	28.18264	29.68758	31.15232	32.30824	32.73538	32.70218	32.48015	31.92360	31.05950	30.30148
1400.000	21.00000	21.44045	20.60215	19.36346	17.62973	15.79785	14.14801	12.41543	10.58116	8.93885	7.55438
1600.000	11.00000	10.50016	9.19852	7.58376	5.96876	4.74198	3.69319	2.66605	1.79207	1.12589	.62716
1800.000	4.00000	3.56521	2.79428	1.91855	1.21620	.73691	.35957	.12207	.02784	.00439	.00050
2000.000	1.00000	.76533	.42873	.13068	.01785	.00121	.00005	.00000	.00000	.00000	.00000

APPENDIX D

EXPERIMENTAL DATA

Weight measurements after attrition : Effects of Attrition Factors

(initial weight = 500 g)

1. Velocity and Time

Weight Reduction of Bed Mat as a Function of Time

Time(min)	2 m/s (g)	2 m/s (%)	3 m/s (g)	3 m/s (%)	4 m/s (g)	4 m/s (%)	5 m/s (g)	5 m/s (%)
0	500.0	100.0	500.0	100.0	500.0	100.0	500.0	100.0
30	468.8	93.8	434.8	87.0	430.0	86.0	404.9	81.0
60	449.5	89.9	423.7	84.7	390.4	78.1	374.5	74.9
120	418.3	83.7	376.2	75.2	317.3	63.5	294.4	58.9
180	410.3	82.1	330.6	66.1	309.9	62.0	284.6	56.9
300	387.1	77.4	309.1	61.8	268.7	53.7	227.2	45.4

Weight Reduction of Bed Matas a Function of Velocity

Velocity (m/s)	30 min (g)	30 min (%)	1 hr (g)	1 hr (%)	2 hr (g)	2 hr (%)	3 hr (g)	3 hr (%)	5hr (g)	5hr (%)
2	468.8	93.8	449.5	89.9	418.3	83.7	410.3	82.1	387.1	77.4
3	434.8	87.0	423.7	84.7	376.2	75.2	330.6	66.1	309.1	61.8
4	430.0	86.0	390.4	78.1	317.3	63.5	309.9	62.0	268.7	53.7
5	404.9	81.0	374.5	74.9	294.4	58.9	284.6	56.9	227.2	45.4

2. Temperature

Temperature (F)	Weight Reduction of Bed Material (V = 4 m/s and 1 hour) (g)	(%)	extent of attrition	
70	390.4	78.1	109.6	21.9
150	451.0	90.2	49.0	9.8
250	475.5	95.1	24.5	4.9
350	482.8	96.6	17.2	3.4

3. Initial Weight (Wo)

Wo (g)	V = 4 m/sMMD = 1764.0 Weight Reduction of Bed Material (g)	(%)	extent of attritio	V = 2 m/sMMD = 903.0 (g)	(%)	extent of attrition
250	231.7	92.7	7.3	235.8	94.3	5.7
400	322.1	80.5	19.5			
500	390.4	78.1	21.9	427.8	85.6	14.4
600	458.6	76.4	23.6			
750	624.9	83.3	16.7	652.5	87.0	13.0

1000	813.5	81.4	18.7	874.6	87.5	12.5

4. Sintering effects on Attrition

Sintering Reduction Weight Reduction of Bed Material (V = 4 m/s and 1, and Temperature = 70 F)

Time(hr)	of BET(%)	(g)	(%)
0	100	390.4	78.1
1	92.1	402.1	80.4
2	82.5	367.1	73.4
9	72.8	332.7	66.5

5. Particle Size

Weight Reduction of Bed Material as a Function of (Velocity = 2 m/s and Temperature = 70 F)

Time(min)	MMD =	1764	MMd =	903
	(g)	(%)	(g)	(%)
30	459.9	92.0	468.8	93.8
60	427.8	85.6	449.5	89.9
120	395.6	79.1	418.3	83.7
180	363.8	72.8	410.3	82.1
300	340.6	68.1	387.1	77.4

Size Measurements of lime samples before and after attrition

I. Velocity = 2 m/s and Temperature = 70 F

(1)Raw Sample

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	89.40	78.80	84.10	33.61	100.00	736.13	1.53E-04
1190.0	16	2000.0	10	1595.0	149.20	157.70	153.45	61.33	66.39	978.23	3.85E-04
1008.0	18	1190.0	16	1099.0	8.80	11.20	10.00	4.00	5.06	43.92	3.64E-05
841.0	20	1008.0	18	924.5	0.30	0.20	0.25	0.10	1.06	0.92	1.08E-06
595.0	30	841.0	20	718.0	0.10	0.10	0.10	0.04	0.96	0.29	5.57E-07
400.0	50	595.0	30	497.5	2.40	2.20	2.30	0.92	0.92	4.57	1.85E-05
				SUM	250.20	250.20	250.20	100.00	Mass Mean Dimeter	1764.06	5.94E-04

(2)A30MIN.2MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	40.10	40.10	40.10	16.01	100.00	350.57	7.31E-05
1190.0	16	2000.0	10	1595.0	172.50	172.50	172.50	68.86	83.99	1098.35	4.32E-04
1008.0	18	1190.0	16	1099.0	28.90	28.90	28.90	11.54	15.13	126.79	1.05E-04
841.0	20	1008.0	18	924.5	3.30	3.30	3.30	1.32	3.59	12.18	1.42E-05
595.0	30	841.0	20	718.0	2.80	2.80	2.80	1.12	2.28		

										8.03	1.56E-05
400.0	50	595.0	30	497.5	2.90	2.90	2.90	1.16	1.16	5.76	2.33E-05
				SUM	250.50	250.50	250.50	100.00	Mass Mean Dimeter	1601.68	6.63E-04

Surface Mean Dia. 1508.53

(3)A1HR.2MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative	Ave Dia x Weight % /100	Ave Dia./Weight Fr
micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	
2000.0	10	2380.0	8	2190.0	39.60	39.60	39.60	15.81	100.00	346.20	7.22E-05
1190.0	16	2000.0	10	1595.0	169.00	169.00	169.00	67.47	84.19	1076.07	4.23E-04
1008.0	18	1190.0	16	1099.0	32.80	32.80	32.80	13.09	16.73	143.90	1.19E-04
841.0	20	1008.0	18	924.5	4.10	4.10	4.10	1.64	3.63	15.13	1.77E-05
595.0	30	841.0	20	718.0	2.20	2.20	2.20	0.88	2.00	6.31	1.22E-05
400.0	50	595.0	30	497.5	2.80	2.80	2.80	1.12	1.12	5.56	2.25E-05
				SUM	250.50	250.50	250.50	100.00	Mass Mean Dimeter	1593.17	6.67E-04

Surface Mean Dia. 1499.90

(4)A2HR.2MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative	Ave Dia x Weight % /100	Ave Dia./Weight Fr
micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	
2000.0	10	2380.0	8	2190.0	32.70	32.70	32.70	13.04	100.00	285.54	5.95E-05
1190.0	16	2000.0	10	1595.0	165.70	165.70	165.70	66.07	86.96	1053.79	4.14E-04
1008.0	18	1190.0	16	1099.0	38.60	38.60	38.60	15.39	20.89		

										169.14	1.40E-04
841.0	20	1008.0	18	924.5	8.10	8.10	8.10	3.23	5.50	29.86	3.49E-05
595.0	30	841.0	20	718.0	3.20	3.20	3.20	1.28	2.27	9.16	1.78E-05
400.0	50	595.0	30	497.5	2.50	2.50	2.50	1.00	1.00	4.96	2.00E-05
				SUM	250.80	250.80	250.80	100.00	Mass Mean Dimeter	1552.45	6.87E-04

Surface Mean Dia. 1456.57

(5)A3HR.2MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	30.30	30.30	30.30	12.09	100.00	264.79	5.52E-05
1190.0	16	2000.0	10	1595.0	163.70	163.70	163.70	65.32	87.91	1041.91	4.10E-04
1008.0	18	1190.0	16	1099.0	43.20	43.20	43.20	17.24	22.59	189.45	1.57E-04
841.0	20	1008.0	18	924.5	9.70	9.70	9.70	3.87	5.35	35.78	4.19E-05
595.0	30	841.0	20	718.0	2.30	2.30	2.30	0.92	1.48	6.59	1.28E-05
400.0	50	595.0	30	497.5	1.40	1.40	1.40	0.56	0.56	2.78	1.12E-05
				SUM	250.60	250.60	250.60	100.00	Mass Mean Dimeter	1541.30	6.87E-04

Surface Mean Dia. 1454.55

(6)A5HR.2MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr

2000.0	10	2380.0	8	2190.0	30.50	30.50	30.50	12.21	100.00	267.39	5.58E-05
1190.0	16	2000.0	10	1595.0	154.00	154.00	154.00	61.65	87.79	983.31	3.87E-04
1008.0	18	1190.0	16	1099.0	44.70	44.70	44.70	17.89	26.14	196.66	1.63E-04
841.0	20	1008.0	18	924.5	13.90	13.90	13.90	5.56	8.25	51.44	6.02E-05
595.0	30	841.0	20	718.0	4.40	4.40	4.40	1.76	2.68	12.65	2.45E-05
400.0	50	595.0	30	497.5	2.30	2.30	2.30	0.92	0.92	4.58	1.85E-05
				SUM	249.80	249.80	249.80	100.00	Mass Mean Dimeter	1516.03	7.08E-04

II. Velocity = 3 m/s and Temperature = 70 F

(1)Raw Sample

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	89.40	78.80	84.10	33.61	100.00	736.13	1.53E-04
1190.0	16	2000.0	10	1595.0	149.20	157.70	153.45	61.33	66.39	978.23	3.85E-04
1008.0	18	1190.0	16	1099.0	8.80	11.20	10.00	4.00	5.06	43.92	3.64E-05
841.0	20	1008.0	18	924.5	0.30	0.20	0.25	0.10	1.06	0.92	1.08E-06
595.0	30	841.0	20	718.0	0.10	0.10	0.10	0.04	0.96	0.29	5.57E-07
400.0	50	595.0	30	497.5	2.40	2.20	2.30	0.92	0.92	4.57	1.85E-05
				SUM	250.20	250.20	250.20	100.00	Mass Mean Dimeter	1764.06	5.94E-04

(2)A30MIN.3MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative

Ave Dia x Weight % /100 Ave Dia./Weight Fr

micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	
2000.0	10	2380.0	8	2190.0	47.80	47.80	47.80	19.12	100.00	418.73	8.73E-05
1190.0	16	2000.0	10	1595.0	147.80	147.80	147.80	59.12	80.88	942.96	3.71E-04
1008.0	18	1190.0	16	1099.0	26.40	26.40	26.40	10.56	21.76	116.05	9.61E-05
841.0	20	1008.0	18	924.5	11.60	11.60	11.60	4.64	11.20	42.90	5.02E-05
595.0	30	841.0	20	718.0	8.90	8.90	8.90	3.56	6.56	25.56	4.96E-05
400.0	50	595.0	30	497.5	7.50	7.50	7.50	3.00	3.00	14.93	6.03E-05
				SUM	250.00	250.00	250.00	100.00	Mass Mean Dimeter	1561.13	7.14E-04

Surface Mean Dia. 1400.32

(3)A1HR.3MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative	Ave Dia x Weight % /100	Ave Dia./Weight Fr
micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	
2000.0	10	2380.0	8	2190.0	46.30	46.30	46.30	18.45	100.00	404.13	8.43E-05
1190.0	16	2000.0	10	1595.0	154.30	154.30	154.30	61.50	81.55	980.90	3.86E-04
1008.0	18	1190.0	16	1099.0	28.00	28.00	28.00	11.16	20.05	122.65	1.02E-04
841.0	20	1008.0	18	924.5	10.20	10.20	10.20	4.07	8.89	37.58	4.40E-05
595.0	30	841.0	20	718.0	5.90	5.90	5.90	2.35	4.82	16.88	3.28E-05
400.0	50	595.0	30	497.5	6.20	6.20	6.20	2.47	2.47	12.29	4.97E-05
				SUM	250.90	250.90	250.90	100.00	Mass Mean Dimeter	1574.44	6.98E-04

Surface

Mean Dia. 1433.13

(4)A2HR.3MS

Min micron	Min mesh	Max micron	Max mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100	Ave Dia./Weight Fr micron
2000.0	10	2380.0	8	2190.0	45.30	45.30	45.30	18.06	100.00	395.40	8.24E-05
1190.0	16	2000.0	10	1595.0	158.80	158.80	158.80	63.29	81.94	1009.51	3.97E-04
1008.0	18	1190.0	16	1099.0	28.50	28.50	28.50	11.36	18.65	124.84	1.03E-04
841.0	20	1008.0	18	924.5	11.70	11.70	11.70	4.66	7.29	43.11	5.04E-05
595.0	30	841.0	20	718.0	4.90	4.90	4.90	1.95	2.63	14.02	2.72E-05
400.0	50	595.0	30	497.5	1.70	1.70	1.70	0.68	0.68	3.37	1.36E-05
			SUM		250.90	250.90	250.90	100.00	Mass Mean Dimeter	1590.26	6.74E-04

Surface Mean Dia. 1483.95

(5)A3HR.3MS

Min micron	Min mesh	Max micron	Max mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100	Ave Dia./Weight Fr micron
2000.0	10	2380.0	8	2190.0	34.80	34.80	34.80	13.86	100.00	303.63	6.33E-05
1190.0	16	2000.0	10	1595.0	155.90	155.90	155.90	62.11	86.14	990.68	3.89E-04
1008.0	18	1190.0	16	1099.0	30.70	30.70	30.70	12.23	24.02	134.42	1.11E-04
841.0	20	1008.0	18	924.5	18.50	18.50	18.50	7.37	11.79	68.14	7.97E-05
595.0	30	841.0	20	718.0	7.80	7.80	7.80	3.11	4.42	22.31	4.33E-05
400.0	50	595.0	30	497.5	3.30	3.30	3.30	1.31	1.31		

										6.54	2.64E-05
				SUM	251.00	251.00	251.00	100.00	Mass Mean Dimeter	1525.73	7.13E-04

Surface Mean Dia. 1401.64

(6)A5HR.3MS

Min micron	Min mesh	Max micron	Max mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	24.90	24.90	24.90	12.41	100.00	271.70	5.67E-05
1190.0	16	2000.0	10	1595.0	125.90	125.90	125.90	62.73	87.59	1000.55	3.93E-04
1008.0	18	1190.0	16	1099.0	24.50	24.50	24.50	12.21	24.86	134.16	1.11E-04
841.0	20	1008.0	18	924.5	15.70	15.70	15.70	7.82	12.66	72.32	8.46E-05
595.0	30	841.0	20	718.0	8.10	8.10	8.10	4.04	4.83	28.98	5.62E-05
400.0	50	595.0	30	497.5	1.60	1.60	1.60	0.80	0.80	3.97	1.60E-05
				SUM	200.70	200.70	200.70	100.00	Mass Mean Dimeter	1511.68	7.18E-04

III. Velocity = 4 m/s and Temperature = 70 F

(1)Raw Sample

Min micron	Min mesh	Max micron	Max mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	89.40	78.80	84.10	33.61	100.00	736.13	1.53E-04

1190.0	16	2000.0	10	1595.0	149.20	157.70	153.45	61.33	66.39	978.23	3.85E-04
1008.0	18	1190.0	16	1099.0	8.80	11.20	10.00	4.00	5.06	43.92	3.64E-05
841.0	20	1008.0	18	924.5	0.30	0.20	0.25	0.10	1.06	0.92	1.08E-06
595.0	30	841.0	20	718.0	0.10	0.10	0.10	0.04	0.96	0.29	5.57E-07
400.0	50	595.0	30	497.5	2.40	2.20	2.30	0.92	0.92	4.57	1.85E-05
				SUM	250.20	250.20	250.20	100.00	Mass Mean Dimeter	1764.06	5.94E-04

(2)A30MIN.4MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative	Ave Dia x Weight % /100	Ave Dia./Weight Fr
micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	
2000.0	10	2380.0	8	2190.0	50.30	50.30	50.30	20.12	100.00	440.63	9.19E-05
1190.0	16	2000.0	10	1595.0	150.10	150.10	150.10	60.04	79.88	957.64	3.76E-04
1008.0	18	1190.0	16	1099.0	27.30	27.30	27.30	10.92	19.84	120.01	9.94E-05
841.0	20	1008.0	18	924.5	9.70	9.70	9.70	3.88	8.92	35.87	4.20E-05
595.0	30	841.0	20	718.0	5.70	5.70	5.70	2.28	5.04	16.37	3.18E-05
400.0	50	595.0	30	497.5	6.90	6.90	6.90	2.76	2.76	13.73	5.55E-05
				SUM	250.00	250.00	250.00	100.00	Mass Mean Dimeter	1584.25	6.97E-04

Surface Mean Dia. 1435.00

(3)A1HR.4MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative	Ave Dia x Weight % /100	Ave Dia./Weight Fr
micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	

2000.0	10	2380.0	8	2190.0	36.10	36.10	36.10	14.44	100.00	316.24	6.59E-05
1190.0	16	2000.0	10	1595.0	150.70	150.70	150.70	60.28	85.56	961.47	3.78E-04
1008.0	18	1190.0	16	1099.0	30.90	30.90	30.90	12.36	25.28	135.84	1.12E-04
841.0	20	1008.0	18	924.5	14.60	14.60	14.60	5.84	12.92	53.99	6.32E-05
595.0	30	841.0	20	718.0	6.60	6.60	6.60	2.64	7.08	18.96	3.68E-05
400.0	50	595.0	30	497.5	11.10	11.10	11.10	4.44	4.44	22.09	8.92E-05
				SUM	250.00	250.00	250.00	100.00	Mass Mean Dimeter	1508.57	7.46E-04

Surface Mean Dia. 1341.35

(4)A2HR.4MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	28.30	28.30	28.30	11.30	100.00	247.51	5.16E-05
1190.0	16	2000.0	10	1595.0	155.10	155.10	155.10	61.94	88.70	987.96	3.88E-04
1008.0	18	1190.0	16	1099.0	34.10	34.10	34.10	13.62	26.76	149.66	1.24E-04
841.0	20	1008.0	18	924.5	18.90	18.90	18.90	7.55	13.14	69.78	8.16E-05
595.0	30	841.0	20	718.0	9.10	9.10	9.10	3.63	5.59	26.09	5.06E-05
400.0	50	595.0	30	497.5	4.90	4.90	4.90	1.96	1.96	9.74	3.93E-05
				SUM	250.40	250.40	250.40	100.00	Mass Mean Dimeter	1490.74	7.35E-04

Surface Mean Dia. 1359.70

(5)A3HR.4MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative	Ave Dia x Weight % /100	Ave

Dia./Weight Fr											
micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	
2000.0	10	2380.0	8	2190.0	20.30	20.30	20.30	8.11	100.00	177.69	3.70E-05
1190.0	16	2000.0	10	1595.0	149.50	149.50	149.50	59.75	91.89	953.05	3.75E-04
1008.0	18	1190.0	16	1099.0	40.20	40.20	40.20	16.07	32.13	176.58	1.46E-04
841.0	20	1008.0	18	924.5	24.30	24.30	24.30	9.71	16.07	89.79	1.05E-04
595.0	30	841.0	20	718.0	11.30	11.30	11.30	4.52	6.35	32.43	6.29E-05
400.0	50	595.0	30	497.5	4.60	4.60	4.60	1.84	1.84	9.15	3.70E-05
				SUM	250.20	250.20	250.20	100.00	Mass Mean Dimeter	1438.68	7.63E-04

Surface Mean Dia. 1311.00

(6)A5HR.4MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative	Ave Dia x Weight % /100	Ave Dia./Weight Fr
micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	
2000.0	10	2380.0	8	2190.0	15.70	15.70	15.70	7.85	100.00	171.83	3.58E-05
1190.0	16	2000.0	10	1595.0	118.20	118.20	118.20	59.07	92.15	942.17	3.70E-04
1008.0	18	1190.0	16	1099.0	31.70	31.70	31.70	15.84	33.08	174.10	1.44E-04
841.0	20	1008.0	18	924.5	20.70	20.70	20.70	10.34	17.24	95.64	1.12E-04
595.0	30	841.0	20	718.0	10.20	10.20	10.20	5.10	6.90	36.60	7.10E-05
400.0	50	595.0	30	497.5	3.60	3.60	3.60	1.80	1.80	8.95	3.62E-05
				SUM	200.10	200.10	200.10	100.00	Mass Mean Dimeter	1429.30	7.69E-04

IV. Velocity = 5 m/s and Temperature = 70 F

(1)Raw Sample

Min micron	Min mesh	Max micron	Max mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	89.40	78.80	84.10	33.61	100.00	736.13	1.53E-04
1190.0	16	2000.0	10	1595.0	149.20	157.70	153.45	61.33	66.39	978.23	3.85E-04
1008.0	18	1190.0	16	1099.0	8.80	11.20	10.00	4.00	5.06	43.92	3.64E-05
841.0	20	1008.0	18	924.5	0.30	0.20	0.25	0.10	1.06	0.92	1.08E-06
595.0	30	841.0	20	718.0	0.10	0.10	0.10	0.04	0.96	0.29	5.57E-07
400.0	50	595.0	30	497.5	2.40	2.20	2.30	0.92	0.92	4.57	1.85E-05
				SUM	250.20	250.20	250.20	100.00	Mass Mean Dimeter	1764.06	5.94E-04

(2)A30MIN.5MS

Min micron	Min mesh	Max micron	Max mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	49.80	49.80	49.80	19.87	100.00	435.20	9.07E-05
1190.0	16	2000.0	10	1595.0	165.40	165.40	165.40	66.00	80.13	1052.73	4.14E-04

1008.0	18	1190.0	16	1099.0	26.20	26.20	26.20	10.45	14.13	114.90	9.51E-05
841.0	20	1008.0	18	924.5	5.20	5.20	5.20	2.08	3.67	19.18	2.24E-05
595.0	30	841.0	20	718.0	1.50	1.50	1.50	0.60	1.60	4.30	8.34E-06
400.0	50	595.0	30	497.5	2.50	2.50	2.50	1.00	1.00	4.96	2.01E-05
				SUM	250.60	250.60	250.60	100.00	Mass Mean Dimeter	1631.27	6.51E-04
									Surface Mean Dia.	1537.26	

(3)A1HR.5MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	24.70	24.70	24.70	9.86	100.00	215.85	4.50E-05
1190.0	16	2000.0	10	1595.0	158.80	158.80	158.80	63.37	90.14	1010.72	3.97E-04
1008.0	18	1190.0	16	1099.0	49.60	49.60	49.60	19.79	26.78	217.52	1.80E-04
841.0	20	1008.0	18	924.5	13.90	13.90	13.90	5.55	6.98	51.28	6.00E-05
595.0	30	841.0	20	718.0	2.00	2.00	2.00	0.80	1.44	5.73	1.11E-05
400.0	50	595.0	30	497.5	1.60	1.60	1.60	0.64	0.64	3.18	1.28E-05
				SUM	250.60	250.60	250.60	100.00	Mass Mean Dimeter	1504.28	7.06E-04
									Surface Mean Dia.	1415.75	

(4)A2HR.5MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr

2000.0	10	2380.0	8	2190.0	27.20	27.20	27.20	10.85	100.00	237.51	4.95E-05
1190.0	16	2000.0	10	1595.0	158.20	158.20	158.20	63.08	89.15	1006.10	3.95E-04
1008.0	18	1190.0	16	1099.0	43.30	43.30	43.30	17.26	26.08	189.74	1.57E-04
841.0	20	1008.0	18	924.5	19.30	19.30	19.30	7.70	8.81	71.14	8.32E-05
595.0	30	841.0	20	718.0	1.80	1.80	1.80	0.72	1.12	5.15	1.00E-05
400.0	50	595.0	30	497.5	1.00	1.00	1.00	0.40	0.40	1.98	8.01E-06
				SUM	250.80	250.80	250.80	100.00	Mass Mean Dimeter	1511.63	7.03E-04

Surface Mean Dia. 1421.79

(5)A3HR.5MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	16.40	16.40	16.40	8.18	100.00	179.13	3.73E-05
1190.0	16	2000.0	10	1595.0	123.40	123.40	123.40	61.55	91.82	981.66	3.86E-04
1008.0	18	1190.0	16	1099.0	38.20	38.20	38.20	19.05	30.27	209.39	1.73E-04
841.0	20	1008.0	18	924.5	19.50	19.50	19.50	9.73	11.22	89.91	1.05E-04
595.0	30	841.0	20	718.0	2.40	2.40	2.40	1.20	1.50	8.59	1.67E-05
400.0	50	595.0	30	497.5	0.60	0.60	0.60	0.30	0.30	1.49	6.02E-06
				SUM	200.50	200.50	200.50	100.00	Mass Mean Dimeter	1470.18	7.24E-04

Surface Mean Dia. 1380.33

(6)A5HR.5MS

Min		Max		Ave	weight	weight	Ave	weight	cumulative	Ave Dia x Weight % /100	Ave

micron	mesh	micron	mesh	micron	(1)	(2)	weight	(%)	(%)	micron	Dia./Weight Fr
2000.0	10	2380.0	8	2190.0	19.60	19.60	19.60	9.79	100.00	214.41	4.47E-05
1190.0	16	2000.0	10	1595.0	125.40	125.40	125.40	62.64	90.21	999.07	3.93E-04
1008.0	18	1190.0	16	1099.0	31.10	31.10	31.10	15.53	27.57	170.72	1.41E-04
841.0	20	1008.0	18	924.5	19.70	19.70	19.70	9.84	12.04	90.97	1.06E-04
595.0	30	841.0	20	718.0	3.20	3.20	3.20	1.60	2.20	11.48	2.23E-05
400.0	50	595.0	30	497.5	1.20	1.20	1.20	0.60	0.60	2.98	1.20E-05
				SUM	200.20	200.20	200.20	100.00	Mass Mean Dimeter	1489.63	7.20E-04

Size Measurements of Samples (MMD=903 microns) after and before attrition

Velocity = 2 m/s, Temperature = 70 F, and -30 +16 meshes of samples

(1)Raw Sample

Min micron	Min mesh	Max micron	Max mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
1000.0	18	1190.0	16	1095.0	89.20	85.10	87.15	34.71	100.00	380.12	3.17E-04
841.0	20	1000.0	18	920.5	82.10	78.10	80.10	31.91	65.29	293.69	3.47E-04
595.0	30	841.0	18	718.0	74.90	82.10	78.50	31.27	33.38	224.51	4.35E-04
420.0	40	595.0	30	507.5	0.70	1.20	0.95	0.38	2.11	1.92	7.46E-06
297.0	50	420.0	40	358.5	0.10	0.30	0.20	0.08	1.73	0.29	2.22E-06
0.0	~	297.0	50	148.5	4.30	4.00	4.15	1.65	1.65	2.45	1.11E-04
				SUM	251.30	250.80	251.05	100.00	Mass Mean Dimeter	902.99	1.22E-03

(2)B30MIN.2MS

Min micron	Min mesh	Max micron	Max mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
1000.0	18	1190.0	16	1095.0	56.00	56.00	56.00	22.35	100.00	244.69	2.04E-04
841.0	20	1000.0	18	920.5	86.10	86.10	86.10	34.36	77.65	316.26	3.73E-04
595.0	30	841.0	18	718.0	94.30	94.30	94.30	37.63	43.30	270.18	5.24E-04
420.0	40	595.0	30	507.5	10.20	10.20	10.20	4.07	5.67	20.66	8.02E-05
297.0	50	420.0	40	358.5	1.60	1.60	1.60	0.64	1.60		

2.29 1.78E-05
0.0 ~ 297.0 50 148.5 2.40 2.40 2.40 0.96 0.96 1.42
6.45E-05
SUM 250.60 250.60 250.60 100.00 Mass Mean Dimeter
855.50 1.26E-03
Surface
Mean Dia. 791.19
(3)B1HR.2MS

Min Max Ave weight weight Ave weight cumulative
Ave Dia x Weight % /100 Ave
Dia./Weight Fr
micron mesh micron mesh micron (1) (2) weight (%) (%)
micron

1000.0 18 1190.0 16 1095.0 40.90 40.90 40.90 16.31 100.00
178.64 1.49E-04
841.0 20 1000.0 18 920.5 83.60 83.60 83.60 33.35 83.69
306.96 3.62E-04
595.0 30 841.0 18 718.0 104.10 104.10 104.10 41.52 50.34
298.14 5.78E-04
420.0 40 595.0 30 507.5 16.50 16.50 16.50 6.58 8.82
33.40 1.30E-04
297.0 50 420.0 40 358.5 2.70 2.70 2.70 1.08 2.23
3.86 3.00E-05
0.0 ~ 297.0 50 148.5 2.90 2.90 2.90 1.16 1.16 1.72
7.79E-05
SUM 250.70 250.70 250.70 100.00 Mass Mean Dimeter
822.72 1.33E-03
Surface
Mean Dia. 753.46
(4)B2HR.2MS

Min Max Ave weight weight Ave weight cumulative
Ave Dia x Weight % /100 Ave
Dia./Weight Fr
micron mesh micron mesh micron (1) (2) weight (%) (%)
micron

1000.0 18 1190.0 16 1095.0 34.10 34.10 34.10 13.60 100.00
148.94 1.24E-04
841.0 20 1000.0 18 920.5 84.20 84.20 84.20 33.59 86.40
309.16 3.65E-04
595.0 30 841.0 18 718.0 106.70 106.70 106.70 42.56 52.81

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
										305.59	5.93E-04
420.0	40	595.0	30	507.5	21.70	21.70	21.70	8.66	10.25	43.93	1.71E-04
297.0	50	420.0	40	358.5	2.70	2.70	2.70	1.08	1.60	3.86	3.00E-05
0.0	~	297.0	50	148.5	1.30	1.30	1.30	0.52	0.52	0.77	3.49E-05
				SUM	250.70	250.70	250.70	100.00	Mass Mean Dimeter	812.25	1.32E-03

Surface Mean Dia. 759.09

(5)B3HR.2MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
1000.0	18	1190.0	16	1095.0	27.40	27.40	27.40	10.93	100.00	119.68	9.98E-05
841.0	20	1000.0	18	920.5	77.40	77.40	77.40	30.87	89.07	284.19	3.35E-04
595.0	30	841.0	18	718.0	113.40	113.40	113.40	45.23	58.20	324.78	6.30E-04
420.0	40	595.0	30	507.5	27.80	27.80	27.80	11.09	12.96	56.28	2.19E-04
297.0	50	420.0	40	358.5	3.20	3.20	3.20	1.28	1.87	4.58	3.56E-05
0.0	~	297.0	50	148.5	1.50	1.50	1.50	0.60	0.60	0.89	4.03E-05
				SUM	250.70	250.70	250.70	100.00	Mass Mean Dimeter	790.38	1.36E-03

Surface Mean Dia. 735.51

(6)B5HR.2MS

Min micron	mesh	Max micron	mesh	Ave micron	weight (1)	weight (2)	Ave weight	weight (%)	cumulative (%)	Ave Dia x Weight % /100 micron	Ave Dia./Weight Fr
1000.0	18	1190.0	16	1095.0	21.80	21.80	21.80	10.87	100.00		

										119.00	9.92E-05
841.0	20	1000.0	18	920.5	58.80	58.80	58.80	29.31	89.13	269.82	3.18E-04
595.0	30	841.0	18	718.0	88.70	88.70	88.70	44.22	59.82	317.48	6.16E-04
420.0	40	595.0	30	507.5	27.00	27.00	27.00	13.46	15.60	68.31	2.65E-04
297.0	50	420.0	40	358.5	3.30	3.30	3.30	1.65	2.14	5.90	4.59E-05
0.0	~	297.0	50	148.5	1.00	1.00	1.00	0.50	0.50	0.74	3.36E-05
				SUM	200.60	200.60	200.60	100.00	Mass Mean Dimeter	781.24	1.38E-03

Attrition of lime under wet condition

Weight of fine solid collected by cyclone = 8.6 g/ inch column

File Name = W40V5H4.75A W50V5H4.75A
Water Content (%) = 14 17

Time(min)	Tot.Wt(g)	Cao(g)	Wt.Loss(g)	Bed Wt.(g)	Tot.Wt(g)	CaO(g)	Wt.Loss(g)	Bed Wt.(g)
0	189.20	162.71	0.00	587.29	210.70	174.88	0.00	575.12
10	4.30	3.70	3.70	583.59	12.90	10.71	10.71	564.41
20	12.90	11.09	14.79	572.50	30.10	24.98	35.69	539.43
30	12.00	10.32	25.11	562.18	38.70	32.12	67.81	507.31
40	12.90	11.09	36.21	551.08	64.50	53.54	121.35	453.77
50	21.50	18.49	54.70	532.59	77.40	64.24	185.59	389.53
60	30.10	25.89	80.58	506.71	55.90	46.40	231.99	343.14
70	30.10	25.89	106.47	480.82	30.10	24.98	256.97	318.15
80	34.40	29.58	136.05	451.24				
90	30.10	25.89	161.94	425.35				
100	30.10	25.89	187.82	399.47				
110	25.80	22.19	210.01	377.28				

Weight Reduction of Bed Mat as a Function of Time

Time(min)	W40V5H4		W50V5H4	
	(g)	(%)	(g)	(%)
0	587.29	100.0	575.12	100.0
10	583.59	99.4	564.41	98.1
20	572.50	97.5	539.43	93.8
30	562.18	95.7	507.31	88.2
40	551.08	93.8	453.77	78.9
50	532.59	90.7	389.53	67.7
60	506.71	86.3	343.14	59.7
70	480.82	81.9	318.15	55.3
80	451.24	76.8		
90	425.35	72.4		
100	399.47	68.0		
110	377.28	64.2		