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SCALING OF PRESSURIZED FLUIDIZED BEDS

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Scaling of Pressurized Fluidized Beds

CONTRACT INFORMATION

Cooperative Agreement DE-FC21-92MC29264

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FY 1994 Program Schedule

	O	N	D	J	F	M	A	M	J	J	A	S
Installation	—	—	—	—	—							
Instrumentation						—	—					
Hot Bed Testing				—	—			—	—			
Cold Bed Testing								—	—	—		
Mixing Studies											—	—

OBJECTIVES

This project has two primary objectives. The first is to verify a set of hydrodynamic scaling relationships for commercial pressurized fluidized bed combustors (PFBC). The second objective is to investigate solids mixing in pressurized bubbling fluidized beds.

American Electric Power's (AEP) Tidd combined-cycle demonstration plant will provide time-varying pressure drop data to serve as the basis for the scaling verification. The verification will involve demonstrating that a properly scaled cold model and the Tidd PFBC exhibit hydrodynamically similar behavior.

An important issue in PFBC design is the spacing of fuel feed ports. The feed spacing is dictated by the fuel distribution and the mixing characteristics within the bed. After completing the scaling verification, the cold model will be used to study the mixing characteristics of PFBCs. A thermal tracer technique will be utilized to study mixing both near the fuel feed region and in the far field. The results will allow the coal feed and distributor to be designed for optimal mixing.

BACKGROUND INFORMATION

Hydrodynamic scaling

One of the most difficult problems facing a fluidized bed designer is to determine how bed size and operating parameters affect bed performance. This is particularly true when a large combustor is to be designed based on pilot plant experience. It is also critical in the operation or modification of an existing fluidized bed combustor. Research has been done to show that a cold model, designed using the proper hydrodynamic scaling parameters, closely simulates the hydrodynamic behavior of fluidized bed combustors. Accurate room temperature simulations of fluidized bed combustors allow rapid, inexpensive tests to determine the effects of varying operating parameters and bed design on the hydrodynamics of the combustor.

One of the first systematic developments of the dimensionless scaling parameters which control the modeling of a fluidized bed was presented by Glicksman (1984, 1988). The scaling parameters were developed by nondimensionalizing Anderson and Jackson's (1967) equations of motion. The resulting parameters, which we will refer to as the full set of scaling parameters, are as follows:

$$\frac{\rho_f}{\rho_s} \quad \frac{u_o^2}{gD} \quad \frac{\rho_f u_o D}{\mu} \quad \frac{L}{D} \quad \frac{D}{d_p} \quad \phi_s \quad PSD \qquad (1)$$

A great deal of experimental work has been done to verify that when these dimensionless groups are matched between two fluidized beds they exhibit hydrodynamically similar behavior (e.g. for bubbling beds: Nicastro and Glicksman, 1984; Newby and Keairns, 1986; Roy and Davidson, 1989; Almstedt and Zakkay, 1990; and for circulating beds: Glicksman et al., 1991; Chang and Louge, 1992, and Glicksman et al., 1993.)

When the full set of scaling parameters is used, once the scale model fluidizing gas is specified the size of the model is fixed. For example, if air at atmospheric temperature and pressure is used in a cold model of an atmospheric fluidized bed combustor, the model's linear dimensions will be roughly 1/4 those of the hot bed (scale down by factor of four). For the case of pressurized fluidized beds operating at 10-12 atm, a cold model fluidized using ambient air will have approximately the same linear dimensions as the combustor. This makes scaling large combustors using the full set of scaling parameters less tractable. Therefore, it is desirable to look for simplifications to the full set of scaling parameters which will make it possible to choose the scale factor.

Glicksman et al. (1993) proposed a simplification to the full set of scaling parameters which allows the scale factor to be independently specified. The simplification is based on the fact that the number of dimensionless groups can be reduced if the fluid-particle drag is dominated by either viscous or inertial effects. In both the viscous and inertial limits, the scaling parameters reduce to:

$$\frac{\rho_f}{\rho_s} \quad \frac{u_o^2}{gD} \quad \frac{u_o}{u_{mf}} \quad \frac{L}{D} \quad \phi_s \quad PSD \qquad (2)$$

where the bed Reynolds number and the ratio of the reference bed dimension (D) to the particle diameter (d_p) in the full set [Eqtn. (1)] have been replaced by the ratio of the gas superficial (u_o) and minimum fluidization velocities (u_{mf}). Since this simplified set of parameters holds exactly at both high and low particle Reynolds numbers, it is reasonable to expect it to be approximately valid throughout the range of particle Reynolds numbers. Equation (2) will be referred to as the simplified set of scaling parameters. Glicksman et al. (1993) experimentally verified the simplified set of scaling parameters for atmospheric circulating fluidized beds (CFB) by making hydrodynamic comparisons between three fluidized beds. Hot-bed data was taken from the 2.5 MW_t Studsvik CFB prototype. Scaling comparisons were made between the hot-bed, a 1/4 scale model of the Studsvik CFB based on the full set of scaling parameters, and a 1/16 scale model of the hot-bed based on the simplified set of scaling parameters. The solid fraction profiles of the three beds were found to agree well.

Solids mixing

A properly scaled cold model provides similar hydrodynamics to that of a hot combustor. Solids mixing in bubbling beds is due primarily to bubble characteristics such as bubble size and frequency, which induce mixing in bubble wakes, and to bubble eruptions at the bed surface. A cold scale model with similar hydrodynamics makes it possible to investigate solids mixing for a hot bed combustor.

Lateral and vertical solids mixing is critical in fluidized bed combustors. Adequate mixing is required to ensure high combustion efficiency, sulphur capture, and heat transfer. Solid mixing is typically investigated using tracer techniques. These techniques involve the injection of tracer particles into a fluidized bed and the tracking of their movement in some way. The tracer should have the same density, diameter, and sphericity as the bed material so that its movement will accurately characterize particle motion within the bed. For an ambient air fluidized cold model of a pressurized fluidized bed combustor, the solid density must be approximately 900 kg /m^3. This rules out the use of magnetic tracers or other high density materials. Also, due to the seemingly random behavior of fluidized beds, numerous experiments need to be conducted to characterize the average solids mixing characteristics of the bed. Therefore the technique should not produce an elevated background of the tracer particles which would make it impossible to distinguish between tracers from current and previous experiments. A thermal tracer technique was developed (Valenzuela and Glicksman, 1984) which satisfies these criterion. It has also recently been used to study lateral solids mixing in circulating fluidized beds (Westphalen, 1993). The thermal tracer technique involves the injection of heated bed material particles into the fluidized bed. The motion of the particles is tracked using an array of thermistor probes. This technique has the advantage that the bed material is used as the tracer ensuring that the hydrodynamics will be similar. The heated tracers lose their distinctive signature after some residence time in the bed thus not disturbing the overall background level of subsequent experiments.

PROJECT DESCRIPTION

Hydrodynamic scaling

Experiments will be carried out on the Tidd PFBC and on a cold scale model at MIT. For bubbling beds, important bed characteristics such as gas and solids mixing and heat transfer are a direct function of the bubble characteristics. Thus the experimental verification will be based on a comparison of bubble characteristics.

Time-resolved pressure differences between two vertically spaced static pressure taps give a good indication of the bubble behavior; the amplitude is proportional to the bubble size while the frequency of the fluctuations gives the frequency of bubbles passing between the probes. Comparisons of these quantities can be made by evaluating the probability density function (PDF) and power spectral density (PSD) of the time-varying pressure signal. By placing probes at several locations within the bed, the spatial variation of bubble characteristics can be obtained. Verification of the scaled model with the combustor will be obtained by comparing the PDF and PSD results in nondimensional form.

Solids mixing

After the cold model is verified, it will be used to study solids mixing. The thermal tracer technique will be used.

There are two important sources of mixing which have an impact on the required coal feed spacing. Close to the feed point, mixing is determined by the interaction of the injected fuel and water flow with the bed dynamics. In this region, the momentum of the injected mass and the feed point design may be important. As the material moves away from the feed point into the far field, vertical and lateral mixing of the fuel and volatiles will be determined by the bed dynamics.

To simulate near field mixing in the vicinity of the feed point, preliminary experiments will be carried out using solid tracer and air injected with the same scaled flow rate and momentum as the fuel/water stream. It may also be necessary to simulate the dynamics of the phase change of the water injected with the coal. This may be modeled using chilled liquid refrigerant.

The thermal tracer technique in conjunction with the cold scale model will make it possible to evaluate the effect of varying operating parameters and bed geometry on the solids mixing.

RESULTS

Scaling calculations

Table 1 lists the geometric and operating parameters which are needed to calculate the values of the simplified scaling parameters for the Tidd PFBC. The particle density (ρ_s) was determined by measuring the displacement of a known mass of the Tidd bed material (dolomite). The particle sphericity (ϕ_s) was determined by evaluating a digitized picture of the Tidd bed material using computer software to estimate its average apparent circularity. Chang and Louge (1992) found that the square of the apparent circularity provided a good estimate of the particle sphericity. The particle diameter was determined through sieve analysis, and the minimum fluidization velocity was predicted using an expression proposed by Grace (1982).

Table 1 also lists the parameters for a 1/4 scale cold model of the Tidd PFBC based on the simplified set of scaling parameters. The values in the table are those required to exactly match the scaling parameters. The fluidizing gas properties are those of ambient air.

Cold scale model

A quarter scale cold scale model of a section of the Tidd PFBC has been constructed based on the simplified set of scaling laws. The Tidd boiler enclosure (Kinsinger, 1990) is illustrated in Figure 1. The dashed lines represent the section of the Tidd combustor

Table 1. Comparison of Tidd PFBC and required cold model parameters

	Tidd PFBC	Cold Model (1/4 Scale)
T (°K)	1116	322
p (N/m²)	1.013×10^6	1.013×10^5
μ (kg/m-s)	4.5×10^{-5}	2.0×10^{-5}
ρ_f (kg/m³)	3.2	1.1
ρ_s (kg/m³)	2513	875
ϕ_s	0.82	0.82
u_{mf} (m/s)	0.27	0.13
u_o (m/s)	0.91	0.45
D (m)	3.4	0.85
d_p (μm)	920	670

which was scaled. The decision to scale only a section of the combustor was based on the observations of Glicksman and McAndrews (1985) and Glicksman et al. (1987). They found that the bubble distribution is nearly uniform throughout the bed cross-section for large-particle bubbling fluidized beds containing a large array of horizontal tubes.

Figure 2 is a sketch of the MIT cold model. Air from a main blower unit enters the inlet plenum of the model and then passes through a distributor plate fluidizing the bed material. The expanded bed height corresponds approximately with the top of the tube bank. The air leaving the bed passes through a cyclone to capture elutriated bed material. Finally the air exhausts into the room after passing through a filter box.

A granular linear low-density polyethylene manufactured by Union Carbide was chosen as the cold bed material. It has a solid density of

Figure 1. Tidd boiler enclosure with scaled section designated

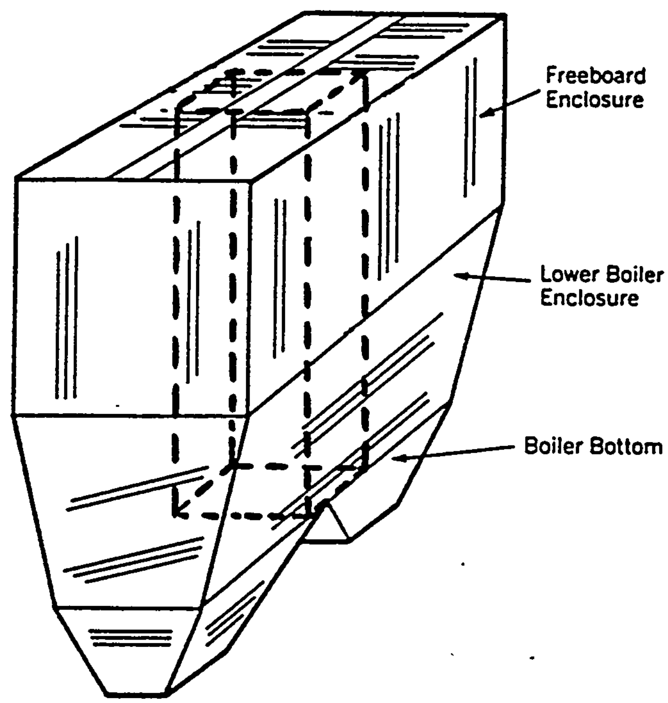
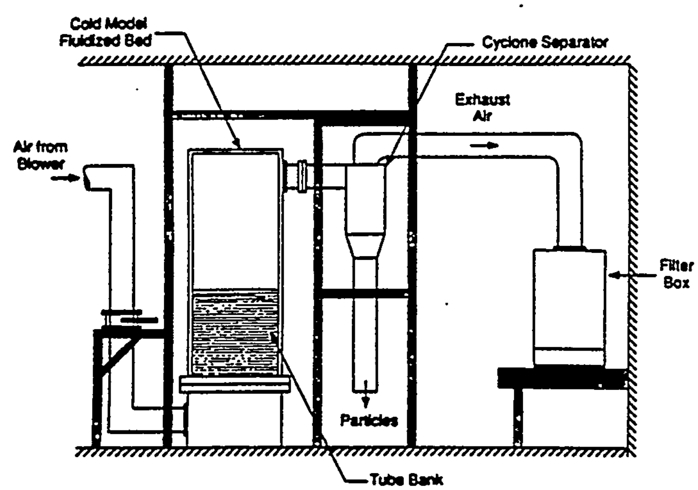


Figure 2. MIT cold model of Tidd PFBC



918 kg/m³ which allows the hot bed density ratio to be matched within 5%. The cold bed material particle sphericity is 0.85 which matches the hot bed value within 4%. Approximately 300 lbs of this material is required to achieve the full bed height.

Preliminary scaling comparisons

Some uncertainty exists in the mean particle diameter and particle size distribution of the Tidd bed material. It is not possible to obtain a particle sample from the center of the bed. Samples typically are taken from bed drains or sorbent reinjection vessels. These may or may not be representative of the material in the bed. The cold bed data presented here were taken with a mean particle diameter of approximately 420 μm which is smaller than the 670 μm particle diameter required to match all the scaling parameters. This was done to evaluate the sensitivity of the scaling to particle size. In the cold bed data u_o/u_{mf} and the particle size distribution were not matched between the hot and cold beds while u_o^2/gD, ρ_f/ρ_s, and L/D were matched. Table 2 summarizes the operating conditions for the hot bed and the cold model. Table 3 compares the values of the simplified scaling parameters for the two beds.

Figure 3 compares the Tidd bed and cold model solid fraction profiles. The solid fraction is the fraction of the bed between two pressure taps which is occupied by the bed material. In gas fluidized beds it is given approximately by

$$1 - \varepsilon \approx \frac{\Delta p}{\rho_s g \Delta h} \qquad (3)$$

Figure 3 shows that in the cold model, the solid fraction is lower (higher voidage) in the bottom of the bed and approximately constant in the upper part of the bed. The hot bed data appear to exhibit a similar trend. One possible explanation for the lower solid fraction in the bottom of the bed could be the presence of small slow moving bubbles causing a high voidage. As the bubbles coalesce they rise faster reducing the voidage. Throughout the tube bank the bubbles are prevented from growing any further producing a fairly flat solid fraction profile. The disagreement between the hot and cold bed solid fraction profiles in the bottom of the bed may be due to the mis-scaled particle size in the cold model. It is difficult to draw any definitive conclusions until data are taken from the cold model with all the scaling parameters matched. More hot bed data is needed to verify the preliminary data.

Table 2. Tidd PFBC and MIT cold model operating conditions

	Tidd PFBC	MIT Cold Model (1/4 Scale)
T (°K)	1116	322
p (N/m^2)	1.013x10^6	1.013x10^5
μ (kg/m-s)	4.5x10^{-5}	2.0x10^{-5}
ρ_f (kg/m^3)	3.2	1.1
ρ_s (kg/m^3)	2513	918
ϕ_s	0.82	0.85
u_{mf} (m/s)	0.27	0.06
u_o (m/s)	0.91	0.45
D (m)	3.4	0.85
d_p (μm)	920	420

Table 3. Comparison of Tidd PFBC and MIT cold model scaling parameters

	Tidd PFBC	MIT Cold Model (1/4 Scale)
ρ_s/ρ_f	795	834
u_o^2/gD	0.025	0.025
u_o/u_{mf}	3.37	7.5
ϕ_s	0.82	0.85

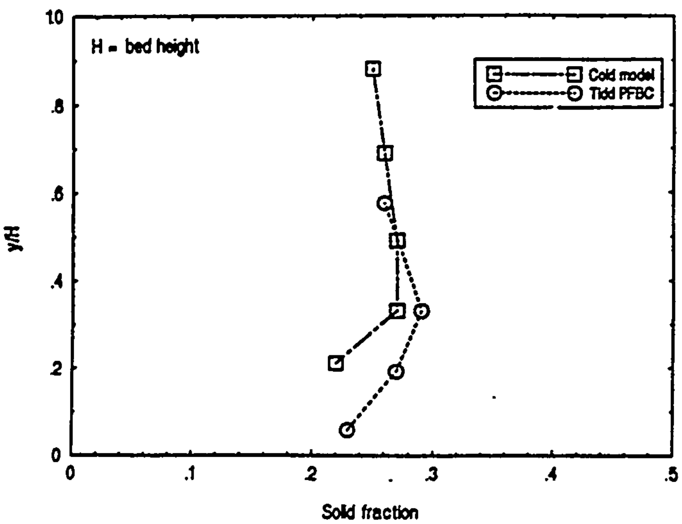


Figure 3. Comparison of Tidd and cold model solid fraction profiles

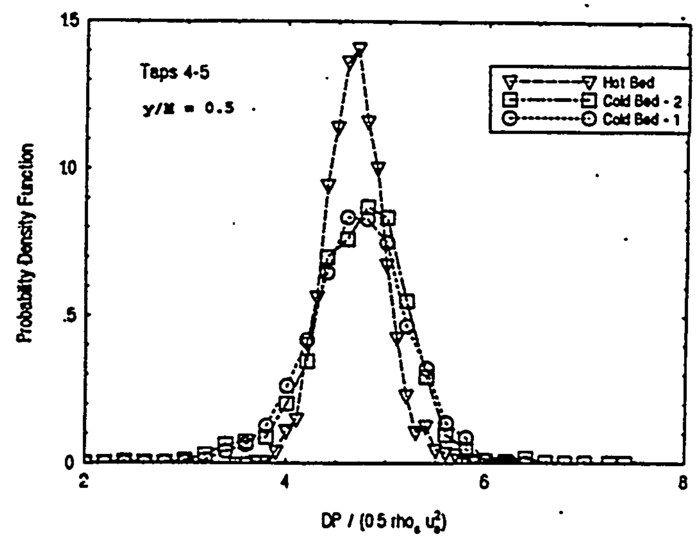


Figure 4. Comparison of probability density functions of Tidd and cold model pressure drop data

High speed time-varying pressure drop data have been taken by Babcock and Wilcox on the Tidd plant. As mentioned previously, the probability density function (PDF) and the power spectral density (PSD) are used to characterize the amplitude and the frequency of the time-varying pressure signal. The PDF measures the probability of the amplitude of the pressure fluctuations being in a certain interval. The PSD gives analogous information about the frequency of the fluctuations. Figure 4 compares the PDFs of the hot and cold bed pressure data as a function of the dimensionless pressure drop. Similarly, Figure 5 compares the PSD of the hot and cold bed pressure data as a function of the dimensionless frequency. These two figures correspond to a single differential pressure location in the bed, similar plots could be generated for the other locations in the bed. Again, due to the fact that all the scaling parameters have not been matched it is presently difficult to draw any conclusions. When data are taken on the cold model with all the scaling parameters matched, it will be possible to assess the level of agreement with the Tidd PFBC, and to evaluate the sensitivity of the scaling to the particle size.

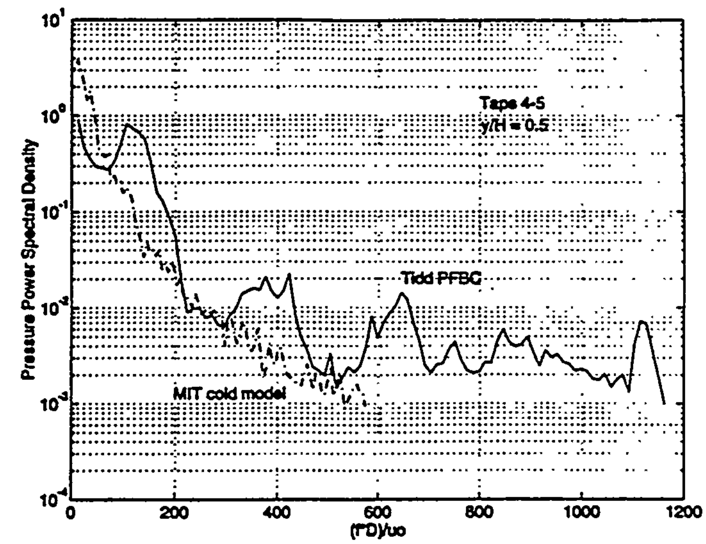


Figure 5. Comparison of power spectral densities of Tidd and cold model pressure drop data

FUTURE WORK

Hydrodynamic scaling

The properly scaled particle size and size distribution must be attained in the cold model. This will permit direct scaling comparisons between the Tidd PFBC and the MIT cold scale model. Additional high speed hot bed data must also be obtained to corroborate the validity of the initial set of Tidd pressure data. Based on the results of the scaling comparison, the cold model tube bank details will be refined, if necessary, to obtain good agreement between the hot bed and the cold model. Current plans are to complete this work by August 1994.

Solids mixing

Once the cold scale model has been verified it will be possible to begin to investigate the solids mixing in the bed. The emphasis will be on obtaining information to help designers determine the necessary fuel feed spacing. Studies will also be done to evaluate the effects of varying bed operating and geometric parameters on solids mixing.

Tidd support

One of the advantages of having a cold scale model of an existing combustor is that it can be used as a diagnostic tool to evaluate problems related to the bed hydrodynamics. Tidd has experienced a number of problems related to solids mixing including: insufficient heat transfer surface area, poor fuel distribution, and sinter formation. It is often difficult to perform the detailed measurements necessary to solve a problem in the hostile environment of a combustor. AEP is currently interested in trying to obtain information from the cold model to give them guidance in addressing some of these problems.

NOMENCLATURE

D	Reference bed dimension
d_p	Surface-volume mean particle diameter
g	Acceleration due to gravity
L	Bed dimension
PSD	Dimensionless particle size distribution
u_{mf}	Minimum fluidization velocity
u_o	Gas superficial velocity
Δh	Distance between pressure taps
H	Expanded bed height
Δp	Incremental pressure drop
ε	Voidage
μ	Fluidizing gas dynamic viscosity
ϕ_s	Particle sphericity
ρ_f	Fluidizing gas density
ρ_s	Particle solid density

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