

Final Report

**DEVELOPMENT OF A VORTEX COMBUSTOR
(VC) FOR SPACE/WATER HEATING APPLICATIONS
(COMBUSTION TESTS)**

to

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SUMMARY

This is the final report for Interagency Agreement DE-AI22-87PC79660 on "Combustion Test" for vortex combustor (VC) development for commercial applications. The work culminated in the successful demonstration of a 2 MB/H proof-of-concept (POC) model firing coal-water fuel (CWF).

This development is concerned with a new concept in combustion, and there is a general lack of relevant information. The work therefore began (in addition to the companion cold flow modeling study) with the design and test of two subscale models (0.15 and 0.3 MB/H) and one full scale model (3 MB/H) to obtain the needed information. With the experience gained, the 2 MB/H POC model was then designed and demonstrated. Although, these models were designed somewhat different from one another, they all performed well and demonstrated the superiority of the concept.

In summary, test results have shown that VC can be fired on several coal fuels (CWF, dry ultrafine coal, utility grind pulverized coal) at high combustion efficiency (>99%), high firing intensity (up to 0.44 MB/H-ft³), and at temperatures sufficiently low for dry ash removal. The combustion process is completed totally inside the combustor. Conventional combustion enhancement techniques such as: preheating (air and/or fuel), pre-combustion, and post combustion are not needed.

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CHAPTER 1
INTRODUCTION

Since the early 1970's, the continual increase in oil price and the potential oil shortage in the near future have led to a great deal of interest in coal as a replacement fuel for power and heating applications. The United States has been endowed with the largest total and recoverable coal reserves in the world [1]. However, coal has rarely been used during the recent decades in residential, commercial, and even light industrial sectors as fuels for boilers or fluid heaters for space heating, water heating, and process heat. In the commercial sector, boilers of sizes less than 10 MB/H (10^6 Btu/hr) have been dominated by fuel oil and natural gas for heating various buildings such as hotels, institutions, warehouses, industrial plants, apartment buildings, hospitals, office complexes, etc. [2].

Small-scale coal-fueled heating units are inconvenient to operate due to lack of automatic control, lack of fuel delivery and ash removal infrastructure, and incapability of meeting the emission standards in an economical way. Conventional coal combustion technologies, such as stoker-fired, pulverized coal fired, fluidized-bed, and cyclone combustors, have shown successes in large-scale applications. Their potentials for commercial heating applications in an environmentally and socially acceptable way remain an uncertainty. Novel coal combustion technologies engineered for small- and medium-scale boiler applications

are therefore needed.

In 1986, the Pittsburgh Energy Technology Center (PETC), U.S. Department of Energy, issued a Procurement of Research and Development Announcement (PRDA) [3], soliciting proposals on advanced combustors firing dry ultrafine coal (DUC) and/or coal-water fuel (CWF) capable of penetrating into the small- and medium-scale boiler market. The vortex combustor (VC) concept was proposed to fire both CWF and DUC for commercial space/water heating applications. The developmental work of the VC was awarded to the Naval Civil Engineering Laboratory (NCEL) for combustion tests under an interagency agreement No.: DE-AI22-87PC79660, and to the Catholic University of America (CUA) for cold flow modeling study under contract No.: DE-AC22-87PC79661. This is the final report on the results of VC combustion tests, a 36-month research effort starting on October 1, 1987 [4].

Project Objective and Requirements

The objective of this project is to develop a 2-4 MB/H proof-of-concept (POC) VC which meets the performance requirements specified in the PETC's 1986 PRDA [3] and the design goals characterizing the unique features of the VC as summarized in Table 1.1.

The VC Concept

The VC concept evolved from our basic understanding of swirling multiphase flows and combustion in vortex chambers [5-8]. It is characterized by a strong swirl, low temperature combustion environment, which integrates the advantages of

Table 1.1 Performance requirements and design goals for the VC.

BASIC REQUIREMENTS (PRDA Specifications):	
Thermal input capacity	2 - 4 MB/H
Application range	Commercial space/water heating
Primary fuel	CWF or DUC
Secondary fuel	Oil or gas
System thermal efficiency	≥ 80 %
Combustion efficiency	≥ 99 %
Turndown ratio	≥ 3 : 1
DESIGN GOALS (VC Features):	
Combustion temperature	1,600-2,200°F (870-1,200°C)
Ash removal	Non-slugging (dry flyash)
Flow field in combustor	Swirling, recirculating, and developing
Combustion air preheating	Not needed

cyclone combustor, swirl burner, multistage combustion, and fluidized-bed combustor, while eliminating some of their inherent disadvantages. As shown in Figure 1.1, the VC is featured with a gas-tight vertical annular combustion chamber with a coaxial center exhaust tube. The fuel, such as CWF, DUC, and pulverized coal (PC) is atomized (or pneumatically fed) into the combustor bottom. Combustion air is tangentially injected into the chamber through one, two, or more arrays of air nozzles located at strategic levels to form a strong swirling, recirculating, and developing turbulent flow field. Fuel droplets (or particles) are dried, devolatilized, ignited, and finally burned out while ascending to the exit at the top. Heat transfer surfaces, such as water jacket, are provided to remove the excess heat and control the combustor temperature to be always below the ash fusion point so that only dry ash (i.e., no slags or clinkers) will form. By virtue of the characteristic features of the VC,

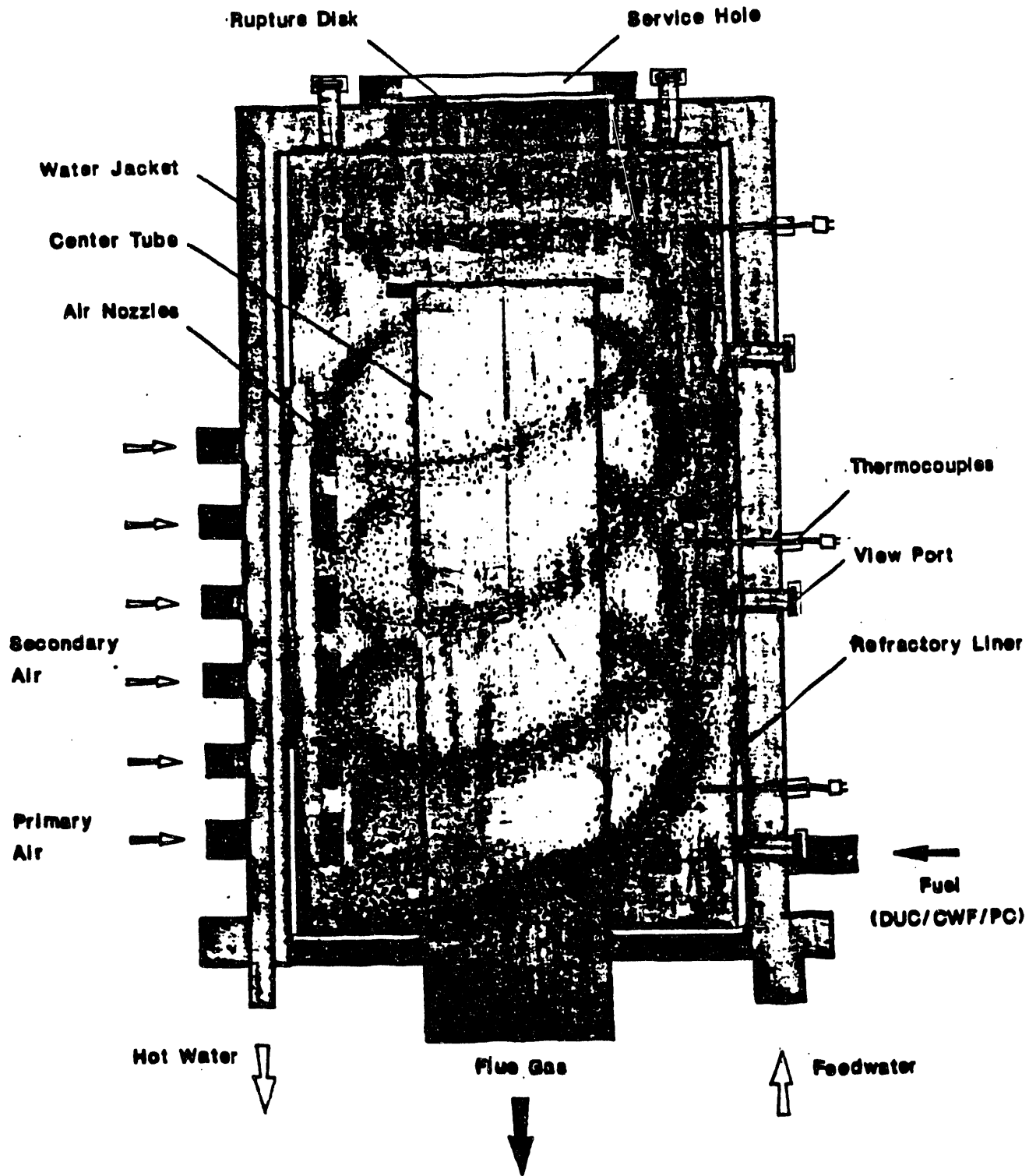


Figure 1.1 Conceptual design of the vortex combustor.

NO_x formation is inherently low and SO_2 , if any, can be effectively controlled by the well established limestone (or lime) injection technique. The pollutant emission of concern from coal firing in VC therefore may be reduced to one of particulate matter removal only.

The benefits of swirl in both non-reactive and reactive flow systems have been recognized for many years [9,10]. Swirl flows occur in a very wide range of applications. In non-reacting flow systems, applications include cyclone separators, spraying machines, jet pumps, etc. In combustion (reacting) systems, the design of strong swirls for the injected air and fuel are extensively adopted as an effective technique for flame stabilization, fuel burnout, and pollution abatement. These applications include industrial furnaces, utility boilers, internal combustion engines, gas turbines, and many heating devices. Swirl flows can be established from a tangential velocity component created by the use of swirling vanes, axial-plus-tangential entry swirl generators, or direct tangential injection of gas into the chamber. Experimental studies show that the swirl can have large-scale effects on gas-particle flow and combustion, such as entrainment and decay; heat and mass transfer; flame size, shape, and stability; and combustion intensity [9].

Two types of conventional swirl combustors are widely used: swirl burners and cyclone combustors. With sufficiently high Reynolds number and swirl number, large toroidal recirculation zones and intense turbulent mixing can be generated in both systems. This toroidal vortex plays an important role in fuel

ignition and flame stabilization since it constitutes a well-mixed zone of heat and chemically active species. Heat, mass, and momentum are then transferred effectively from combustion products to freshly fed fuel and air by the vigorous turbulence that prevails in the vortex region. However, in conventional swirl burners the turbulence is primarily generated close to the internal recirculation boundary and is not effectively utilized for mixing control. The controlled mixing of gas-gas and gas-particle is beneficial for controlling heat generation and dissipation, minimizing pollutant formation, and enhancing flame stability. Furthermore, the strength of swirl and level of mixing in a swirl burner usually decays rapidly along the flow direction, which may hinder the burnout of fuel particles and the overall combustor performance. The conventional cyclone combustor featuring single air-fuel inlet has a strong swirl and good mixing at large radii. It also becomes weakened rapidly toward the core region and along the axial direction. Modifications to the combustor are needed to preserve the rigidity of a strong swirl, to minimize the effects of weak swirl, and to minimize the combustor volume. The center tube of the VC and distributed injection of combustion air warrant the above desired improvement [11]. From the standpoint of gas-particle flow, VC is unique in creating, preserving, and intensifying the swirl and the associated intense gas-gas and gas-particle mixing. From the combustion point of view, VC is unique in its low, non-slagging combustion temperature which is beneficial in pollution abatement and system operation.

Technical Approach

Being a brand new combustion concept and a novel combustion device, no experimental or theoretical data is available pertaining to the design and operation of a VC. The overall technical approach therefore must include parallel efforts of experimental study and theoretical analysis. Experiments should include cold flow measurements of aerodynamics and particle dynamics, CWF atomization and compatibility tests, and combustion tests and improvement of the VCs. Theoretical studies should include refinement of the VC concept and mathematical modeling of the VC processes. Cold flow measurements and mathematical modeling of VC have been successfully completed and the results are reported in [11]. The work reported here is the remaining part of the overall developmental effort. It includes exploratory studies in subscale and preliminary POC VC hot models and systematic combustion tests in a full-scale POC VC.

Figure 1.2 depicts the technical approach adopted for the development and demonstration of a POC VC and for the establishment of the needed technical data base for VC design and operation. Based on cold flow studies accounting for the desired thermal and combustion performances, and energy and mass balances, a preliminary exploratory (PExp) subscale hot model (~0.15 MB/H firing capacity) will be designed and tested. The purpose of this PExp VC is to reduce the VC concept into practice for the first time; achieve on-time ignition and flame stabilization of all the fuels intended for this work (i.e., CWF, DUC and PC); and explore the overall behavior and operational requirements of VC.

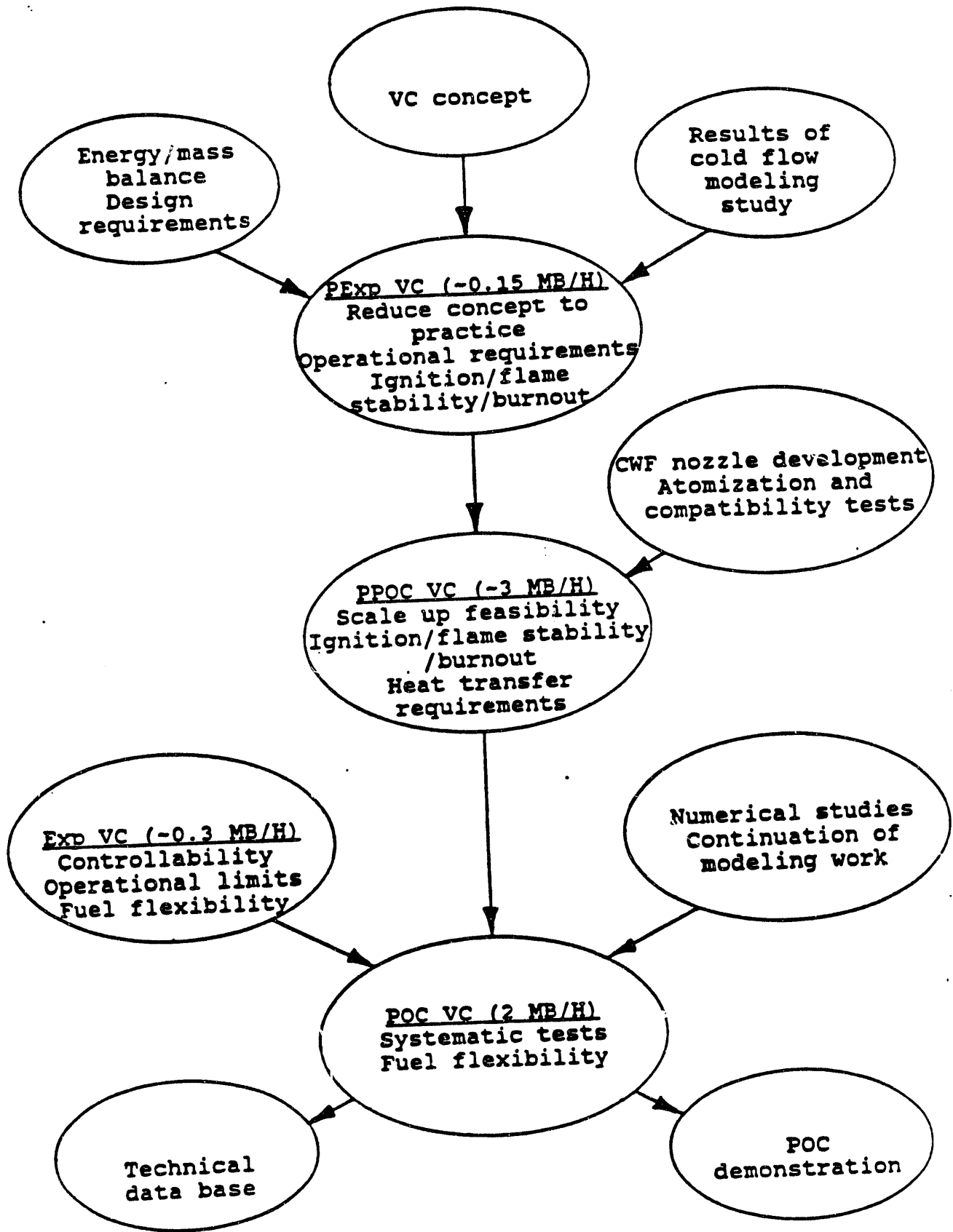


Figure 1.2 Technical approach for the development and demonstration of a POC VC.

The CWF nozzles needed to match the unique VC configuration will be developed. The nozzle atomization and compatibility tests will be conducted. A full-scale preliminary POC (PPOC) VC hot model (~3 MB/H) will be designed and built utilizing the experience and data obtained from the PExp VC. The purpose of this PPOC VC is to study the feasibility of scaling-up, strive again to achieve on-time ignition and flame stabilization of all fuels, exercise and evaluate the role of heat transfer in combustion control, and explore the limits of combustion performance and operational requirements of a full-scale VC.

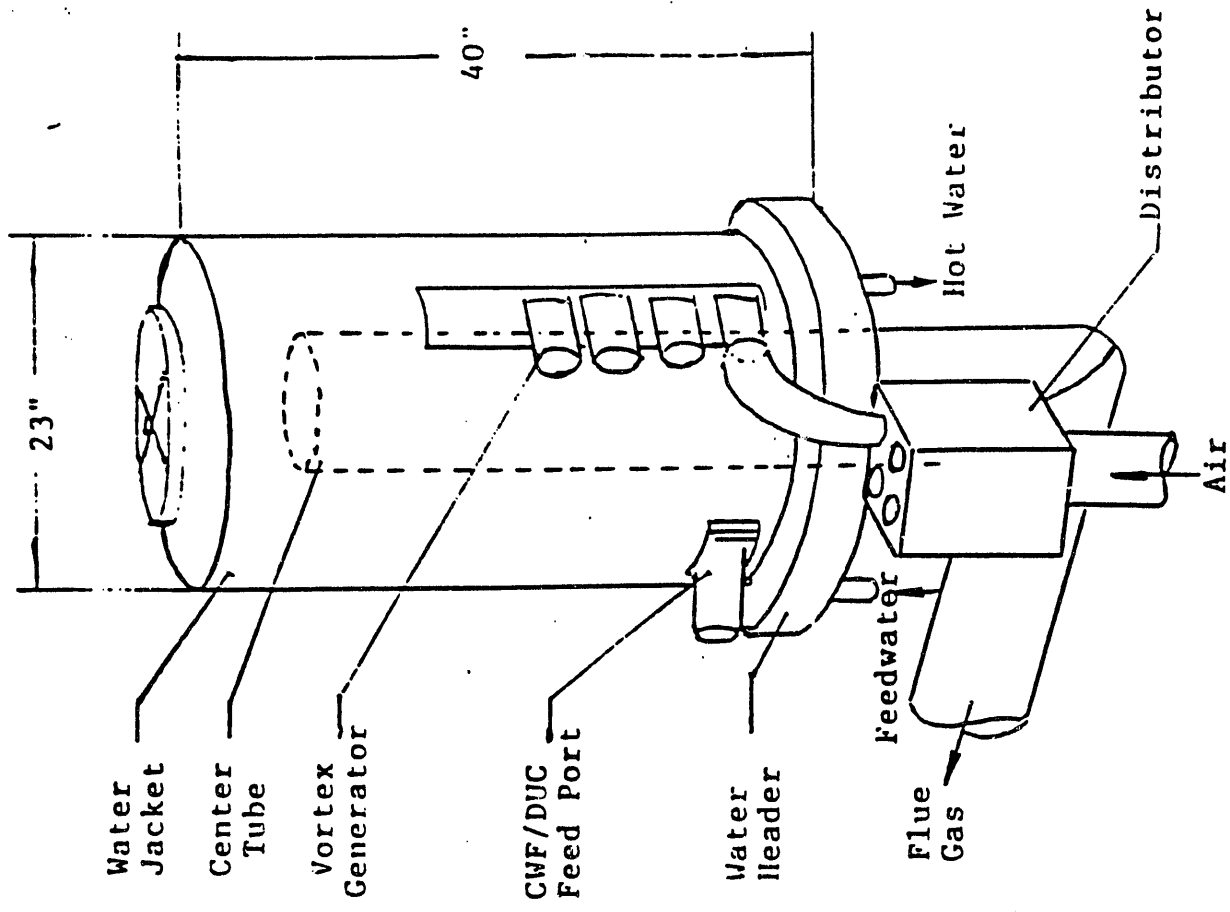
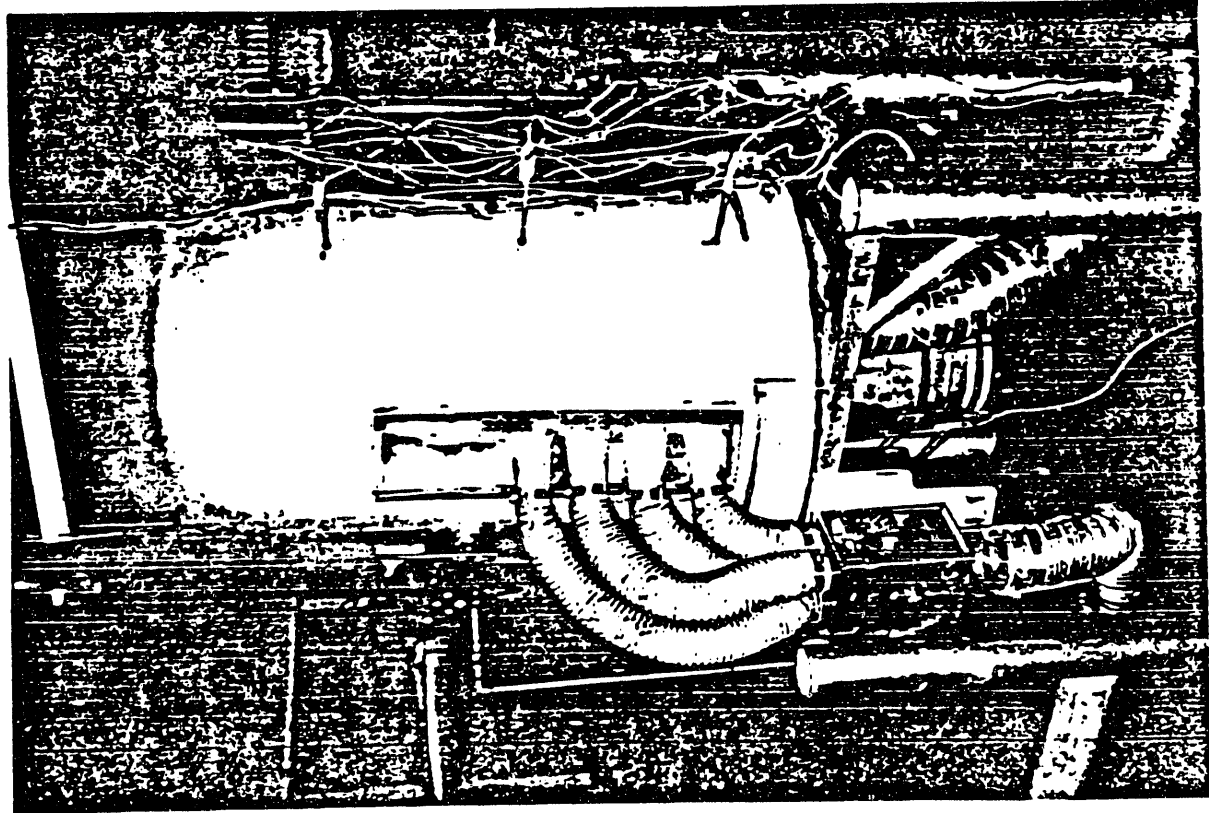
An improved subscale hot model (~0.3 MB/H), the exploratory (Exp) VC, will be built and tested to generate any supplemental information needed for the POC VC design. Provisions of independently controlled secondary air injection and heat removal capabilities will be built into this model to evaluate the controllability of VC performance via vortex generator and heat transfer. The flexibility of VC firing different fuels will also be explored.

With the data and experience obtained from PExp, PPOC, and Exp VCs, a POC VC will be designed and built. Systematic combustion tests of CWF, DUC, and PC will be conducted. Data on thermal, flow, combustion, and pollution performance of the POC VC at full load and partial loads will be collected and analyzed. Modifications will be made as necessary for both simplifying the design and meeting the PRDA's performance requirements. Proof-of-concept tests of coal-fired VC for commercial heating applications will be demonstrated.

In order to explore the detailed characteristics of the VC performance and to help in any possible design modifications, numerical calculations will be pursued simultaneously with the combustion tests of the POC VC. These calculations will be a meaningful continuation of the cold modeling study [11] into practical applications.

Report Organization

This report is divided into six chapters. Chapter 1 discusses the background and objective, the VC concept, and the technical approach of this project. Chapter 2 describes the auxiliary subsystems for VC test models, test fuels, and instrumentation for VC combustion measurements. Chapter 3 describes in detail the design considerations, features, and test results of PExp, PPOC, and Exp VC hot models. The design features of the POC VC are also presented. Chapter 4 presents and discusses the results of systematic combustion tests and performance characteristics of POC VC firing CWF, DUC, and PC. Chapter 5 presents the centralized operational concept and the economic analysis of a commercial-scale VC heating plant. Numerical simulation of the POC VC showing the detailed characteristics of flow, thermal, and combustion performances is also presented in this Chapter. Finally, Chapter 6 presents the achievements and conclusions of this research effort.



Proof-of-Concept Vortex Combustor Hot Model (CUA/NCEL)

CHAPTER 2

AUXILIARY SUBSYSTEMS, INSTRUMENTATION, AND TEST FUELS

In this chapter, the auxiliary subsystems of VC test setup, instrumentation for combustion tests, and properties of test fuels are presented. Figure 2.1 shows a schematic of the overall test setup for full-scale POC and PPOC VC models. The auxiliary subsystems include air supply, water supply, fuel supply, flue gas exhaust, ash collection, and ignition. The fuel supply subsystems are described in Section 2.1 and other auxiliary subsystems in Section 2.2. Figure 2.2 is a schematic diagram of the test setup for subscale Exp and PExp VC models. The instrumentation for flow, temperature, combustion, and pollution measurements and the computer-assisted data acquisition system are discussed in Section 2.3. Section 2.4 discusses the fuels tested in the VC models including CWF, DUC, PC, No.2 heating oil, and propane gas. The performance of CWF nozzles specially developed for the VC tests is also presented.

2.1 Fuel Supply Subsystems

Since the VCs are designed to burn both dry powdered coals (DUC and PC) and their water slurries (CWF), two separate fuel storage, handling, and feeding subsystems were installed for the combustion tests. In order to ensure that CWF can be properly atomized and burned in the VC, a separate CWF atomization test

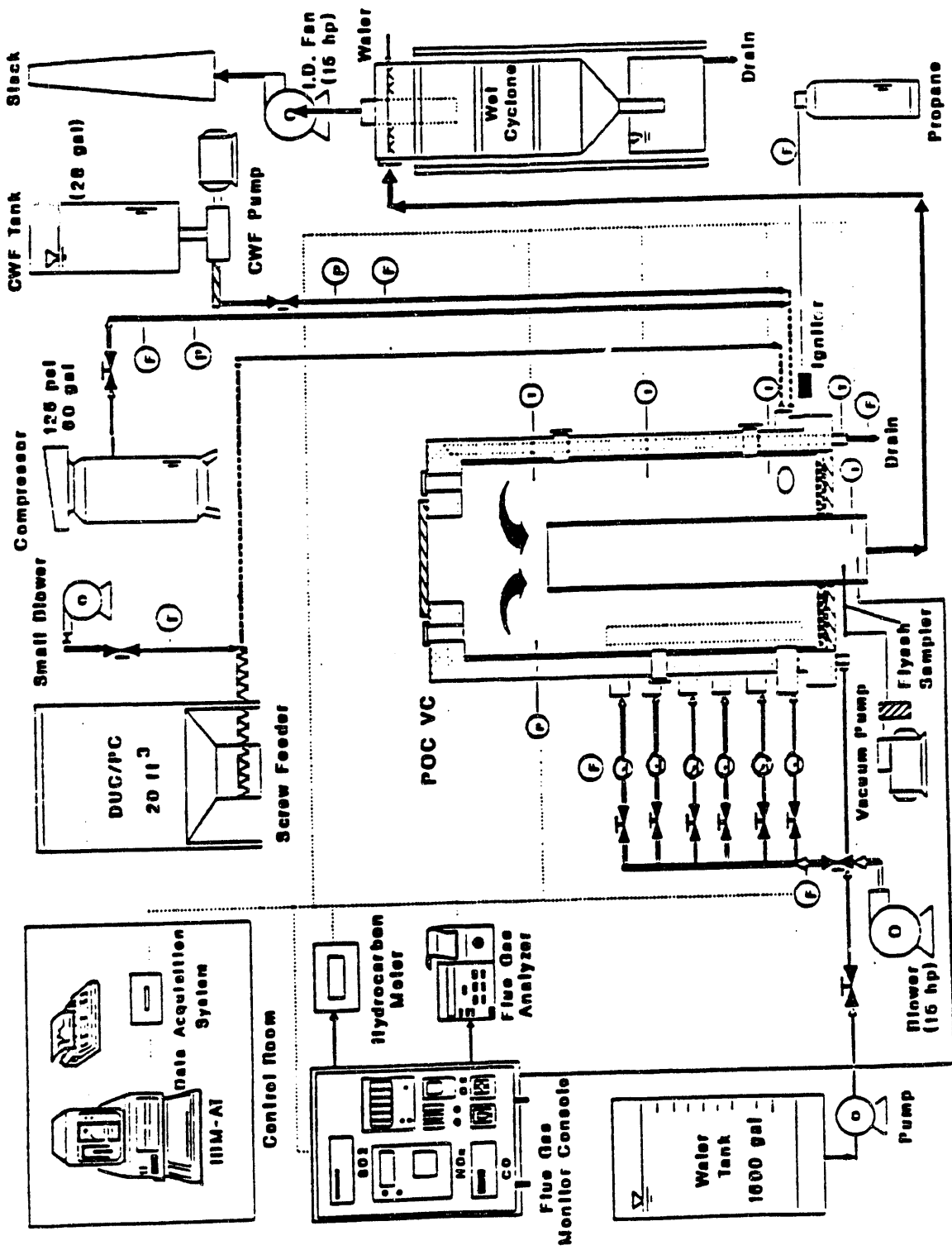


Figure 2.1 Schematic diagram of POC VC test setup.

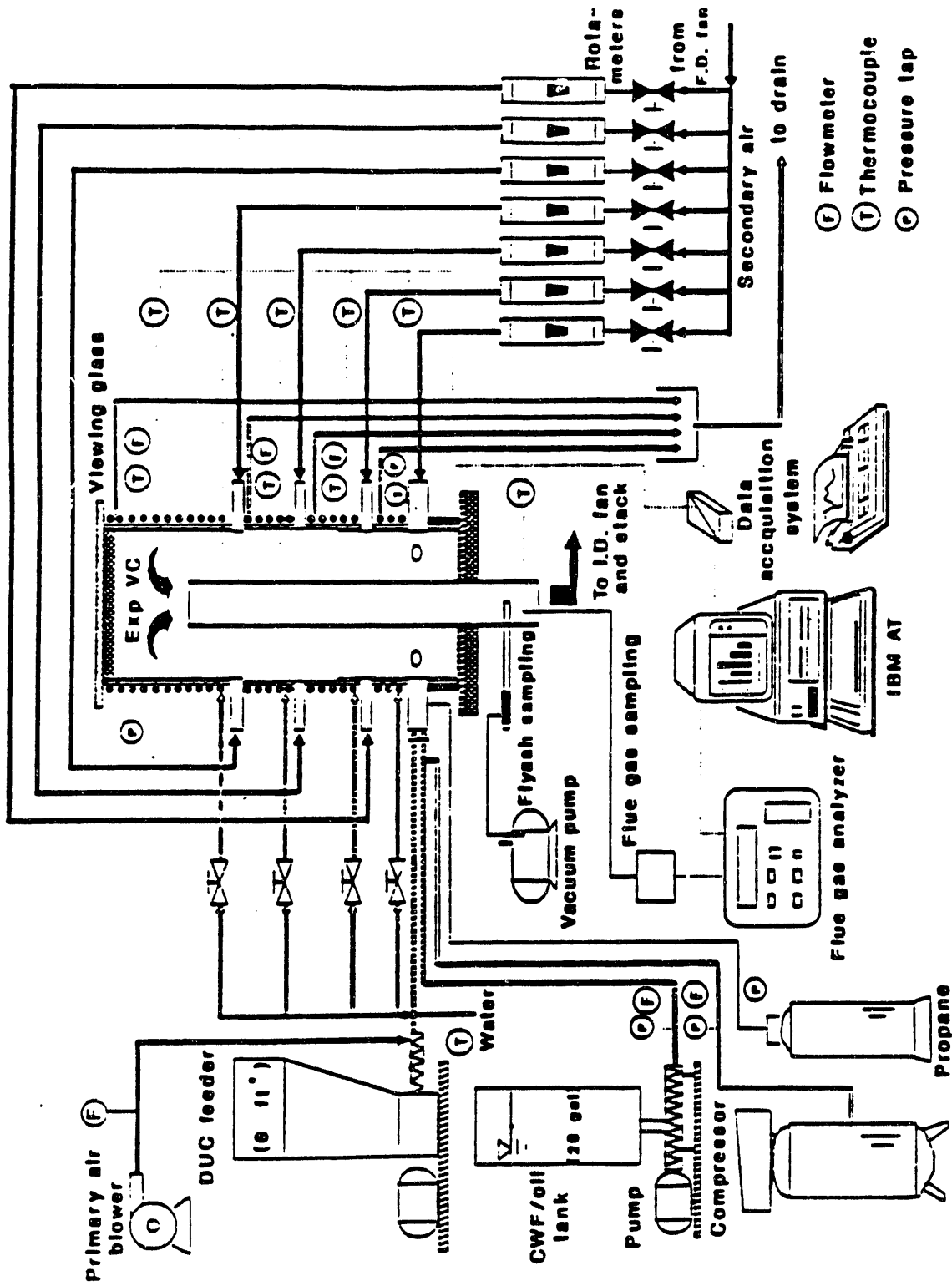


Figure 2.2 Schematic diagram of Exp VC test setup.

system was also built to study and improve the nozzle atomization characteristics.

DUC/PC-Primary Air Supply Subsystem

The dry powdered coal supply subsystem shown in Figure 2.1 is basically a screw feeding and pneumatic conveying system. It consists of a 20-ft³ coal hopper, a Vibra Screw coal feeder with a vibrating bottom, a feed rate control box (0 - 300 lb/hr), a portable high pressure centrifugal blower, conveying pipelines, and feed nozzles. A preset rate of coal is fed by the feeder into the primary air stream at room temperature. A 1-hp blower is used to provide primary air up to 30% of the total combustion air. Coal-air mixture is then injected tangentially into the VC bottom through either one or two feed nozzles. The hopper can hold about 800 pounds of DUC or PC, which is sufficient for 6 hours of continuous testing at 2 MB/H load. When testing CWF, this subsystem is used to supply only the primary air. For PExp and Exp VC model tests, a similar DUC/PC supply system but with a smaller capacity was used, as shown in Figure 2.2.

One of the problems encountered in combustion tests was the fluctuation of coal feed rates at low loads, which often results in unstable ignition and combustion. Several attempts have been made to alleviate this problem. The most effective approach to achieve uniform and steady feeding at low flow rates was to blend the coal with air first in a small mixing chamber. While being constantly stirred, the mixture is injected into the conveying pipeline.

CWF Supply/Atomization Subsystem

As shown in Figure 2.3, the CWF supply/atomization subsystem consists of an air compressor (125 psi, 60 gallons), a storage tank (28 gallons) with a 30 mesh metal screen filter at the top, two progressive cavity pumps, piping and gauges for two independent supply lines, recirculation/back flushing loops, CWF nozzles, and an atomization test chamber. The temperature and pressure of CWF are measured and recorded during the tests. The rotating speed of CWF pumps can be continuously varied to achieve the desired feed rates up to 1.2 gpm (or 580 lb/hr). The recirculation loop helps stabilize CWF feed rate at low loads and stir the CWF in the tank to prevent sedimentation. Back flushing of the pipeline for cleaning is achieved by running water through the drain to the system. During start-up, it was found very important to first run the system with water to moisten all internal surfaces before switching to CWF operation. High pressure atomizing air is connected to CWF nozzles through a pressure regulator, a rotary flowmeter, and a steel-reinforced flexible hose.

The atomization test chamber is a 29"x29"x28" enclosure made of Plexiglas to facilitate spray visualization and measurements. In CWF atomization tests, the spray cone angle, droplet size and spatial distributions, CWF flow rate distribution, and other atomization characteristics can be either observed or measured in this test chamber or via a camera-assisted microscopic examination scheme [12,13].

The atomization quality of CWF nozzle and flow rate of each supply line can be independently adjusted, a feature essential

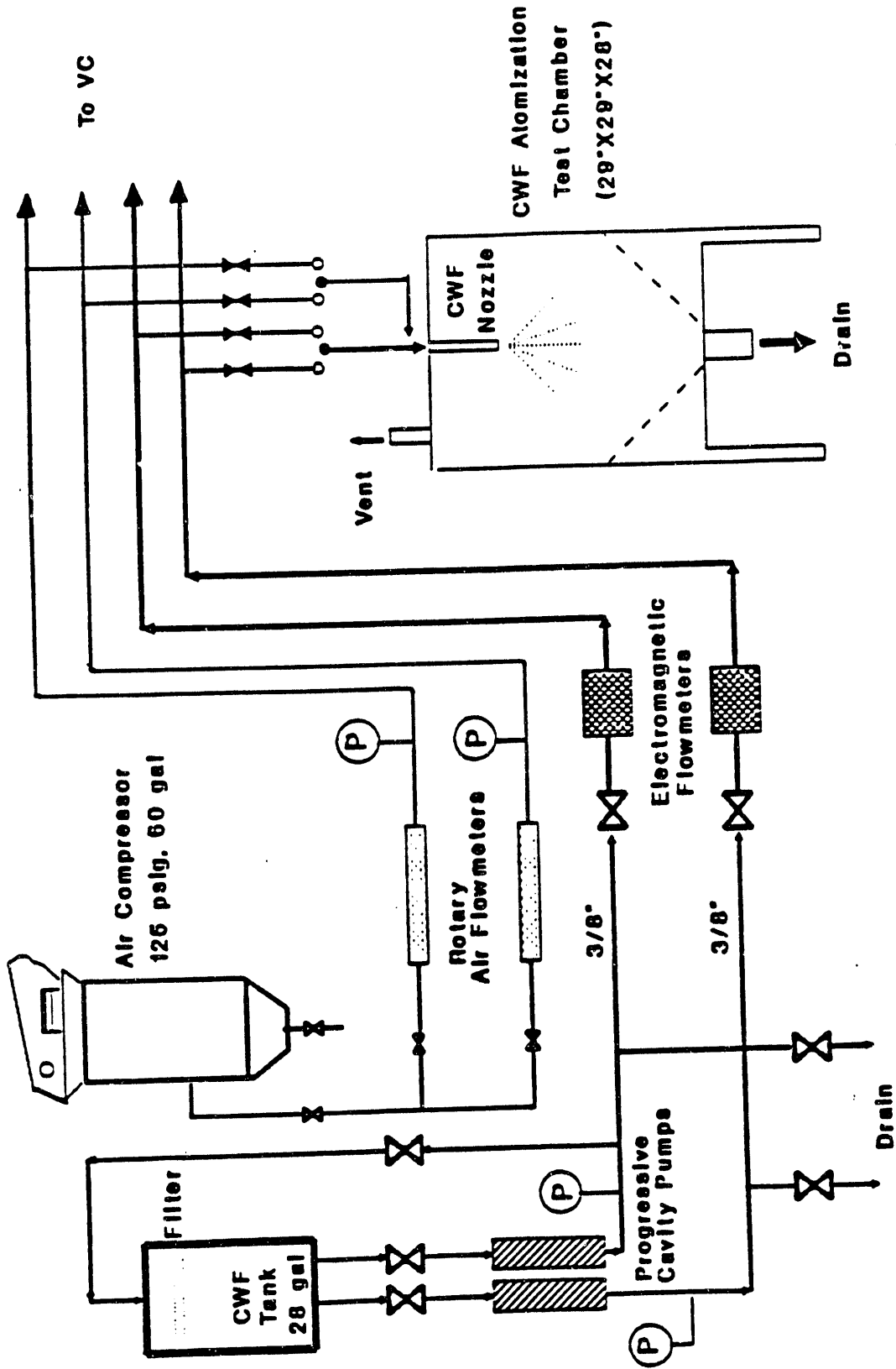


Figure 2.3 CWF supply subsystem and atomization test chamber.

for achieving stable CWF combustion, particularly at high firing rates. The same CWF supply line and atomization test system were used for PExp and Exp VC models.

2.2 Other Auxiliary Subsystems

Air Supply Subsystem

The primary air for each VC model was supplied by separate small blowers, as shown in Figures 2.1 and 2.2. The secondary air was supplied by a large high pressure blower (15 hp, 1,300 scfm, 47" of water static head). The blower (F.D. fan) is connected to the VC models by several 2" PVC pipes via a 4" or 6" header pipe. The flow rates are conveniently controlled by 7 valves at strategic locations and monitored by 6 miniature Pitot tube type flowmeters. A photograph of the POC VC and its various subsystems is shown in Figure 2.4.

Water Supply Subsystem

The water circulation subsystem for removing the excess heat from combustion consists of a 1,600-gallon water tank, a pump, and make-up water connecting pipeline. During combustion tests, water at ambient temperature is pumped into the water jacket or cooling tubes of the test models. Hot water or low quality steam is generated, measured, and finally discharged into the sewage system. The flow rate and inlet and outlet temperatures are monitored and recorded for combustor operation adjustments and later for heat and mass balance calculations.

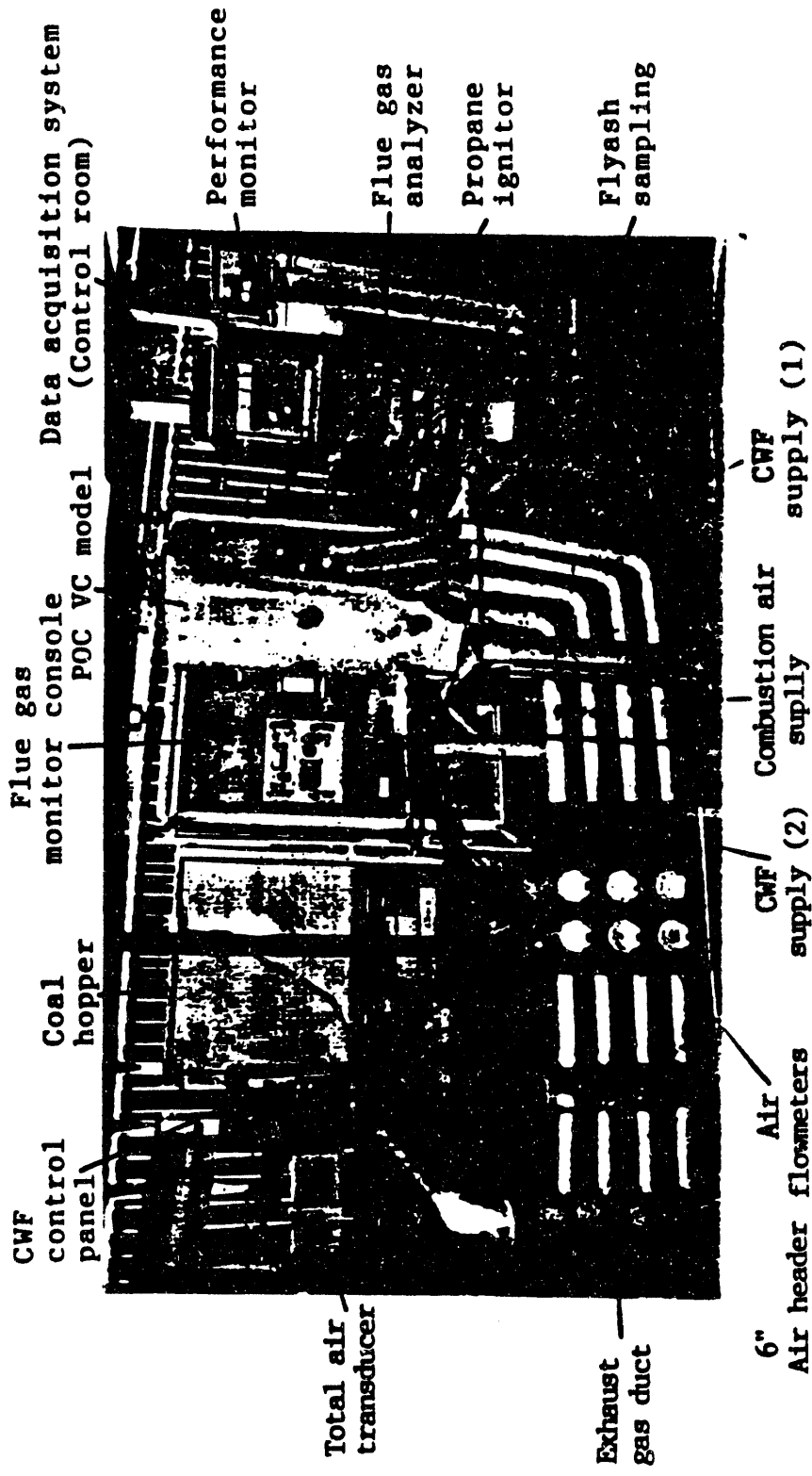


Figure 2.4 Pictorial view of test facility of POC VC model

Flue Gas Exhaust Subsystem

The flue gas exhaust subsystem shown in Figures 2.1 and 2.5 is specially designed and installed for controlling particulate emissions. It consists of a cyclone dust collector, a water-spray flue gas cooler, an I.D. fan, a 25' stack, and 14" connecting ducts [14]. The 5' dia. x 15' tall stainless steel cyclone separator is also equipped with an internal water spray to minimize emission of particulate matter. The particulate concentration discharged into the atmosphere was found in most tests to be around 250 mg/Nm³. The flue gas cooler is a direct contact heat exchanger using water spray to reduce the flue gas temperature and volume to protect the I.D. fan and exhaust system. The dampers and cold fresh air inlets were used to adjust the draft in the combustor. This exhaust gas subsystem and the performance of VC models have been reviewed by the environmental control officers of the Washington DC Government. A certificate on environmental control was granted permitting us to conduct coal combustion tests.

Ignition Subsystem

Propane gas was used as the starting fuel. As schematically shown in Figures 2.1 and 2.2, the ignition subsystem consists of two 100 lb propane gas cylinders, regulators, miniature flowmeters, propane burners, an electric spark igniter, and connecting tubing. Propane was first ignited by the spark igniter during a cold start. Coal is injected immediately after the propane is ignited. Both fuels are fired simultaneously for about 10 to 15 minutes to achieve a stable combustion. The propane is then cut

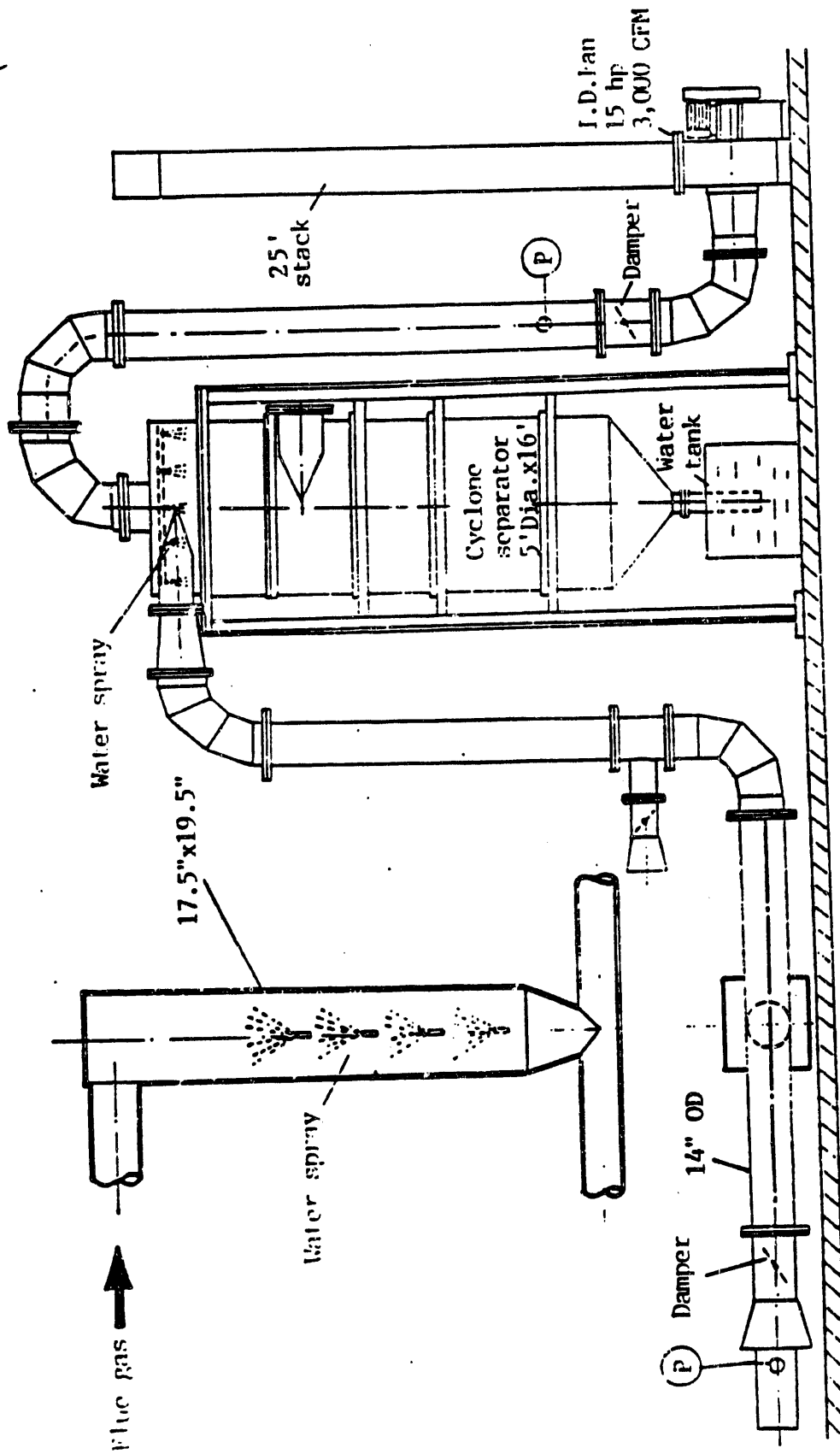


Figure 2.5. Flue gas cleaning subsystem.

off and self-sustained combustion is usually established at this point.

2.3 Instrumentation

A computer-assisted data acquisition system has been developed to accelerate the data taking process and to eliminate human errors. Four major types of instrumentation are used for measurements in combustion tests: temperature, flow, combustion, and pollutant emissions. These are summarized in Table 2.1 and a schematic of the overall arrangement is shown in Figure 2.6.

Temperature Measurements and Data Acquisition System

Both K- and R-type thermocouples are used for temperature measurements. They are connected to an IBM AT compatible computer via a multiplexer, as shown in Figure 2.6. The computer-assisted data acquisition system includes two A/D interface boards with a supporting software package (Labtech SWDLTN-2) [15], and data printout systems: color plotter and LaserJet printer. This system has a 38-channel capability for data collection, reduction, and display. In most combustion tests, only 8 channels were enabled: 5 channels for temperature measurements and monitoring, and one each for total air flow rate, CWF flow rate, and oxygen or unburned combustible gas concentrations. In PPOC VC tests, a total of 28 thermocouples were installed and linked with the data acquisition system for monitoring various temperatures in the test system. Real time temperature data can be displayed on a computer monitor, printed, and stored on floppy

Table 2.1 Instruments used for measurements.

Parameter	Type	Manufacturer, Model No.	Range (error)
Temperature, °F	Thermocouples K-, R-type	Omega Engineering	0-2375 (±0.3%)
Flow			
Air flowrate, cfm	Pitot tube/Kurz flow transducer	Omega/Kurz PX714	0-400 (±2 %)
Excess air, %	Gas analyzer	Energy Efficiency Systems, Enerac 2000	0-80 (±4 %)
CWF flow rate, gpm	Electromagnetic	Taylor Instrument	0-0.75 (±2 %)
Cooling water flowrate, lb/hr	Flowmeter		0-1103 (±5 %)
DUC/PC feed rate, lb/hr	Control box	AccuRate 600	0-300 (±2 %)
Combustion/Emissions			
CO, ppm	Infrared absorption	Beckman model 856	0-2500 (±6 %)
NO _x , ppm	Chemiluminescent	Thermo Electron model 10A	0-1500 (±4 %)
SO ₂ , ppm	Ultraviolet absorption	Western Research model 721A	0-500 (±3 %)
HC, ppm	Combustible gas analyzer	United Tech. TLV/FM Sniffer	0-1000 (±2 %)
O ₂ , ppm	Micro-fuel cell	Teledyne model 326A	0-25 (±1 %)
Carbon residue in ash, %	Isokinetic probe and muffle oven	Fisher Scientific model 2000	0-100% (±3 %)

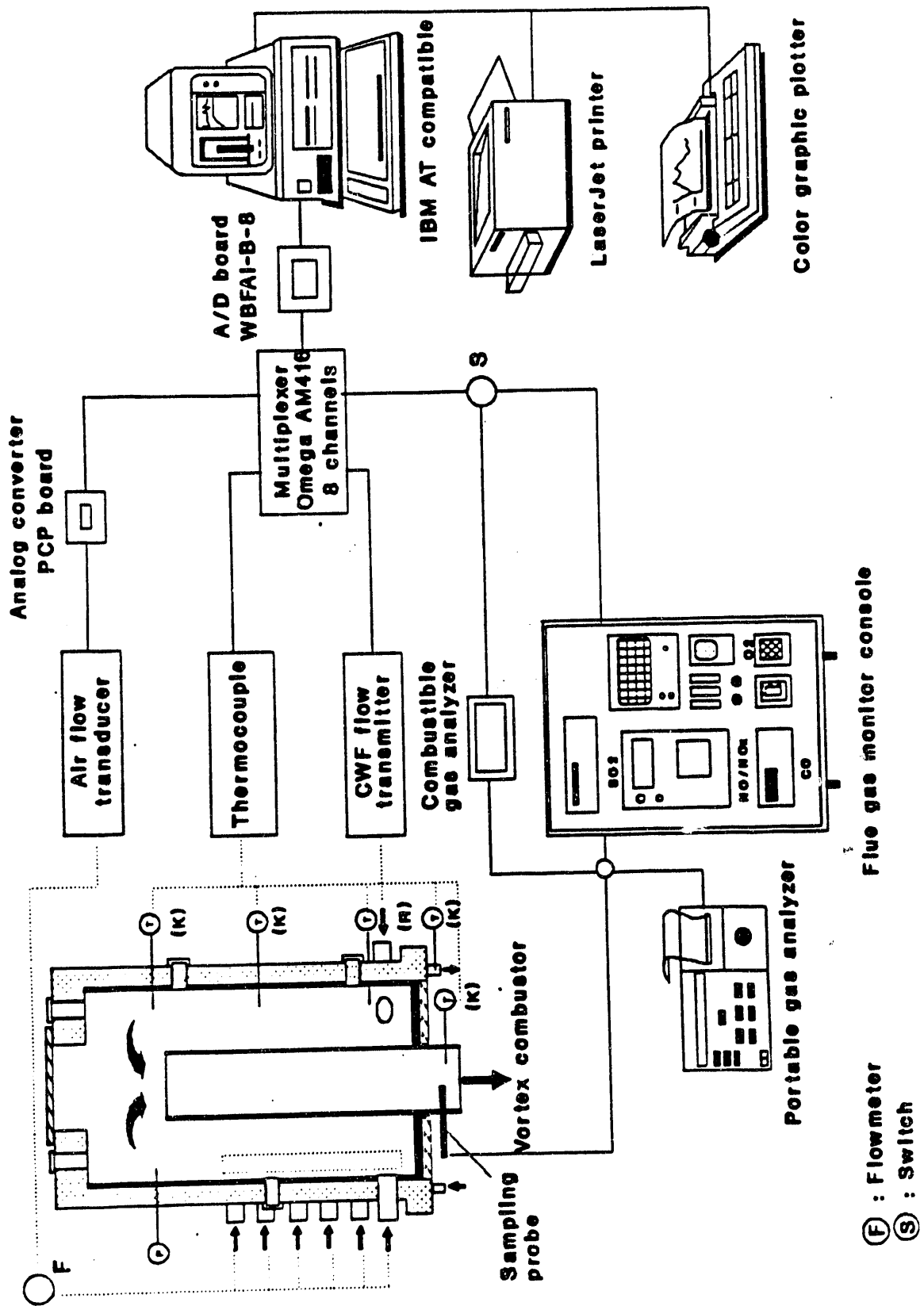


Figure 2.6 Schematic diagram of the computer-assisted data acquisition system.

disks for later processing. The errors of temperature measurements are about $\pm 0.3\%$ of the readings.

Flow Measurements

A Kurz air flow transducer with a digital readout was used to measure the total flow rate of secondary air to the VC test model. The flow rates of all air nozzles are each measured separately by use of Pitot tubes. A voltage-to-current analog converter (PCP board model 132 4-20 mA) is connected between the Kurz transducer and the interface board (WBFAI-B-8) for recording air flow rate data into the computer system and display on computer monitor and the Kurz digital readout, as shown in Figure 2.6. The measurement errors of air flow rates are $\pm 2\%$ of the readings.

Dry powdered coal, either DUC or PC, is fed by the AccuRate screw feeder with a feed rate control box into a pneumatic pipeline. The primary air from a centrifugal blower carries and injects the coal into the VC model through feed nozzles. The feed rate is determined by the pre-calibrated rotating speed of the screw of the feeder. The feed rate data from the control box is linked to the data acquisition system for display and automatic recording. (DUC and PC require different conversion factors for feed rates.) The measurement errors are $\pm 2\%$ in the range of 0 - 300 lb/hr.

The flow rate of CWF was measured by an electromagnetic flowmeter with an operating range of 0.075 - 0.75 gpm. A Taylor Instrument 1100 TB Mag-pipe transmitter was used to amplify the AC signals generated from the sensing head of the flowmeter and

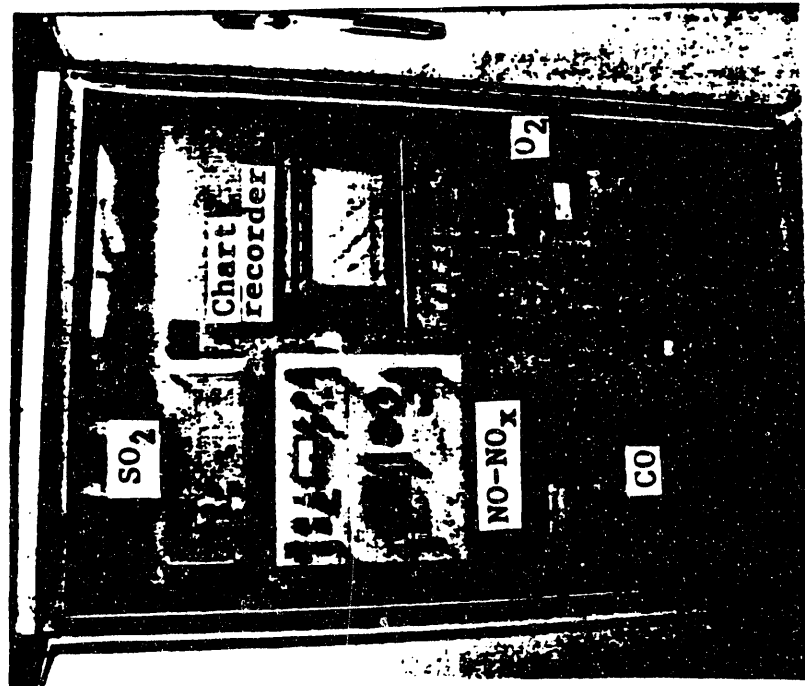
convert them to a 4 to 20 mA DC output which is directly proportional to the CWF flow rate. The converted signals are forwarded to the data acquisition system for display and recording. The measurement errors are $\pm 2\%$ of the readings.

The atomization quality of CWF spray was observed in the test chamber as discussed in Section 2.1. The droplet size distribution was examined by a microscope and analyzed statistically. CWF and compressed air for atomization were measured by various pressure gauges and flowmeters. The flow rate of feedwater to the VC model was monitored by a flowmeter and frequently checked by a stop watch/graduated container arrangement. The pressures in the combustor and auxiliary components were monitored by various manometers and gauges.

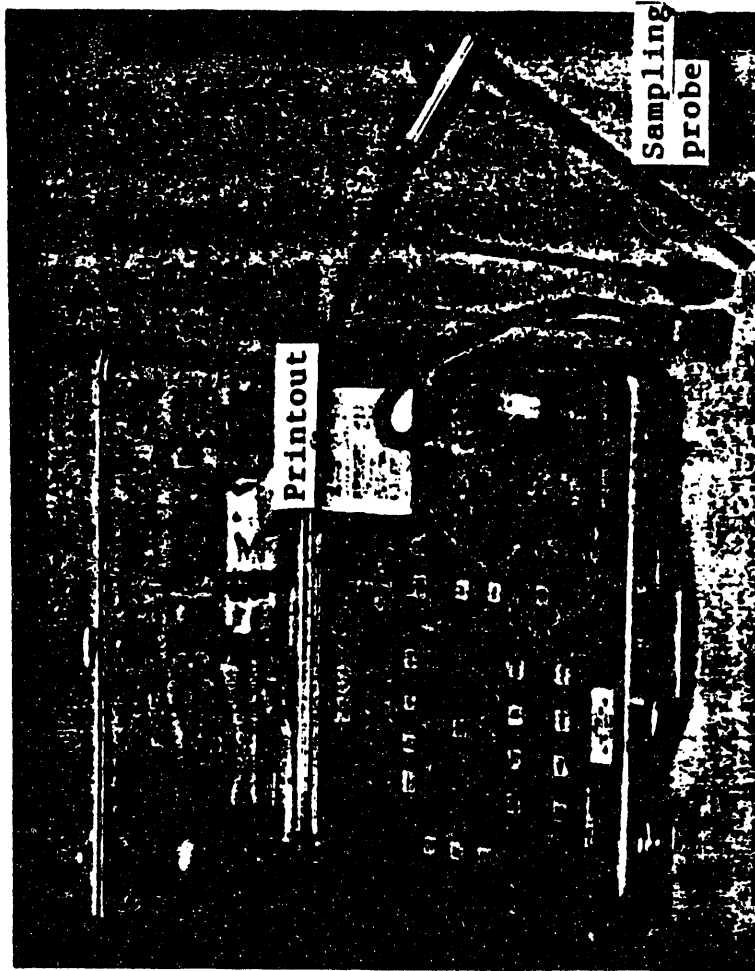
Flue Gas Composition Measurements

A KVB continuous flue gas monitor console was used to measure the composition of flue gases. This monitor console has an automatic self-calibrating feature. It can sample, condition, and measure oxides of nitrogen, carbon monoxide, sulfur dioxide, and oxygen on a continuous basis [16]. The sample analysis system consists of four analyzers as listed in Table 2.1. This system will correct for oxygen variation in flue gas on NO_x/NO and SO_2 measurements. In addition to the flue gas monitor console, a portable gas analyzer (ENERAC 2000) [17] was also used to cross check the flue gas composition readings. These flue gas measuring systems are shown in Figure 2.7.

Measurements of combustion products by the KVB console start at the sampling probe which is inserted into the outlet of the



(a) Flue gas monitor console



(b) ENERAC 2000 flue gas analyzer

Figure 2.7 Flue gas measuring systems.

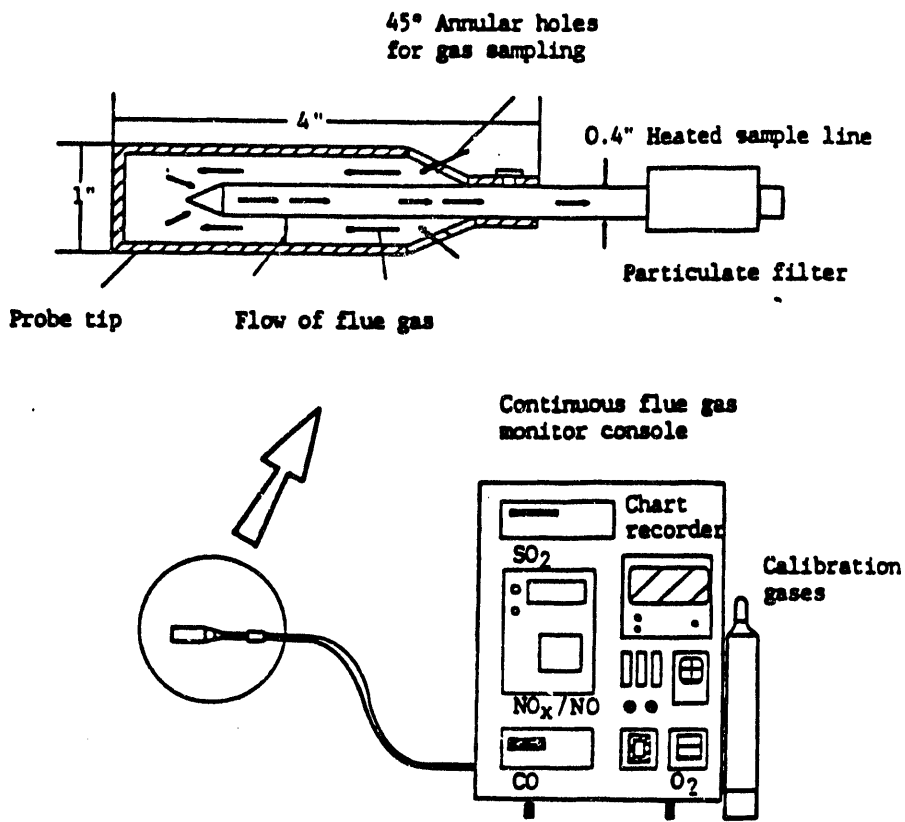
center exhaust tube of the VC. The construction of this probe is shown in Figure 2.8(a). The sampled flue gases are transported via a heated sample line to the console. This line maintains the gas sample at approximately 170°F to prevent water condensation and further reactions in the sample line. Inside the console, the hot sample gas is first fast dried by running it through a refrigerator to remove the condensable moisture and then a drying agent and a filter to rid it of any water vapor and particles. This conditioned dry gas sample is then connected to the automated valving system and distributed for the following analyses:

1. Carbon Monoxide (CO)

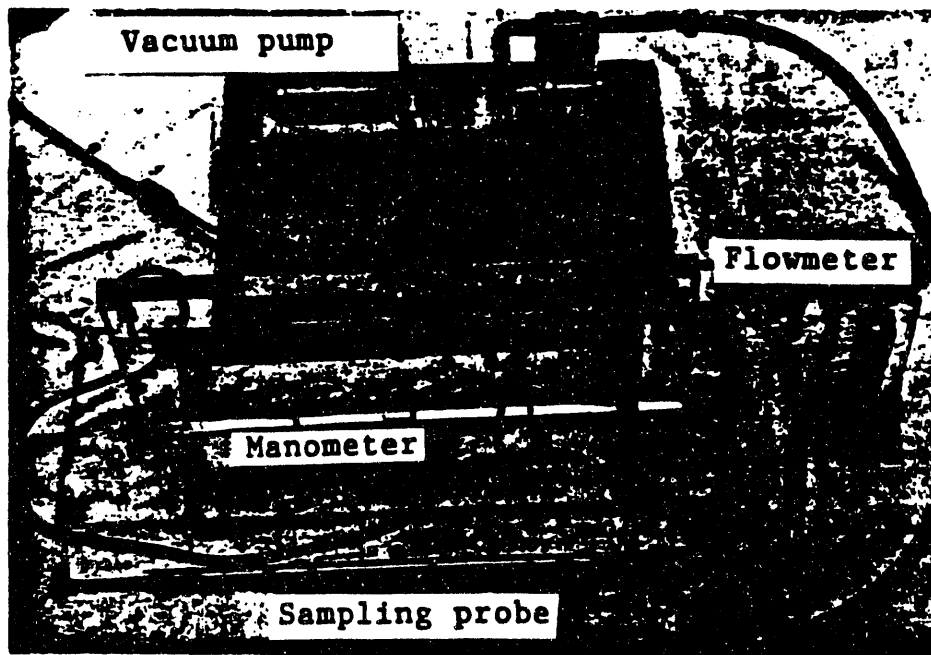
Beckman model 865 analyzer was used to determine the concentration of CO, which is based on a differential measurement of the absorption of infrared energy [16]. Two equal-energy infrared beams are directed through two optical cells: a flow through sample cell and a sealed reference cell. Solid state electronic circuitry continuously measures the difference between the amount of infrared energy absorbed in the two cells. This difference indicates the concentration of CO in the flue gas through the sample cell. The measurement range of CO is 0 - 2,500 ppm with measurement errors of ±6% of the readings.

2. Oxides of Nitrogen (NO_x)

Thermo Electron model 10A analyzer was used to measure the concentrations of both nitric oxide (NO) and total oxides of nitrogen NO_x (i.e., NO + NO₂) in the sampled flue gas. This instrument utilizes chemiluminescence principle and can continuously measure NO and NO_x in eight linear, full-scale ranges from



(a) Exhaust gas sampler.



(b) Flyash sampler.

Figure 2.8 Exhaust gas/flyash sampling systems.

2.5 to 10,000 ppm. The measurement error is $\pm 4\%$ of the readings [18].

3. Sulfur dioxide (SO_2)

A Western Research model 721A analyzer was used to provide continuous analysis of SO_2 . It is based on ultraviolet absorption. The measurement range of SO_2 is 0 - 500 ppm with measurement errors of $\pm 4\%$ of the readings [19].

4. Oxygen (O_2)

The Teledyne model 326A analyzer uses a micro-fuel cell to measure concentration of O_2 . Oxygen in the flue gas is consumed by the cell which produces a micro-ampere current [16]. This signal is amplified by a solid-state IC amplifier which can either drive a high impedance chart recorder or interface with the data acquisition system as shown in Figure 2.6. The measurement range of O_2 is 0 to 25 % with $\pm 1\%$ measurement error.

Carbon Residue in Flyash

The flyash sampling system shown in Figure 2.8(b) was used to extract representative flyash samples from the flue gas to determine their carbon contents for combustion efficiency calculations. It is composed of an isokinetic probe, a vacuum pump, a rotary flowmeter for measuring the sampling rate, and an inclined manometer to monitor the isokinetic condition. The flyash sampling point is located at the end of the center exhaust tube where the most representative flyash sample can be drawn. The collected flyash is dried first at about 226°F in a Fisher Scientific model 510 Isotemp oven for one hour and the mass measured

by a digital balance. The dried flyash is then heated again in a Fisher Scientific model 2000 muffle oven at 1,830°F for 3 hours. The weight loss of flyash sample in the oven represents the unburned combustible residues in the ash (basically carbon), and is used to determine the combustion efficiency. The measurement errors are estimated to be $\pm 3\%$.

Unburned Combustible Gases

The amount of unburned volatiles and CO in flue gases was measured by a TLV Sniffer combustible gas analyzer. This instrument has an overall detecting sensitivity range up to 10,000 ppm. It has a monitoring system providing an audible note of warning in response to excessive negative drift in signals and other malfunctions. The analog signal output of 0 - 100 mV is connected to the computer-assisted data acquisition system as shown in Figure 2.6. Typical results of the combustible gas concentrations are about 500 ppm during DUC tests and 120 to 200 ppm during CWF tests. This low level of unburned combustible gases does not noticeably affect our combustion efficiency calculations. It may give indications of the extent of gas-gas and gas-particle mixing in the combustor, however. The instrument error is $\pm 2\%$ of the readings.

2.4 Test Fuels and CWF Atomization Tests

One of the potential advantages of the VC concept is that different fuels (types, properties, and sizes) may be burned in it with high combustion efficiency by only adjusting the operat-

ing conditions rather than the hardware or the design. To demonstrate this important feature of VC, five types of fuels (propane, No. 2 fuel oil, CWF, DUC, and PC) have been tested. It should be noted here that when burning heating oil, the same CWF supply/atomization subsystem could be used without any operation and compatibility problems.

Fuel Properties

DUC, PC, and CWF used for VC combustion tests are all prepared from the same parent coal from Upper Elkhorn, West Virginia (I.D. No.: UE3-191-PCO-E). It is a premium grade, deep-cleaned coal with ash content less than 2% and sulfur content less than 0.7%. Analyses of the fuels used are summarized in Table 2.2.

Fast sedimentation of CWF was observed in the shipping containers, CWF storage tank, and supply pipeline. An effort was made to determine the sedimentation rate. CWF was filled to 4" high in a glass beaker and let stand still at room temperature. A 0.2" sediment layer was measured in a 24-hour period which corresponds to a sedimentation rate of 5% per day. Impurities and large coal particles were also found in CWF, which intermittently blocked the nozzles and interrupted the tests until extensive screening provisions were installed in the supply system.

CWF Nozzles and Atomization Tests

The atomization quality of a CWF nozzle directly affects the ignitability, flame stability, and combustion efficiency of CWF [20,21]. Ideally, the droplets in a CWF spray should be

Table 2.2 Typical analyses of DUC, PC, and CWF used in combustion tests.

PROPERTIES OF PARENT COAL			
I.D. #: UE3-191-PCO-E		Bed: West Virginia Upper Elkhorn #3	
<u>Proximate Analysis (% wt):</u>		<u>Ultimate Analysis (% wt):</u>	
Moisture	0.72 %	Carbon	86.83 %
Volatile Matter	34.80 %	Hydrogen	5.14 %
Fixed Carbon	63.00 %	Oxygen	3.64 %
Ash	1.48 %	Nitrogen	1.54 %
Heating Value	14,756 Btu/lb	Sulfur	0.63 %
		Ash/Moisture	2.22 %
DUC SIZE DISTRIBUTION		PC SIZE DISTRIBUTION	
Mean Particle Dia. (μm)	11.5	Mean Particle Dia. (μm)	40
% < 100 mesh (149 μm)	100	% < 100 mesh (149 μm)	99.7
% < 400 mesh (38 μm)	98	% < 200 mesh (75 μm)	86.9
CWF PROPERTIES		CWF SIZE DISTRIBUTION	
Solid Loading, % wt	65-67	Mean Parent Coal Size	30 μm
Viscosity, cp@100/s	<1,000/110	Top Coal Size	99% < 149 μm
Specific Gravity @ 60 °F	1.2	SMD of Droplets	106 μm
Heating Value, Btu/lb	9,930	Average Droplet Size	75 μm

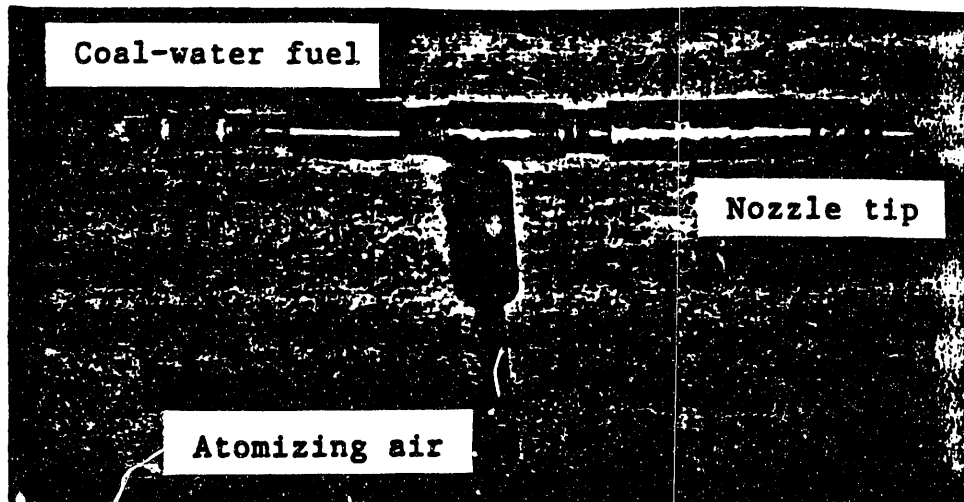
sufficiently fine and have a maximum specific surface area for rapid evaporation and devolatilization [12]. Equally important is that the droplets must be properly dispersed in the ignition zone to ensure intimate fuel-oxygen mixing for complete combustion [22]. Furthermore, the shape and spatial distribution of the spray must fit the geometric confinement of the combustor to warrant high and uniform combustion intensity and to minimize impingement and deposition on solid surfaces [23]. It must be pointed out that the unique configuration of the VC posed a great challenge to the CWF nozzle development. Based on the above considerations, we have developed two types of air-assisted CWF nozzles for VC applications:

Type A: 20 lb/hr, internal mixing (Figure 2.9(a));
Type B: 250 lb/hr, internal-external mixing (Figure 2.9(b)).

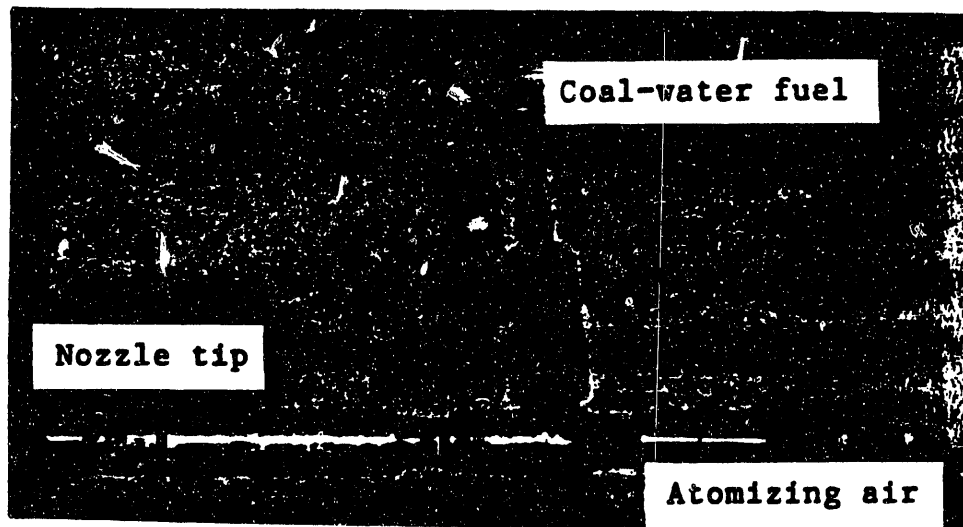
Type A nozzles are for exploratory tests in subscale VC models. Type B nozzles are for tests in full scale VC models. The design of both nozzles incorporates the feature of low CWF velocity and pressure to minimize nozzle tip erosion. Because of the geometric constraint of the combustion space in a VC, CWF nozzles have been designed with small cone angles to minimize spray impingement on adjacent combustor walls. A typical pattern of CWF spray from Type A nozzles (32° cone angle) is shown in Figure 2.9(c).

CWF atomization tests with both Types A and B nozzles were conducted in the atomization test chamber as explained in Section 2.1. The atomizing air was controlled by a pressure regulator and a bypass loop. The CWF flow rate was controlled by the rotating speed of the pump and a regulating valve. Typical test results at room temperature are summarized in Table 2.3.

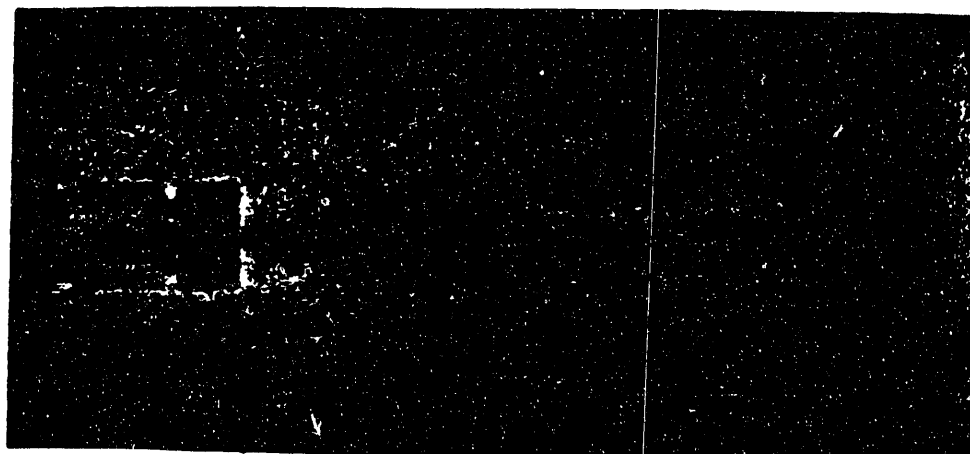
Atomization quality is the key to success of CWF combustion. Fine and evenly distributed droplets are critical for stable ignition and complete burnout. The flame is also affected by the droplet size because of ignition delay due to moisture evaporation. Experience indicates that the atomization quality of a nozzle is primarily governed by air/CWF mass flow ratio. In our case this ratio is kept between 0.15 and 0.2. Good atomization quality was achieved with D_{01} (average or arithmetic mean droplet diameter) ranging from 70 to 110 μm and D_{23} (Sauter mean diame-



(a) Type A nozzle (20 lb/H)



(b) Type B nozzle (250 lb/H)



(c) CWF spray

Figure 2.9 CWF nozzles and spray.

Table 2.3 Typical results of CWF nozzle tests.

Parameter	Type A nozzle		Type B nozzle	
CWF flow rate, lb/hr	25	60	132	200
CWF pump pressure, psi	40	90	45	85
CWF pressure at nozzle inlet, psi	28	75	28	70
Atomizing air pressure at nozzle inlet, psi	20	75	30	74
Atomizing air flow rate, lb/hr	5.2	11	24	30
Air/CWF ratio, %	20	18	18	15
CWF temperature, °F	68	70	68	68
Spray cone angle, deg	30	36	32	32
Average droplet size D_{01} , μm	90	105	75	95
Sauter mean diameter D_{23} , μm	98	165	106	140

ter) ranging from 90 to 170 μm . A typical droplet size distribution of Type B nozzle is shown in Figure 2.10. The distinct CWF spatial distributions of Type A and Type B nozzles may be seen in Figure 2.11, where the flow rate fractions of CWF are plotted against the normalized radius (r/L). Due to high swirling jet in atomization, Type A nozzle spray exhibits a peak at $r/L = 0.16$, and is relatively hollow in the core region. This distribution pattern disperses more uniformly in space, which is favorable for CWF ignition. However, the high concentration at large radii may cause CWF spray impingement. Test results showed that deposition of undried CWF droplets, if any, did not cause problems in stable and continuous operation of our subscale VC models. Type B nozzle spray has a relatively flat spatial dis-

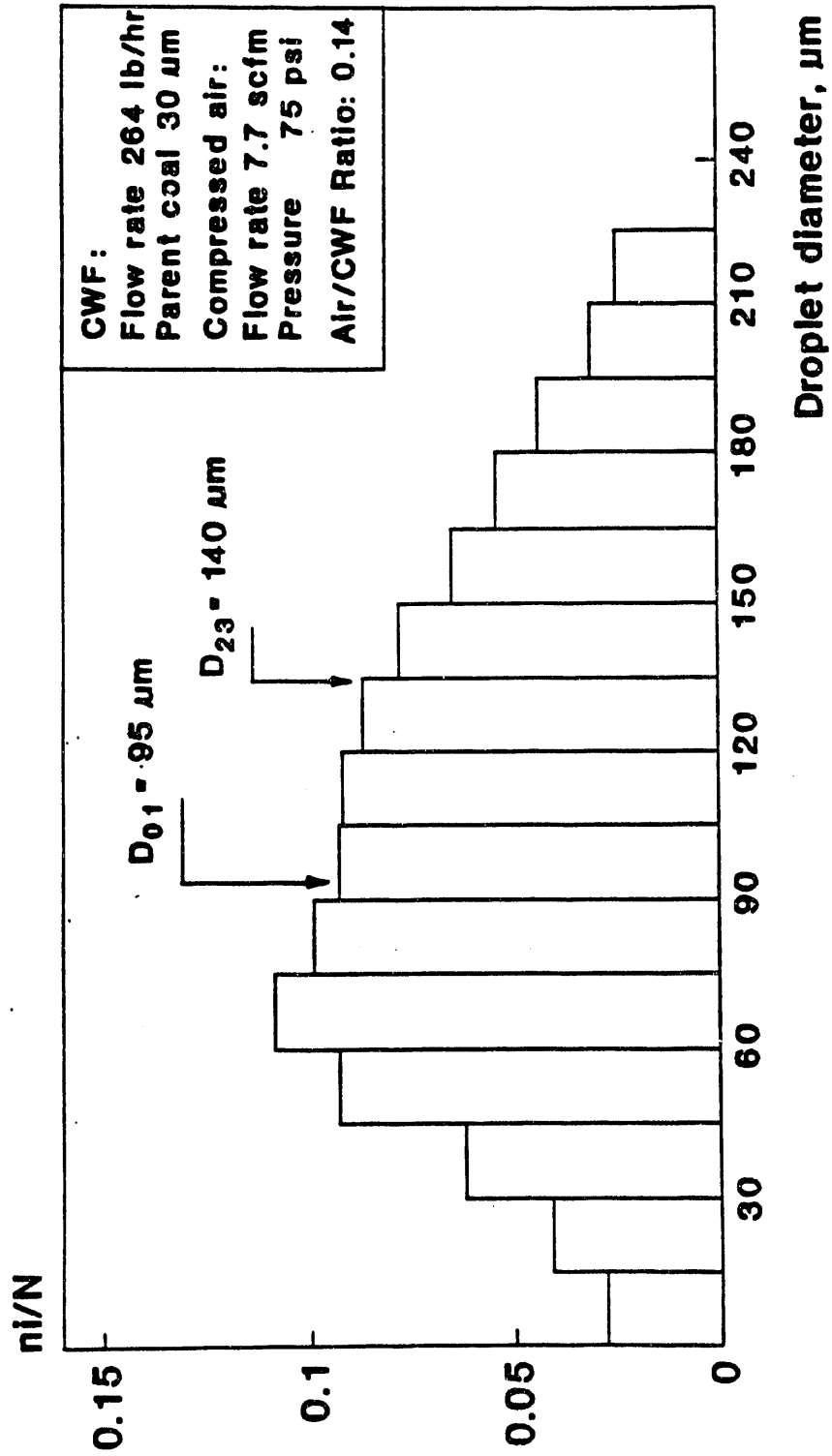


Figure 2.10 Typical droplet size distribution of a Type B CWF nozzle.

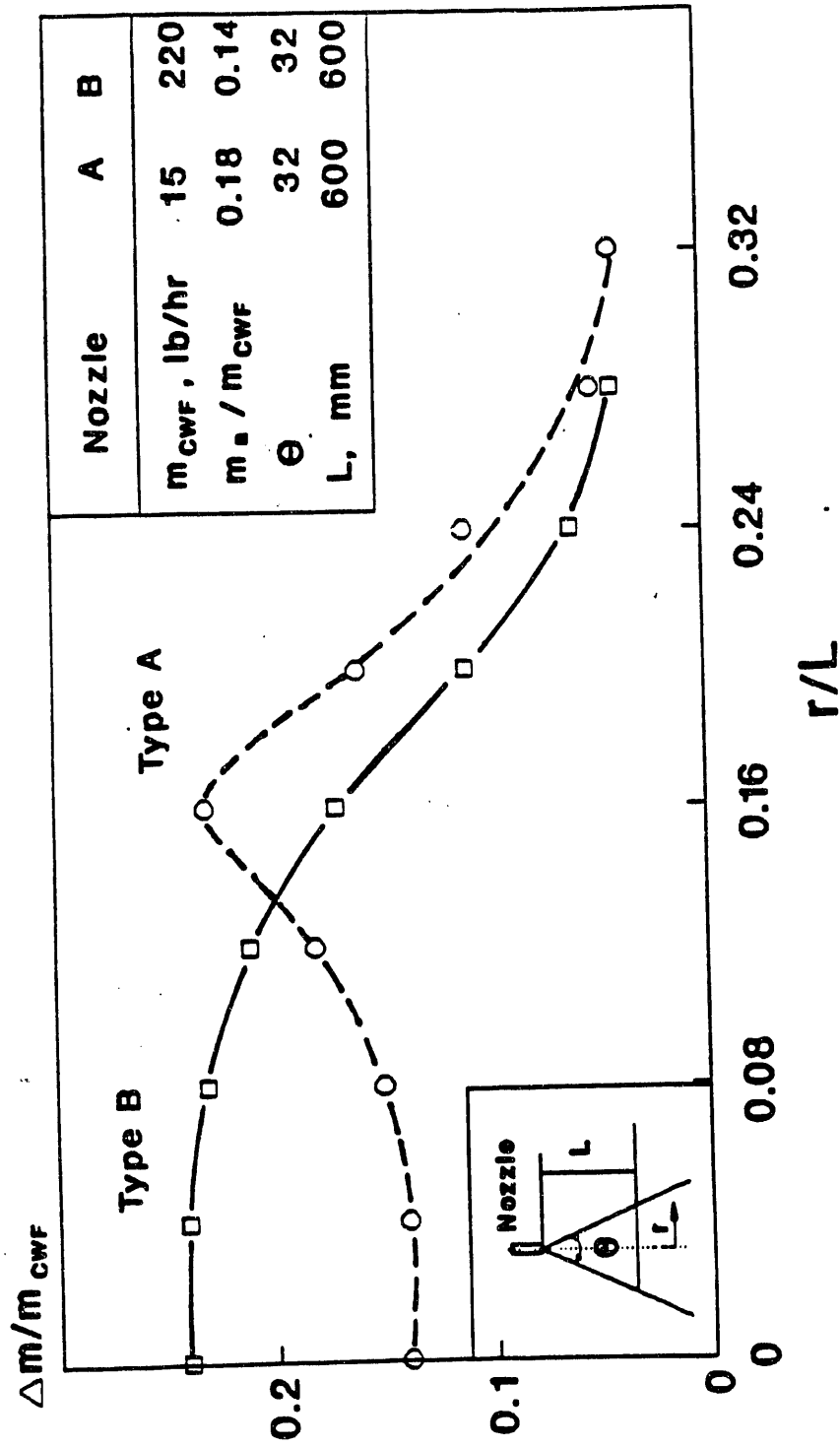


Figure 2. 11 Spatial distributions of CWF sprays for Type A and Type B nozzles.

persion in the core region. It falls off quickly at large radii, which is highly desirable for preventing deposition on the side walls, particularly at large flow rates [20,22].

The effects of flow rate on the atomization quality for Type A and Type B nozzles are shown in Figure 2.12. The operating ranges of CWF flow rates for both nozzles are also indicated in the figure. Clearly, the atomizing quality of both types of nozzles is satisfactory for VC combustion tests within the range of applications.

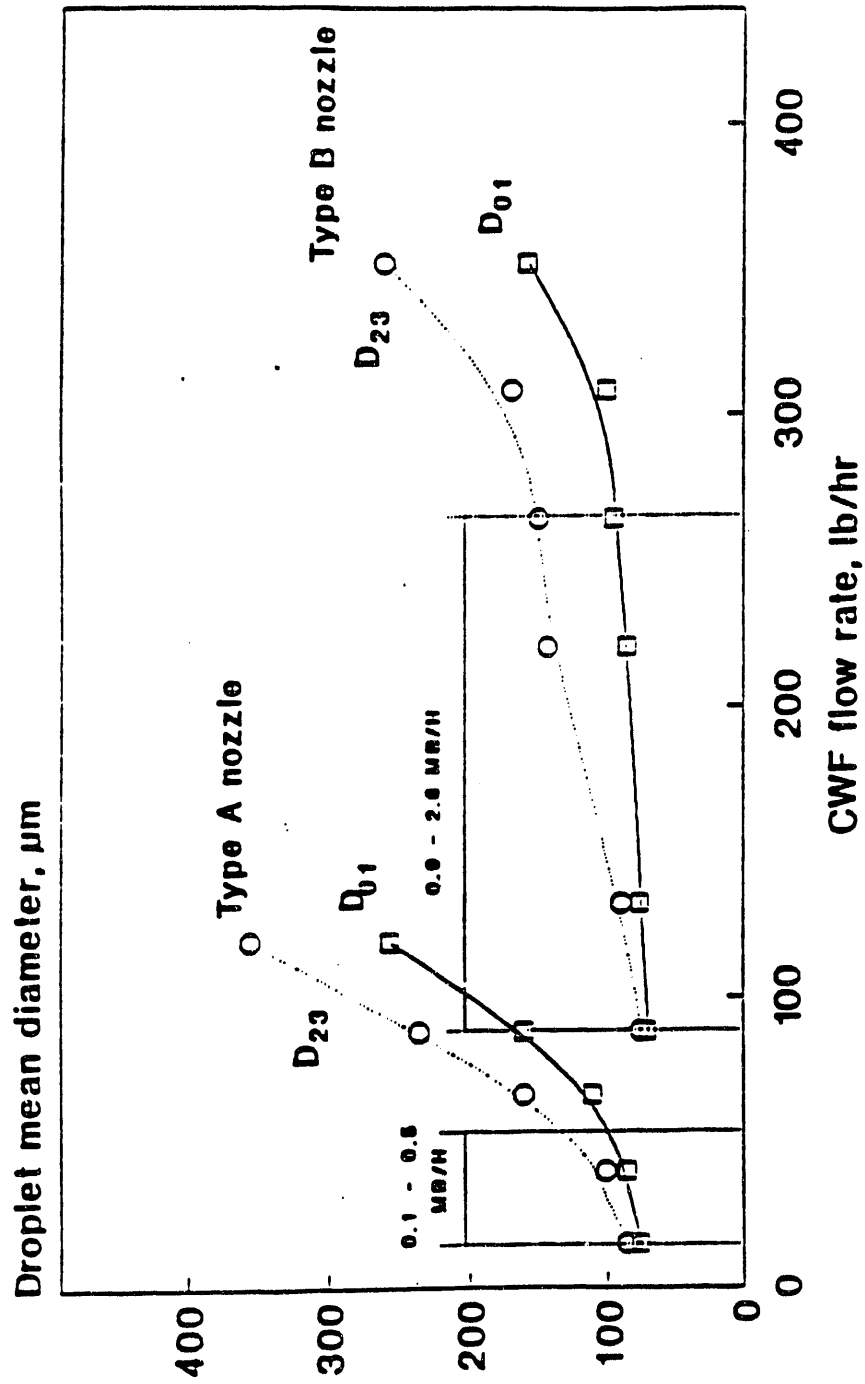


Figure 2.12 Effect of flowrate on atomization quality for Type A and Type B nozzles.

CHAPTER 3

VC TEST MODELS

3.1 Design Considerations

Design Guidelines

Consistent with our VC concept and the required technical performance discussed in Chapter 1, the design guidelines are summarized as follows:

- o Geometrically, a VC is made up of two vertical, concentric circular tubes as shown in Figure 1.1. Ignition and combustion of fuel take place primarily in the annular space in between the two tubes.
- o Fuels (CWF, DUC, or PC) are fed with primary air into the combustor bottom where drying, devolatilization, and ignition are achieved without the need of air or fuel preheating.
- o The vortex generator should produce a strong centrifugal flow field, whose swirl intensity and quality of air injection can be adjusted and controlled.
- o The center tube will be designed to minimize fuel particle elutriation and to maintain the rigidity of the strong swirl for achieving the desired fuel residence time.
- o Arrangement of air injection and heat removal surfaces will be made to maintain the desired low temperature (around 1,600 °F at the combustor exit) with minimal temperature variations in the combustor. Heat removal surfaces may consist of fully or partially water-cooled walls.
- o A proper combustor height-to-diameter ratio will be selected to facilitate the stage combustion and heat removal surface arrangements.

Design Calculations

The design calculations include basically mass and energy

balances [24-26]. It starts with the properties of the given fuel and the desired firing rate. The excess air in the design is set in the range of 10-30%. Based on these parameters, the fuel consumption, total combustion air requirement, amount of flue gases and ash to be generated, and overall combustor dimension are calculated first. Refinements are then made by accounting for the details of the distribution of useful energies and heat losses.

Being a brand new concept and device for combustion, the needed design and operation data for a VC are practically non-existent and must be developed also from this work. Based on the features of strong swirl and low combustion temperature environment, the overall heat transfer coefficient in the VC was assumed to be around 20 Btu/Hft²°F in the preliminary design of PExp VC model. With this, the needed area and location of heat transfer surface can then be estimated. The average firing intensity (volumetric heat release rate) of the VC, which affects the overall size of the combustor, arrangement of heat removal surfaces, and selection of combustor materials, is also not known. Based on our experience with vortexing fluidized bed combustor [6], an average firing intensity of 0.1 MB/Hft³ was chosen as the starting value for the design.

Heat transfer surfaces are used to: (1) control the desired temperature distribution in the combustor and also the exhaust gas temperature to be around 1,600 °F, and (2) assist in the turndown operation. The total available area for heat removal and total volume for combustion depend primarily on the height-to-diameter ratio (H/D) of the VC. Figure 3.1 shows the axial

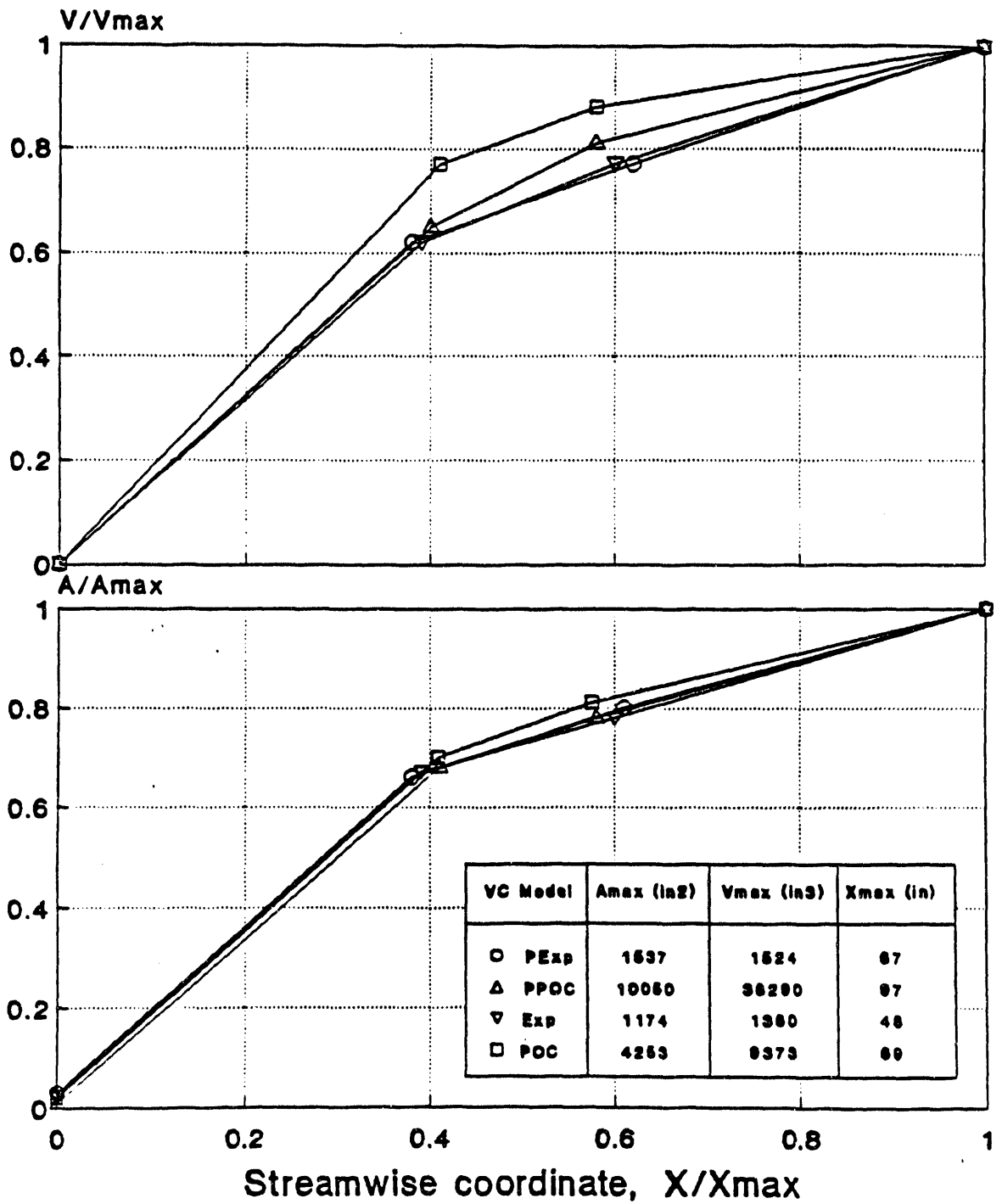


Figure 3.1 Variation of available heat removal surface area and combustion volume along the flow direction in VC test models.

distribution of available area and volume for the four VC models. Judging from the assumed heat transfer coefficient and average firing intensity, it can be shown that the available areas of the VCs are more than adequate for the heat removal needs. This allows flexibility to use the surfaces for reasons other than heat removal, such as ignition and burnout.

The design of fuel nozzle (or atomizer) follows conventional engineering practice: the injecting velocity of fuel-air mixture is chosen to be 40-70 ft/s, with the primary air fraction being 5-30%. Being a part of the vortex generator, the fuel nozzles are designed to be adjustable in protrusion length, location on combustor wall, and injection angle. In the operation of VC models, up to 95% of combustion air may be supplied by the secondary air nozzles. Design considerations for the air nozzles are:

- o Adjustable air injection velocity of 100-180 ft/s;
- o Depending on the combustor capacity, the air nozzles may be arranged as a single vertical array, two arrays at opposite position, or four arrays at 90° apart on combustor circumference;
- o Total number of nozzles, nozzle tip configuration, nozzle elevation, and injection angle should be designed to provide ample flexibility for various test operations.

According to the design practice of cyclone separator and our experience with vortexing fluidized bed combustor [6], the diameter ratio of the center tube and the combustor is kept close to 0.5. The average velocity of the ascending hot gases in the annular space should be kept below 15 ft/s in order to maintain adequate gas residence time and minimal system pressure drop. The gas velocity in the center tube should be kept below 50 ft/s.

In order to establish the needed design and operation data and also to explore the scale-up feasibility, technical merits, and operational limits, two subscale VC models (PExp and Exp) and two full-scale models (PPOC and POC) have been designed, built, and tested. Table 3.1 summarizes the major parameters of these four VC models. The design features and test results are discussed in the following sections.

3.2 PExp VC Model (0.15 MB/H)

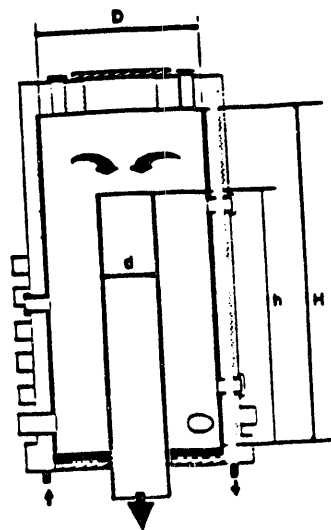
The PExp VC model was designed under the situation that the understanding of the vortex combustion processes was purely based on theoretical considerations and no relevant technical information was existent except for gas-particle flow characteristics. This model is the one which for the first time reduced the VC concept into practice. Based on the preliminary information generated from cold flow modeling studies [11] and complete energy and mass balance calculations [24], the PExp VC model was designed and built. Figure 3.2 shows the PExp VC model and its auxiliary subsystems. It has the following design features:

- o Sub-adiabatic configuration, including a refractory lower chamber (adiabatic) and a water-cooled metal upper chamber (non-adiabatic);
- o A contraction between the upper and lower chambers to enhance recirculation and prolong the fuel residence time in the lower chamber;
- o Low firing intensity and large height-to-diameter ratio.
- o Two feed ports for DUC and one for CWF located near the combustor bottom. The secondary air was tangentially injected at two fixed elevations and with a fixed injection angle into the upper chamber.

Table 3.1 Summary of major parameters of VC test models.

Parameter	PExp	PPOC	Exp	POC
Design				
Firing rate, MB/H	0.15	3.0	0.3	2.0
Configuration, in				
D	7.5	32	7.5	19
d	3.5	15	3	8
H	34.5	45	24	33
h (adjustable)	31	40	18	29
Overall	16x50	48x60	10x24	23x40
Operation (@ design capacity)				
Swirl number	5.0	13.9	12.0	13.1
Average firing intensity, MB/Hft ³	0.1	0.1	0.3	0.3
Air injection velocity, ft/s	100	100	120	120
Fuel injection velocity, ft/s	50	50	60	60
Average gas velocity, ft/s	2.7	4.6	5.4	5.9
Exit gas velocity, ft/s	14.2	14.3	28.4	27.2
Design features				
See details in Chapter 3	§3.2	§3.3	§3.4	§3.5

PExp Preliminary exploratory
PPOC Preliminary proof-of-concept
Exp Exploratory
POC Proof-of-concept



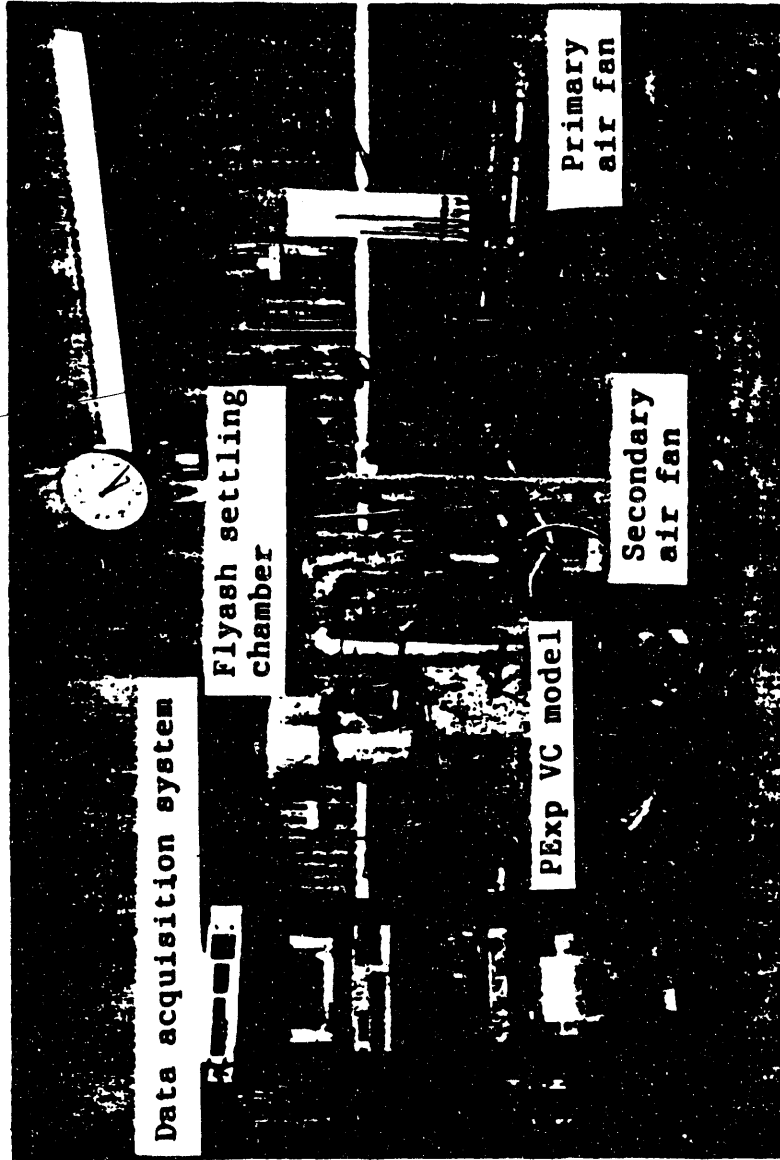


Figure 3.2 PExp VC model and its subsystems.

About 30 test runs totaling 150 hours of test time have been conducted firing both DUC and CWF. The longest continuous running times were 11 hours for DUC and 2 hours for CWF. The data generated and detailed discussions of the results are reported in References 27 and 28. Typical performance of the PExp VC model firing DUC is given below:

Firing rate, MB/H	0.16	0.12
Excess air, %	38	60
Primary air fraction, %	75	70
Secondary air fraction, %	25	30
Combustion gas temperature, °F		
Bottom chamber	2,000	1,848
Contraction	1,830	1,821
Top chamber	1,150	1,143
Center tube	1,760	1,654
CO emission, ppm (@ 3% O ₂)	249	230
Thermal efficiency, %	88	87
Firing intensity, MB/Hft ³	0.15	0.11
Combustion efficiency, %	98.9	99.4

The experience and lessons learned are summarized below:

- o The VC concept for coal firing was proven to be workable in terms of combustion performance and operational convenience;
- o High combustion efficiencies (> 98%), large turndown ratio (> 3:1), acceptable operating temperatures (1,500 - 2,100 °F) are achievable with DUC;
- o The PExp VC and its subsystems were found to be reliable and safe, and exhibit good control characteristics with regard to cold start, load variation, and hot restart;
- o The volume of the lower adiabatic chamber appeared to be oversized for DUC firing, which often led to high local combustion temperatures. It, however, played an important role for CWF ignition and flame stabilization;
- o The contraction is helpful in fuel ignition and flame stabilization. For a premium grade micronized coal, such as DUC, the combustion environment at the combustor bottom was found to be sufficiently adequate, however.

- o Notable erosion of the refractory wall was observed after 120 hours of tests, a result mainly due to the impingement of fast-moving burning coal particles in the strong, swirling gas stream. The center tube was burned through once at the lower section after 30 hours of testing at high loads (see Figure 4.8b);
- o The designed average firing intensity of 0.1 MB/Hft^3 was low and can be increased by use of heat removal surfaces;
- o The operational characteristics of the PExp VC are depicted in Figure 3.3. The difference in operating temperatures are shown for different fuels during cold start and hot restart processes. For all test runs, stable, on-time ignition and self-sustained combustion could be achieved for DUC and CWF without the need of preheating the combustion air or fuels. Supplemental fuel was used only for cold start.

3.3 PPOC VC Model (3 MB/H)

Based on the data and experience obtained from PExp VC model tests and the successful development of CWF atomization nozzles (see Section 2.4), a 3 MB/H full-scale PPOC VC model was designed to explore the feasibility of scaling up, operational limits, fuel flexibility, and the role of heat transfer in combustion control. The major design and operational parameters of PPOC VC are summarized in Table 3.1. Figure 3.4 is a pictorial view of this model and its auxiliary subsystems. The design features and major data are summarized below [29]:

- o The combustor outer wall is practically adiabatic, made of 5" castable refractory. A removable cooling coil made of 1" copper tubing is inserted at the bottom for temperature control.
- o The center tube is water cooled on both sides of the wall. The height of the center tube is adjustable.
- o Two feed ports for CWF and two for DUC are located at the combustor bottom. Secondary air is supplied at three elevations, each with two adjustable air nozzles.

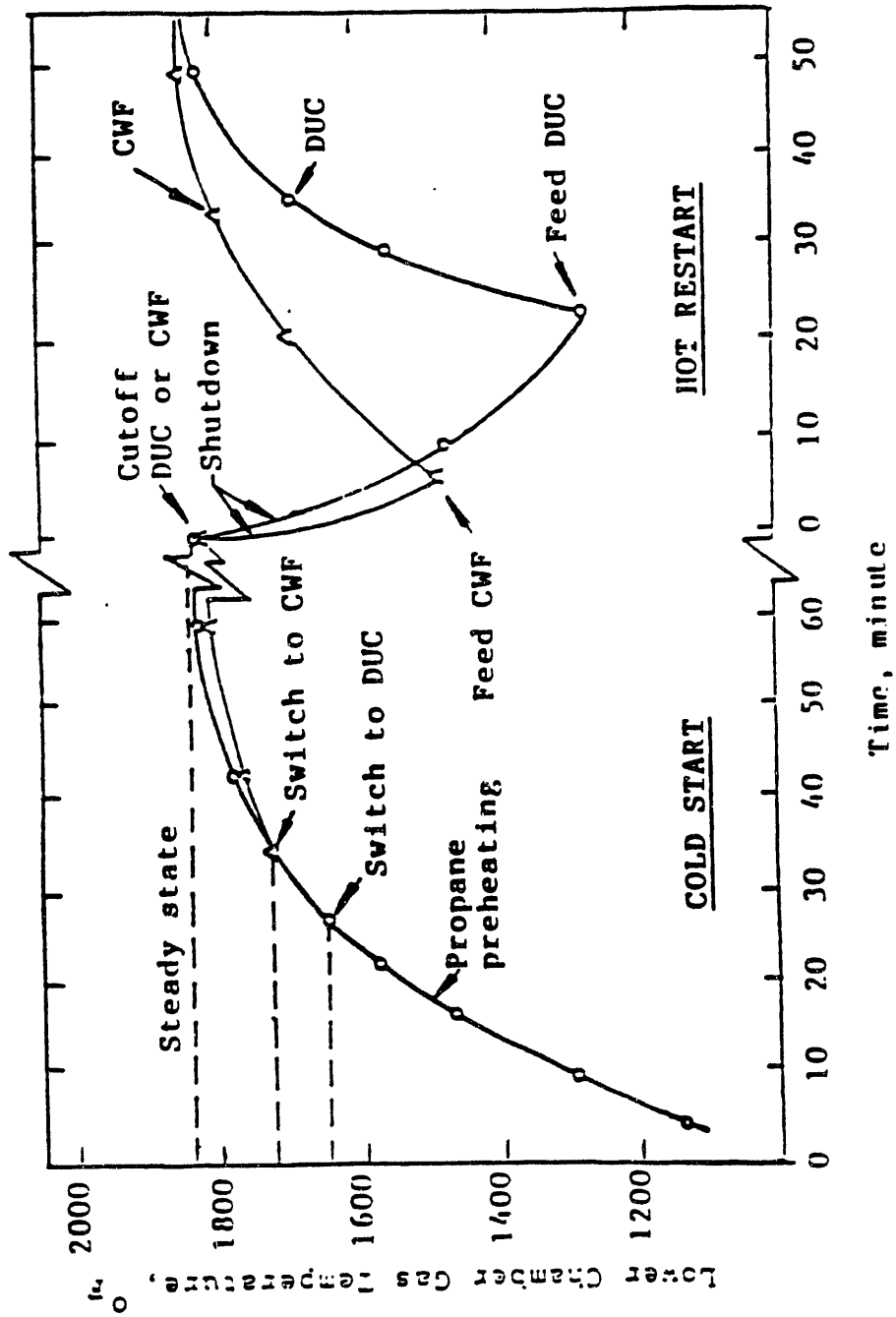


Figure 3.3 Operational characteristics of PExp VC model firing DUC and CWF.

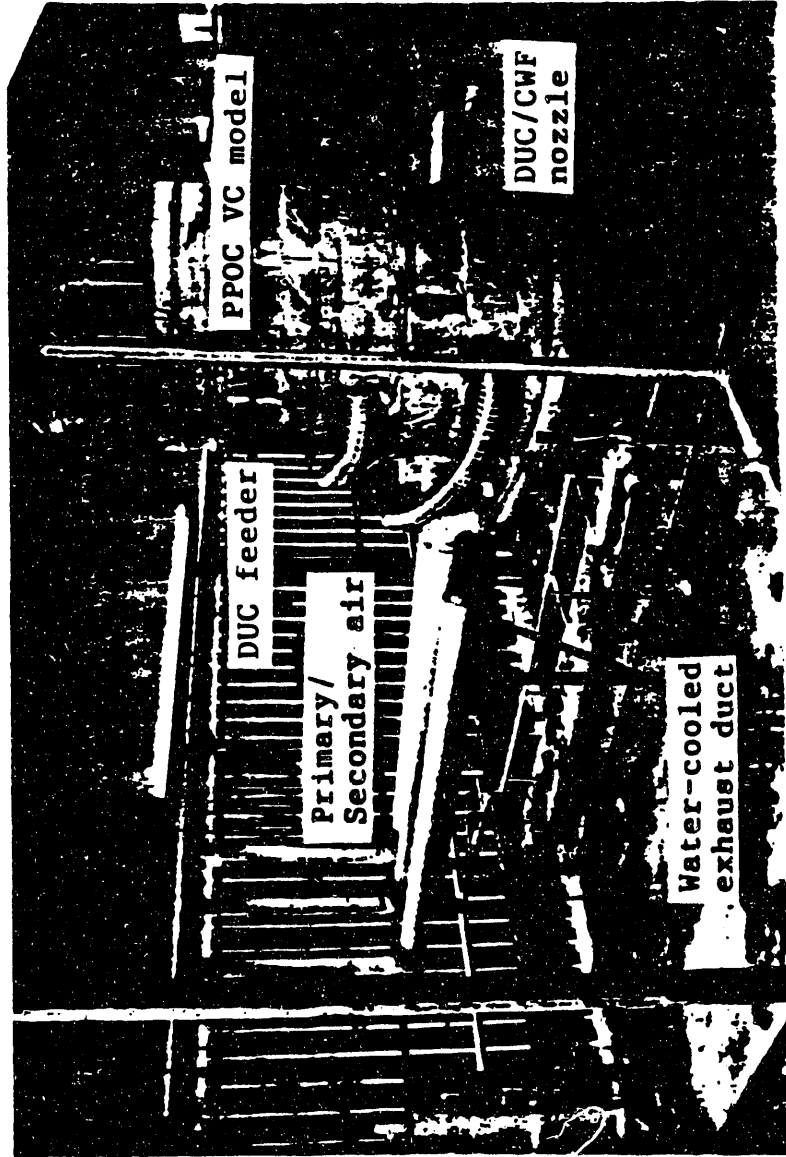


Figure 3.4 Pictorial view of PPOC VC model and its subsystems

- o Adjustable fuel injection angle and deflecting air are provided.
- o A removable contraction is located below the top two rows of secondary air nozzles.

A total of 27 test runs have been conducted with DUC and CWF on this model to explore the combustion performance, operational requirements, and fuel flexibility at various firing rates. Some typical test results are given below:

Fuel type Firing rate, MB/H	DUC 2.99	DUC 2.84	CWF 2.15
Excess air, %	21.6	19.0	22
Primary air fraction, %	24	17	5
Secondary air fraction, %	76	83	95
Combustion gas temperature, °F			
Bottom chamber	2,310	2,253	2,186
Contraction	2,000	1,994	2,011
Top chamber	1,837	1,850	1,532
Center tube	1,369	1,288	1,076
CO, ppm @ 3% O ₂	1,544	1,237	625
NO _x , ppm @ 3% O ₂	397	404	348
Thermal efficiency, %	83	85	82
Firing intensity, MB/Hft ³	0.16	0.15	0.11
Combustion efficiency, %	97.0	97.1	94.0

The data and experience obtained from PPOC VC model are summarized below:

- o Stable, on-time ignition, and self-sustained combustion of DUC was easily achieved at all firing rates up to 3 MB/H.
- o Stable, and self-sustained combustion of CWF was achieved without the need to preheat the air or fuel. Two feed ports were adequate to fire CWF at about 2 MB/H load.
- o Deflecting air was effective in preventing CWF deposition. An innovative "spray shaper" (see Section 4.2) was developed and was found to be extremely useful for intensification of water evaporation and CWF ignition at full load. We were able to ignite and burn up to 225 lb/H of CWF in the narrow annular space of the VC without deposition buildup.

- o We have successfully fired DUC and CWF up to 3 MB/H with combustion efficiency up to 97%. This confirms the up scaling potential of our VC concept.
- o The in-furnace cooling coil can effectively absorb heat and control the combustion temperature.
- o Heat removal surfaces located either on the combustor wall or the center tube can remove heat without adversely affecting combustion.
- o The adiabatic combustor wall was beneficial in fuel ignition and burnout. However, it also has drawbacks of large thermal inertia, large combustor size and space requirement, and air leakage through gaps of refractory blocks.
- o The average firing intensity can be further increased by the increase of heat removal rate and vortex generator arrangement.
- o Type B CWF nozzles performed very well both in atomization quality and in compatibility with the unique VC configuration.

3.4 Exp VC Model (0.3 MB/H)

Research efforts on PExp and PPOC VC models have pointed out the need for detailed information on the arrangement of secondary air distribution and local heat transfer. Although some of the needed information can be generated from PPOC VC model, the combustion tests on this model, however, would require a large amount of fuel and excessive manpower. It was deemed not economical and feasible to continue further tests of CWF and DUC on PPOC VC model. An improved subscale exploratory hot model of 0.3 MB/H, the Exp VC, was designed, built, and tested as shown in Figure 3.5. This Exp VC model has the following features:

- o The combustion chamber was made of a 7.5" I.D. mild steel pipe. The center tube was a 3" I.D. stainless steel pipe. The upper and lower 1/3 of the combustor inner wall was lined with 0.5" refractory in order to meet the needs for ignition and burnout.

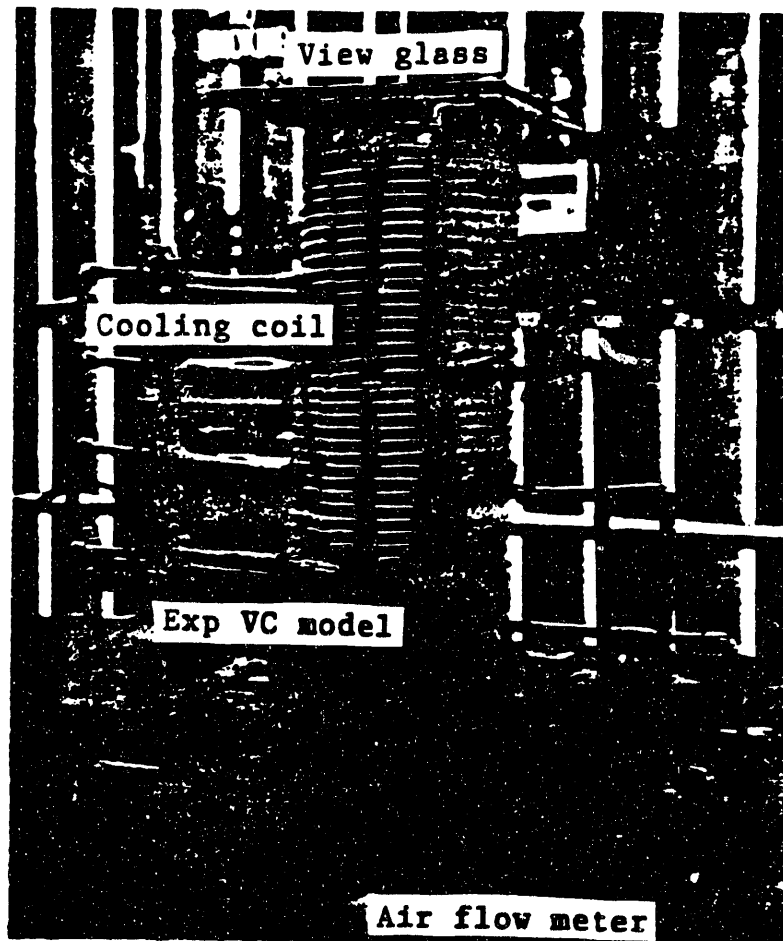


Figure 3.5 Pictorial view of Exp VC model.

- o Four runs of independently controlled water cooling coils were wound on the outer wall for studying the local heat transfer characteristics along the height of the VC.
- o Two feed ports were provided at combustor bottom for both CWF and DUC. Deflecting air was used to prevent fuel deposition and clinker formation.
- o Seven independently adjustable secondary air nozzles were arranged at four elevations. The injection angles, protrusion length, and flow rates can be individually varied conveniently to afford a broad range of flexibility.
- o A 1/4" thick Vycor glass plate was used as the combustor top to facilitate visual observations of the flame and particle behavior during tests.
- o The overall design improved the average firing intensity to as high as 0.44 MB/Hft³.

Numerous exploratory tests have been conducted. Typical results with the fuels tested are summarized below and are discussed in the following paragraphs:

Fuel type	DUC	DUC	PC	#2 oil	Propane
Firing rate, MB/H	0.22	0.31	0.27	0.20	0.30
Excess air, %	45	40	20	50	11
Primary air fraction, %	18	30	39	1	40
Secondary air fraction, %	82	70	61	99	60
Average combustion gas temperature, °F	1,760	1,900	1,700	1,670	1,770
Thermal efficiency, %	86	83	84	87	89
Firing intensity, MB/Hft ³	0.31	0.44	0.38	0.29	0.42
Combustion efficiency, %	97.6	95.4	95.8	99.4	100

Improvement of Firing Intensity

The use of refractory liner to cover only some areas of the basically water-cooled combustor wall has made the heat removal capability of Exp VC much higher than PExp and PPOC VC models. The flow and turbulence was substantially improved via the arrangement of vortex generator. Consequently, a 3-fold improve-

ment on firing intensity over PExp and PPOC models was achieved. This paved the way for a successful design of our POC VC.

Establishment of Local Heat Transfer Data

A series of tests were conducted with different fuels, distinct heat removal surface arrangement, and various combinations of other operating parameters. Heat removal by water for each run of the cooling coil was individually measured to establish local heat transfer data. This provided the needed information on heat transfer surface design. The heat transfer coefficient ranged from 10 to 55 Btu/Hft²°F, depending on the swirling flow and combustion temperature.

Controllability of Temperature

The combustion temperature and its axial distribution can be conveniently controlled by means of secondary air distribution, as illustrated in Figure 3.6. If a large amount of secondary air is injected at the lowest level (90% at level a, 10% at level b) of the combustor, a "hot spot" of 2,500 °F would result near the combustor bottom, accompanied by a sharp decrease of gas temperature along the combustor height, which inevitably increases the NO_x level. By varying the distribution of secondary air such as 45% at level a, 35% at level b, 15% at level c, and 10% at level d, a more uniform gas temperature (2,000 ± 200 °F) can be achieved. The controllability of temperature is potentially significant in applications and is highly beneficial in combustion performance, turndown operations, and pollution control.

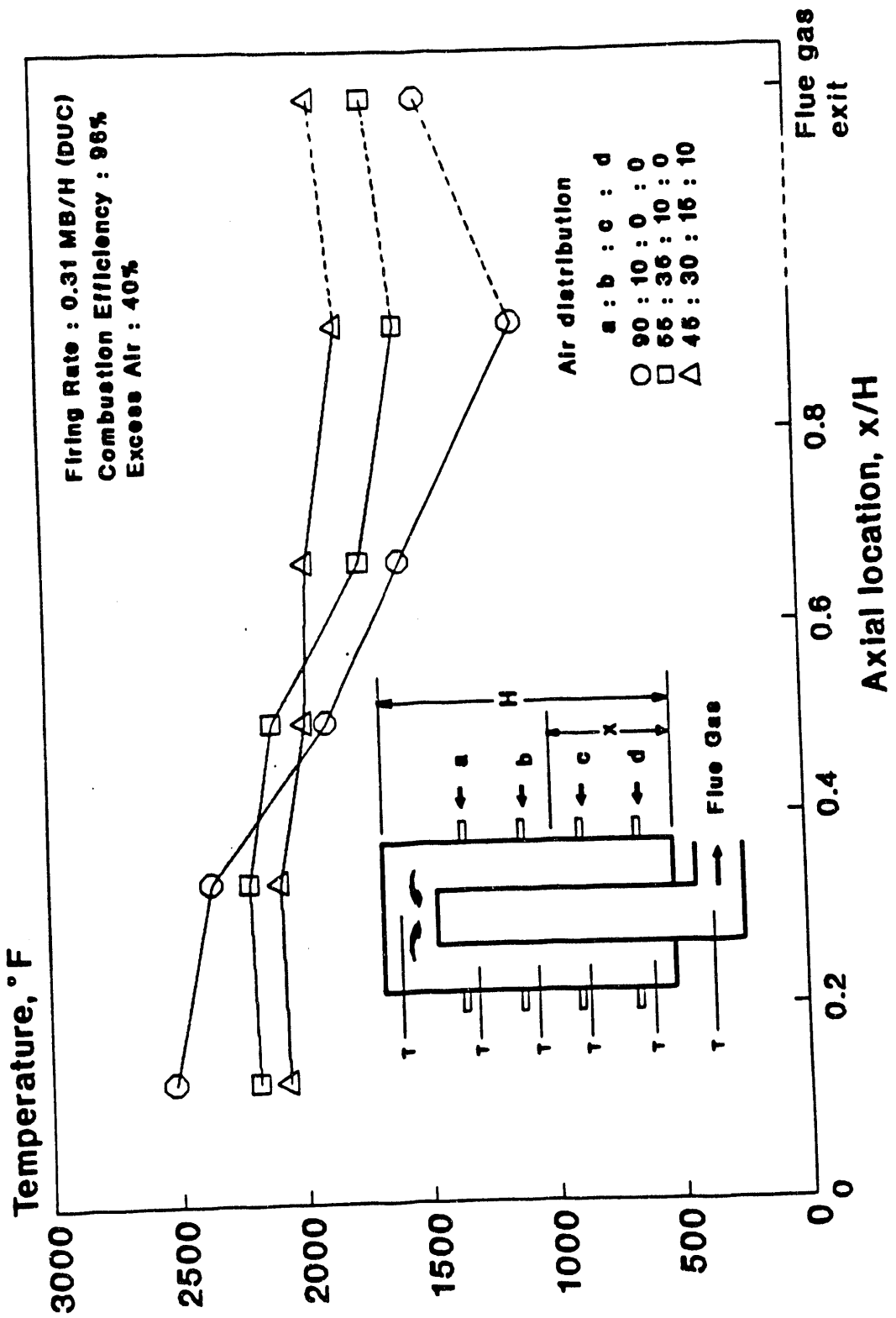


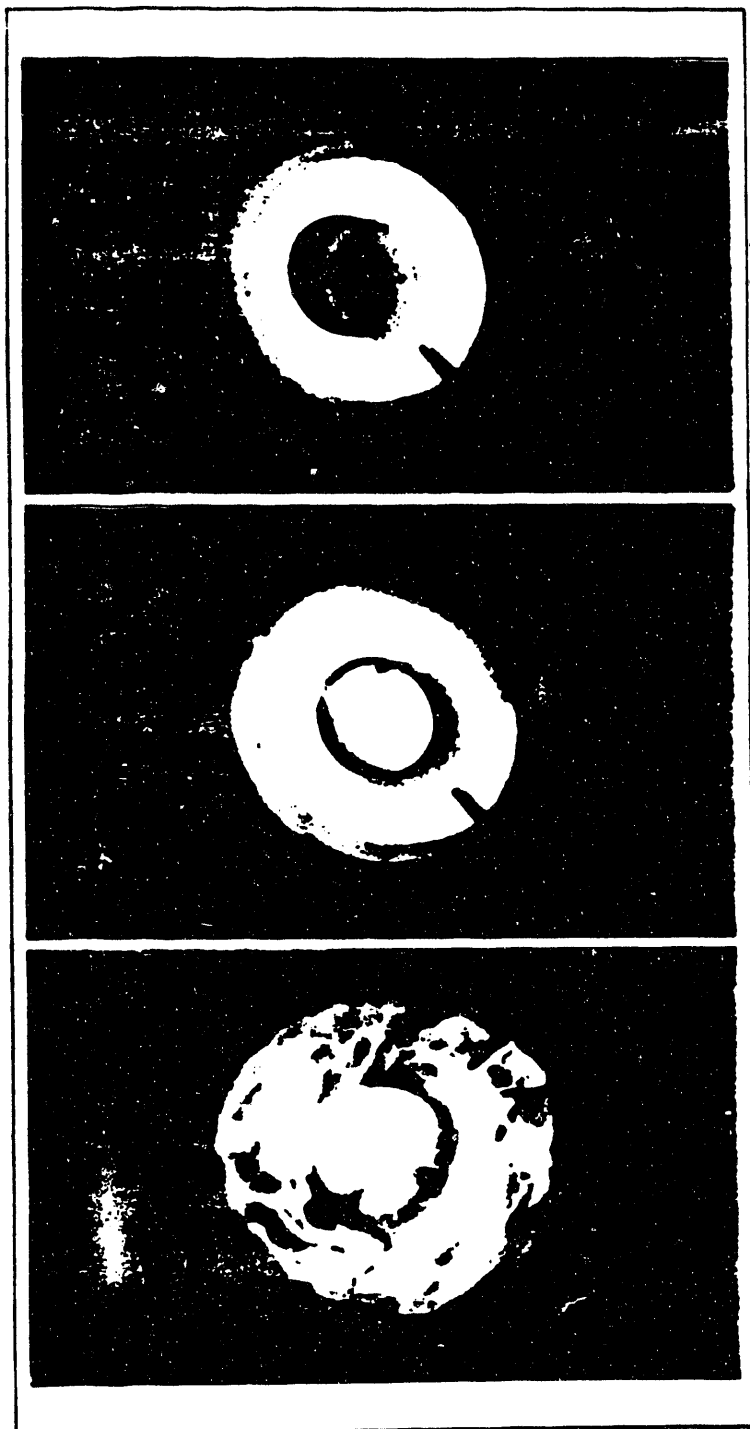
Figure 3.6 Controllability of combustion temperature by air distribution

Controllability of Particle Behavior

The flexibility of VC in controlling fuel particle behavior, for example, elutriation and residence time, has been demonstrated in our cold flow measurements [11]. Distinct particle trajectories and behavior were also observed while firing PC in the PExp model. Large particles either fell to the bottom due to gravity or were confined in the wall region due to strong centrifugal force. It was observed that particles were burning while moving around horizontally, and eventually became completely burned out before exiting the combustor. The controllability of particle behavior is exceedingly important in combustion efficiency and particulate emission control.

Effect of Swirl

Figure 3.7 shows the effect of swirl on flame and combustion. Note the differences on flame shape and luminosity, burn-out volume, combustion temperature, and firing intensity for the cases of no swirl, weak swirl, and strong swirl. An order of magnitude increase of firing intensity can be achieved in VCs. Considering the 3-T principle of combustion, the substantial improvements on "Turbulence" and "Time" overly compensate the deficiency of the low design "Temperature", which enable a VC to attain high combustion performance at low temperature. The VC technology is truly state-of-the-art in coal combustion.



	(a) No Swirl	(b) Weak Swirl	(c) Strong Swirl
Flame shape and luminosity	Dim flare and wiggling	Bright and mild	Bright and blazing
Flame occupied volume	Whole combustor	3/5 combustor	1/3 combustor
Average gas temperature, °F	1290	1740	2280
Firing Intensity, MB/Hft'	0.06	0.16	0.6

Figure 3.7 Effect of swirl on flame and combustion.

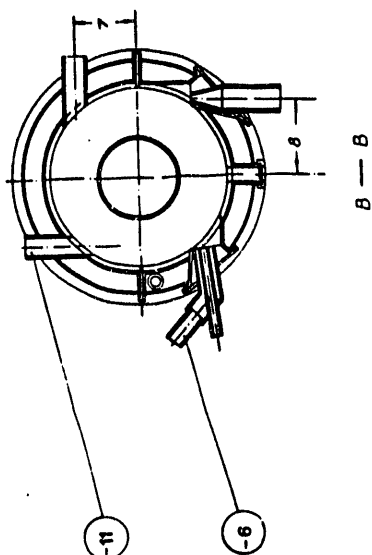
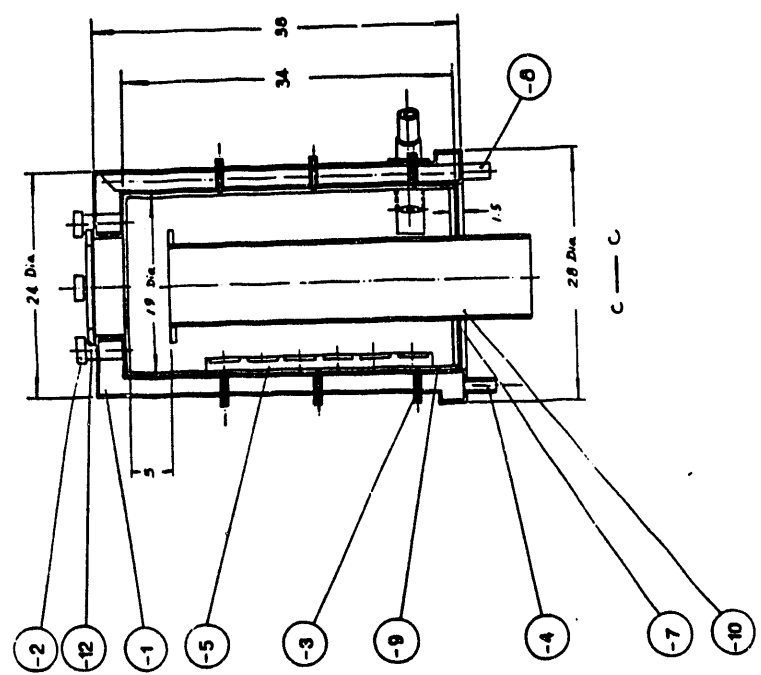
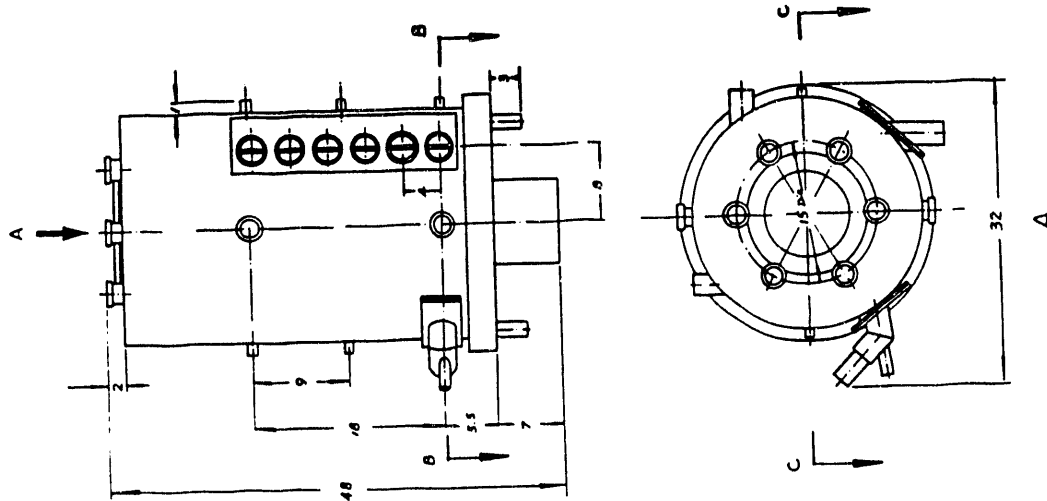
3.5 POC VC Model (2 MB/H)

With the data and experience obtained from PExp, PPOC, and Exp VC hot models, a 2 MB/H POC VC hot model was designed, built, and systematically tested. The detailed design data and major parameters are summarized in Table 3.1 and shown in Figure 3.8.

The design features are summarized below:

- o Water jacket is used as the combustor wall. The lowest 1/4 of the wall is lined with castable refractory to ensure positive ignition, particularly for CWF. The center tube is a steel pipe whose lowest 1/4 is also refractory-lined to prevent corrosion/erosion of the metal surfaces and to enhance the combustion environment.
- o The vortex generator consists of a vertical array of six independent nozzles. The height, tip cross-sectional area and configuration, and injection angle are all adjustable.
- o Two feed ports are provided for the fuels, both CWF and DUC/PC. The fuel nozzles are designed and built to fire multiple fuels. The primary air velocity is kept within 50 to 70 ft/s. To prevent CWF deposition on the chamber wall, the stay cone angle is kept at about 30°.
- o Two types of arrangement of heat removal surfaces have been tested: 25% and 90% of water jacket areas are covered with refractory liner.
- o The center tube is made of 9" O.D. steel pipe. For the convenience of installation and adjustment, it is cut into three sections. The configuration of inlet cap, size of inlet section, and the height of center tube are easily adjustable.
- o Great efforts have been devoted to simplification of the design and operation. The simplicity of POC VC enabled it to be fabricated and assembled by graduate students.

The detailed data, test results, and outstanding performance of the POC VC model are presented in the next chapter.



Note. The following items are adjustable:
 1. Center tube vertical location and orientation.
 2. Air nozzle vertical location and orientation.
 3. Fuel nozzle orientation.

No.	Name	Qty	Material
-12	Rupture Disk	1	1/8" x 13"D steel sheet
-11	Auxiliary Port	2	2"D x 5'L Sch 40 steel pipe
-10	Center Tube	1	8"O.D. x 3/8" wall x 36"L steel pipe
-9	Liner	-	High temp. castable refractory, 1/2" thick
-8	Hot Water Outlet	1	1-1/2"D x 40"L Sch 40 steel pipe
-7	Furnace Bottom	1	1/4" x 19"D steel plate
-6	Fuel Feed Port	1	2" 1-1/2" I Sch 40 steel pipes
-5	Vortex Generator Assy	1	6 air nozzles, 2"O.D. x 5'L steel conduit
-4	Feedwater Inlet	1	1-1/2" x 3.5'L Sch 40 steel pipe
-3	Instrument Port	6	1/4"D x 3'L Sch 40 steel pipe
-2	View Port	9	1-1/2"D x 4'L Sch 40 steel pipe & cap
-1	Water Jacket	1	1/8" thick mild steel
	No.		
	Name		
	Req'd		
POC VC Assembly			
			Date Recd
			Submitted
			Checked
			Approved
			CMFL - 88 - 10

Figure 3.8 The POC VC design.

CHAPTER 4

TEST RESULTS OF POC VC MODEL

A total of 140 hours of combustion test time has been accumulated on the POC VC model firing CWF (5,000 lb), DUC (4,000 lb), and PC (1,500 lb). The longest continuous running time was 6 hours. The performance characteristics of the POC VC have been extensively explored under various operating conditions. Subjects of interest consist of: temperature distribution and variation, combustion efficiency, emission levels, heat fluxes to cooling surfaces, and gas-particle flow behavior. Operational limits in fuel flexibility and system controllability, and performance in cold start, continuous full load operation, partial load operation, hot restart, and shutdown also have been explored. This chapter presents and discusses these results.

4.1 Test Arrangement

Test Setup and Fuels

Figure 2.1 shows the test setup for systematic combustion tests of the POC VC model. The details of the auxiliary subsystems and instrumentation have been presented in Chapter 2. Three types of coals have been used for the tests: CWF, DUC, and PC, whose properties are given in Table 2.1.

Test Plan and Procedure

Parametric studies on the effects of excess air (0-65 %),

firing rate (0.6-2.1 MB/H), secondary air arrangement, and ignition and burnout characteristics have been conducted. A summary of these tests is given in Table 4.1.

Table 4.1 Combustion tests conducted on POC VC model.

Parameter	Fuel	CWF	PC	DUC
Excess air:		5 runs	5 runs	5 runs
< 20%		M*	M	M
20 - 40%		M	M	M
> 40%		M	M	M
Firing rate:		5 runs	1 runs	6 runs
< 1 MB/H		M	O*	M
1.0 - 1.8 MB/H		M	M	M
> 1.8 MB/H		M	O	M
Secondary air:		2 runs		6 runs
Flow rate distribution		O	-	M
Nozzle configuration		O	-	M
Center tube height:		-	-	4 runs
h/H = 0.6 - 0.9				
Refractory liner		2 runs		1 run
		M	O	M
Ignition/Flame stability		4 runs		
		M	O	O
Burnout improvement		1 run		3 runs
		M	O	M

* M - Measurement
O - Observation

The test procedure is briefly described below:

Prepare, inspect, and adjust the combustor and its various subsystems, including the instruments for various measurements; load the fuels sufficient for 4 hours of testing; and test run the subsystems.

- o Start combustion by first igniting propane gas with an electric spark at the fuel port. Inject coal as soon as the propane flame occupies the whole combustor.
- o Co-fire propane and coal for about 10-15 minutes to stabi-

lize the flame, cooling water temperature, and combustor performance at the preset test condition.

- o Shut off propane and conduct systematic measurements on flow, thermal, combustion, and emissions.

Data Collection and Analysis

Except for the flyash samples which were collected manually with a sampling probe system for residue carbon analysis, most major experimental data were collected and reduced by the computer-assisted data acquisition system discussed in Section 2.3 and shown in Figure 2.6. The details of instrumentation and measurement errors for combustion tests are given in Table 2.1. The locations of flowmeters, thermocouples, gauges, flue gas sampling and flyash collection systems on the combustor and subsystems are shown in Figure 2.1. Data were collected and analyzed to identify the effects of controlling parameters on combustor performance such as fuel type, fuel consumption, excess air, primary/secondary air ratio, and secondary air injection arrangement.

4.2 CWF Test Results

CWF is a more difficult-to-burn fuel than dry powdered coals. Since CWF is the design fuel of VC, efforts have been directed to resolve problems associated with CWF handling, atomization, ignition, and burnout. Among the 70 hours of tests with CWF, about 30 hours were devoted to systematic data collection, and 40 hours for fine tuning the combustor and exploratory testing on ignition characteristics and deposition prevention.

Intensification of Water Evaporation

The configuration of VC combustion chamber poses a great challenge for CWF ignition and flame stabilization. CWF is injected horizontally through one or two feed ports into the combustor bottom at an angle for proper dispersing into the main swirling flow stream. Fuel droplets must be dispersed, dried, and ignited in the narrow annular space and in a very short time to prevent wall impingement. Otherwise, any undried CWF particles would deposit, rapidly buildup, and eventually block the flow passage. As discussed in Section 2.4, two types of CWF nozzles, both with a small spray angle close to 30°, were specially developed for VC applications. As depicted in Figure 4.1(a), if this angle is too large, the spray would impinge on the center tube and/or the combustor side and bottom walls near the feed port resulting in deposition buildup. If the angle is too small, the spray would be too strong for timely dispersion before it hits the combustor wall downstream, and also form undesirable depositions [28,30].

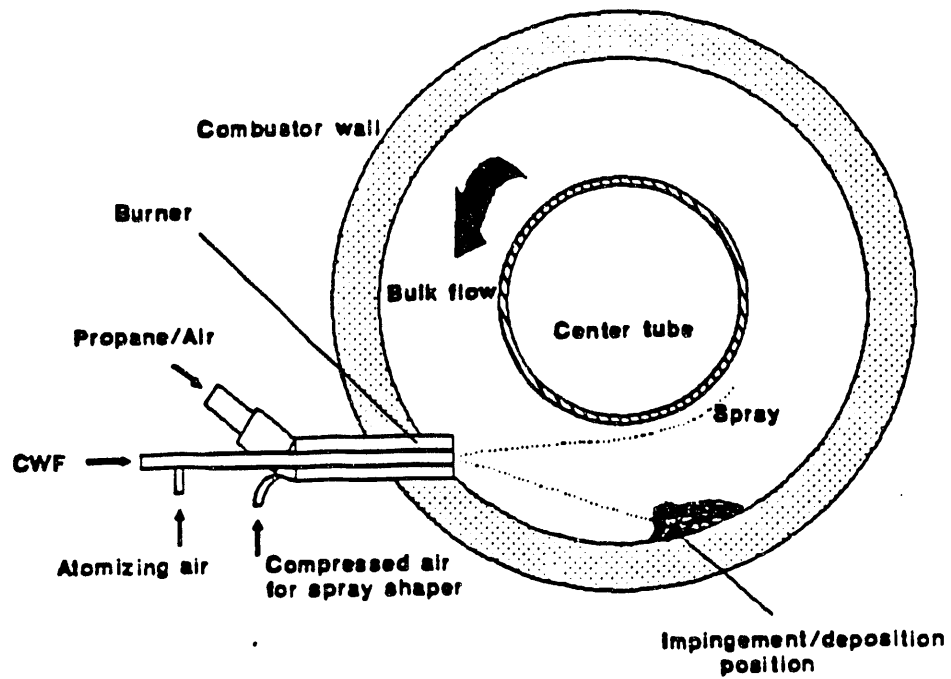
In order to successfully ignite a CWF spray and stabilize the flame, it is critically important to speed up the water evaporation process in the ignition zone. The key to prevent CWF deposition is to keep the needed evaporation time of the droplets, t_{ev} , to be shorter than the droplet flight time, t_f .

That is:

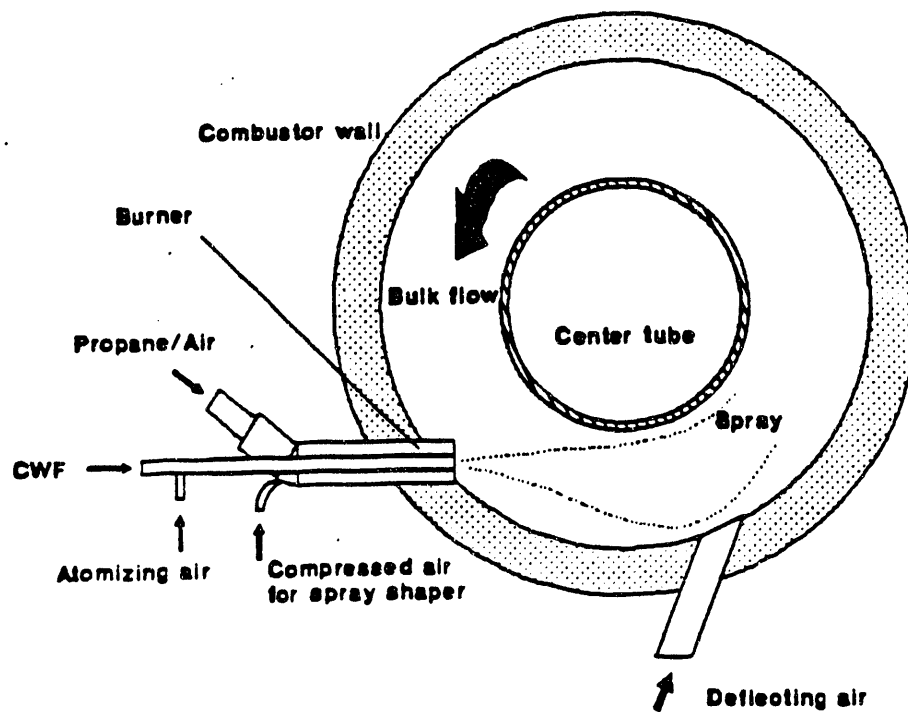
$$t_{ev} = \frac{Q_{ev}}{\dot{Q}_{in}} \leq t_f = \frac{S}{V_n} \quad (4-1)$$

where

Q_{ev} = heat needed for water evaporation,



(a) Deposition of CWF spray.



(b) Deposition elimination by deflecting air.

Figure 4.1 Control of CWF deposition in a VC

\dot{Q}_{in} = heating rate from the surroundings,
 S = droplet flight distance before impingement,
 v = flight velocity of droplets.

Eq.(4.1) can be rewritten as:

$$\frac{\bar{d}_p^2}{\Delta T Nu} \leq c \frac{S}{v} \quad (4-2)$$

where

\bar{d}_p = mean droplet diameter,
 Nu = Nusselt number,
 ΔT = average temperature difference between surrounding hot gases and CWF droplet,
 c = a constant.

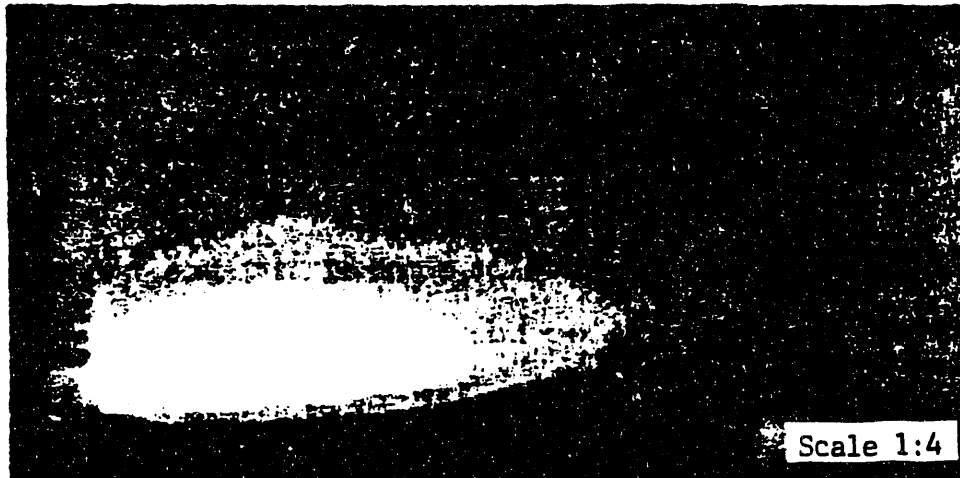
According to Eq.(4-2), the following measures were taken to resolve the deposition/accumulation problem:

- o Improve the CWF nozzle performance to achieve a finer spray, or smaller \bar{d}_p , which was accomplished and presented in Chapter 2.
- o Increase the local temperature, or ΔT , and Nu in the ignition zone by partially lining the water-cooled surface with refractory.
- o Modify the aerodynamic structure in the annular space by introducing a strong jet of deflecting air at the proper location (or timing) to bend the spray toward the main gas stream so that the droplets can fly a longer distances. Figure 4.1(b) shows the working principle and the effect of deflecting air. This method was found to be very effective to prevent CWF droplet deposition, particularly at large loads.
- o Adopt a novel "spray shaper" to better disperse the droplets in the ignition zone, increase turbulent mixing and hence Nu , and attenuate the spray velocity. Figure 4.2 shows the evident effect of spray shaper on CWF atomization. Also shown is its effective attenuation of the average flight velocity of the droplets. The local turbulent mixing and heat exchange are also intensified.

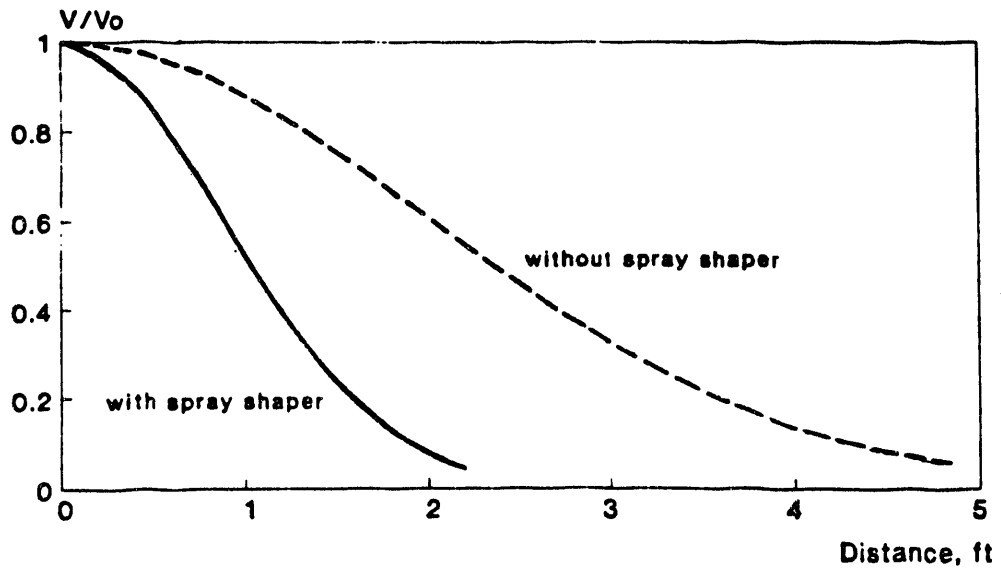
Tests show that with the above measures the water evaporation process was drastically shortened. The droplets are dried up almost as soon as they leave the nozzle.



(a) Without spray shaper



(b) With spray shaper



(c) Spray velocity attenuation

Figure 4.2 Effect of spray shaper.

Combustion Intensification and Burnout Improvement

To achieve high combustion efficiency and intensity, thorough turbulent mixing, high temperature, and long residence time, especially in the burnout zone, are needed. A series of tests was carried out to explore the potential of VC in these aspects. Owing to the strong swirl, the unburned fuel particles are thrown toward the combustor wall by the centrifugal force and form circulating masses of suspension layers [11]. They are trapped in these layers until completely burned out. Finally, they become small in size and mass and are entrained by the flue gas leaving the combustor. The height and the inlet configuration of the center tube are critical in controlling the residence time of fuel particles. Experience shows that long residence times and high combustion efficiencies can be achieved at center tube height h/H about 0.8. A flat steel flange mounted at the lip of the center tube can prevent particles from rising along the center tube outer wall and leaving the combustor prematurely.

In order to maintain a sufficiently high temperature environment in the upper burnout zone for improved combustion efficiencies, a refractory liner was added to cover the top water-cooled surface. This modification together with redistributing the fuel with the spray shaper, can boost the temperature in the burnout zone to 1,850°F. Tests showed that the improvement in burnout zone enabled us to burn CWF and dry powdered coals efficiently at high firing intensity and relatively low temperatures compared with most other combustors. With the measures mentioned above, >99% combustion efficiencies have been consistently achievable in firing CWF.

Test Results

Systematic tests on firing CWF have been conducted to accumulate performance data for VC design and operations, and to demonstrate the superiority of our VC concept. Test results on effects of the various controlling parameters such as excess air, firing rate, primary/secondary air ratio, center tube height and inlet configuration, and heat transfer surface arrangement were obtained and analyzed. Table 4.2 summarizes some of the major results of firing CWF. It should be noted that all CWF tests were carried out with combustion air at ambient temperature of around 50°F. The CWF tested contains 33-35% water by weight and has a mean coal particle size of 30 μm .

1. Effect of Excess Air

Excess air is one of the major operational parameters for combustion adjustments. It also affects the heat loss via stack gas and thus the system thermal efficiency. A series of tests was conducted for excess air ranging from 12% to 58%. Figure 4.3 shows the effect of excess air on combustion efficiency, gas temperature, and emissions. The combustion efficiencies ranged from 97.3% to 99.4%, with more recent results all above 99% (see Table 4.2, run Nos. 25, 28, 29, and 30). It appears that combustion efficiencies are above 99% around 25 % excess air, which was also observed in DUC firing (see Section 4.3). Figure 4.3 also shows that the combustion efficiency does not decrease with the decrease of excess air. This enables the VC to be operated at low excess air and hence high thermal efficiency.

NO_x and CO levels range from 200 to 600 ppm which were

Table 4.2 Major results of POC VC firing CWF.

Parameter	Run No.	24	25	26	28	29	30
Firing rate, MB/H		1.04	1.13	1.03	1.22	1.54	1.81
Center tube height, h/H		0.8	0.8	0.8	0.8	0.8	0.8
Excess air, %		40	27	48	13	26	34
Total air distribution, %							
Primary		8	15	13	12	9	6
Secondary		92	85	87	88	91	94
Secondary air distribution, %							
Nozzle L		40	40	40	30	20	20
Nozzle ML		40	40	40	50	60	60
Nozzle M		10	10	10	10	10	10
Nozzle MH		10	10	10	10	10	10
Nozzle H		0	0	0	0	0	0
Gas temperatures, °F							
Bottom		2098	2133	1996	2163	2132	2129
Middle		2091	2113	2030	1960	1931	1936
Top		1729	1879	1751	1825	1835	1754
Exit		1497	1683	1625	1708	1771	1790
Average		1847	1947	1847	1908	1913	1897
Heat removal, %							
By water		46	45	41	49	47	45
By flue gas		40	43	47	39	44	47
Emissions, ppm @ 3% O ₂							
NO _x		680	528	614	588	776	595
SO _x		325	417	385	308	244	201
CO		496	440	477	597	469	371
Thermal efficiency, %		87	88	87	88	89	89
Firing intensity, MB/Hft ³		0.16	0.17	0.16	0.18	0.23	0.27
Combustion efficiency, %		97.9	99.1	98.8	99.0	99.4	99.1

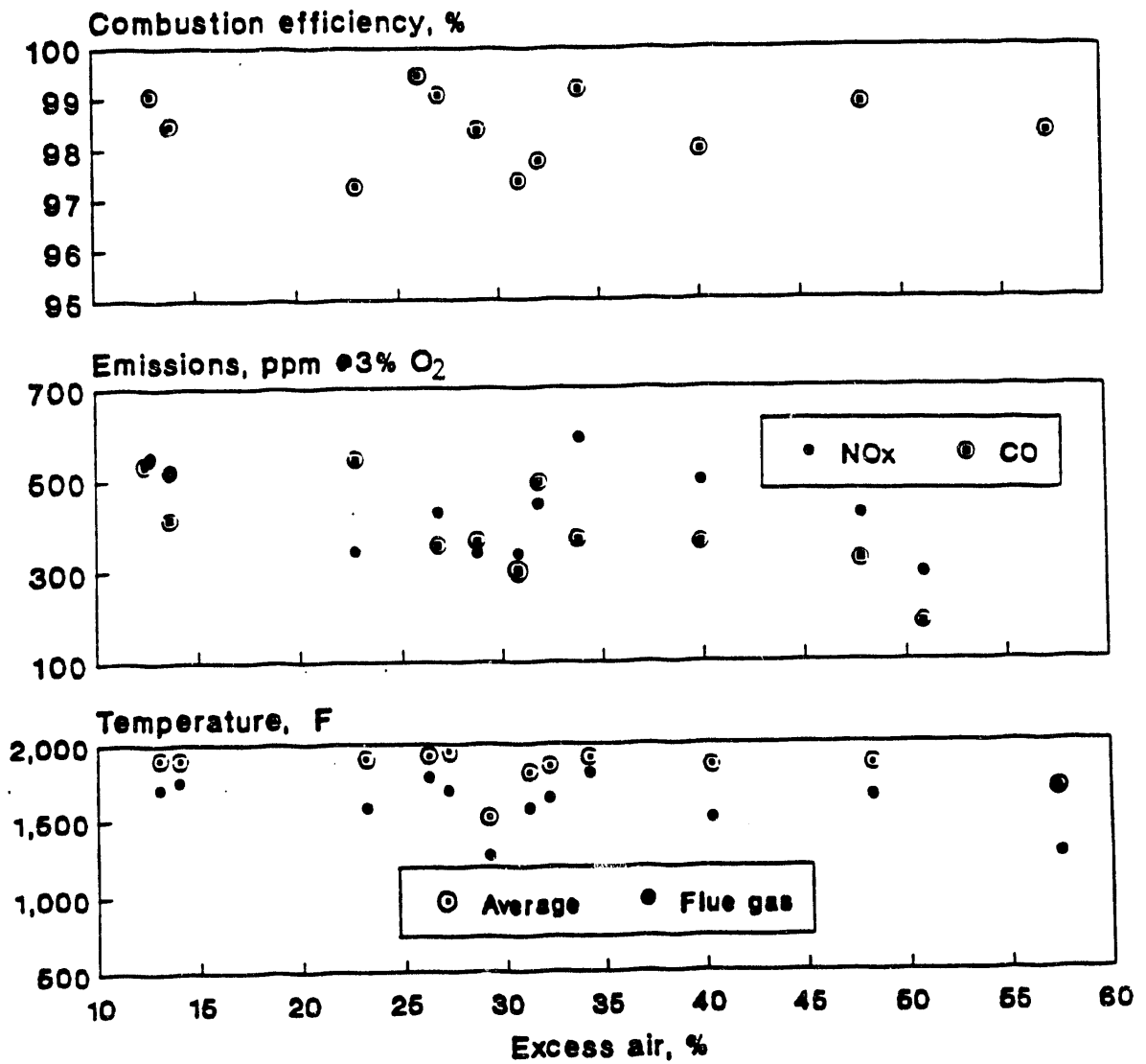


Figure 4.3 Effect of excess air on POC VC performance firing CWF.

obtained with no special effort in emission reduction. Since the VC design is effective in staging the air, the present results suggest a high potential for low NO_x combustion in VC firing. The exiting flue gas temperature and the average gas temperature decrease generally with the increase of excess air. The difference in temperature becomes higher at higher excess air.

2. Effect of Firing Rate

Figure 4.4 shows the combustor performance at firing rates between 1.0 and 1.9 MB/H. Stable ignition, self-sustained combustion, and high combustion efficiencies have all been achieved. All combustion efficiencies are above 97%, and the combustion performance is the best (>99%) at around 1.2 MB/H (or 0.2 MB/H ft^3). NO_x and CO levels generally increase with increasing firing rate and fluctuate within 200 ppm. The average gas temperature was found to be about 200°F higher than the flue gas temperature. Both temperatures seem to be relatively insensitive to the change of firing rates.

3. Effect of Center Tube Height

Figure 4.5 shows the test results at four center tube heights. The combustion efficiencies were 97.1%, 98%, 98.8%, and 97.4% for the center tube at $h/H = 0.6, 0.7, 0.8,$ and $0.9,$ respectively. The center tube height was found to have a significant effect on the combustor performance. The optimal height is around 0.8 at which the combustion efficiencies usually exceed 99%. When the center tube height increases, the levels of CO and NO_x tend to decrease. This trend is particularly clear for the CO level. A higher center tube generally gives somewhat higher

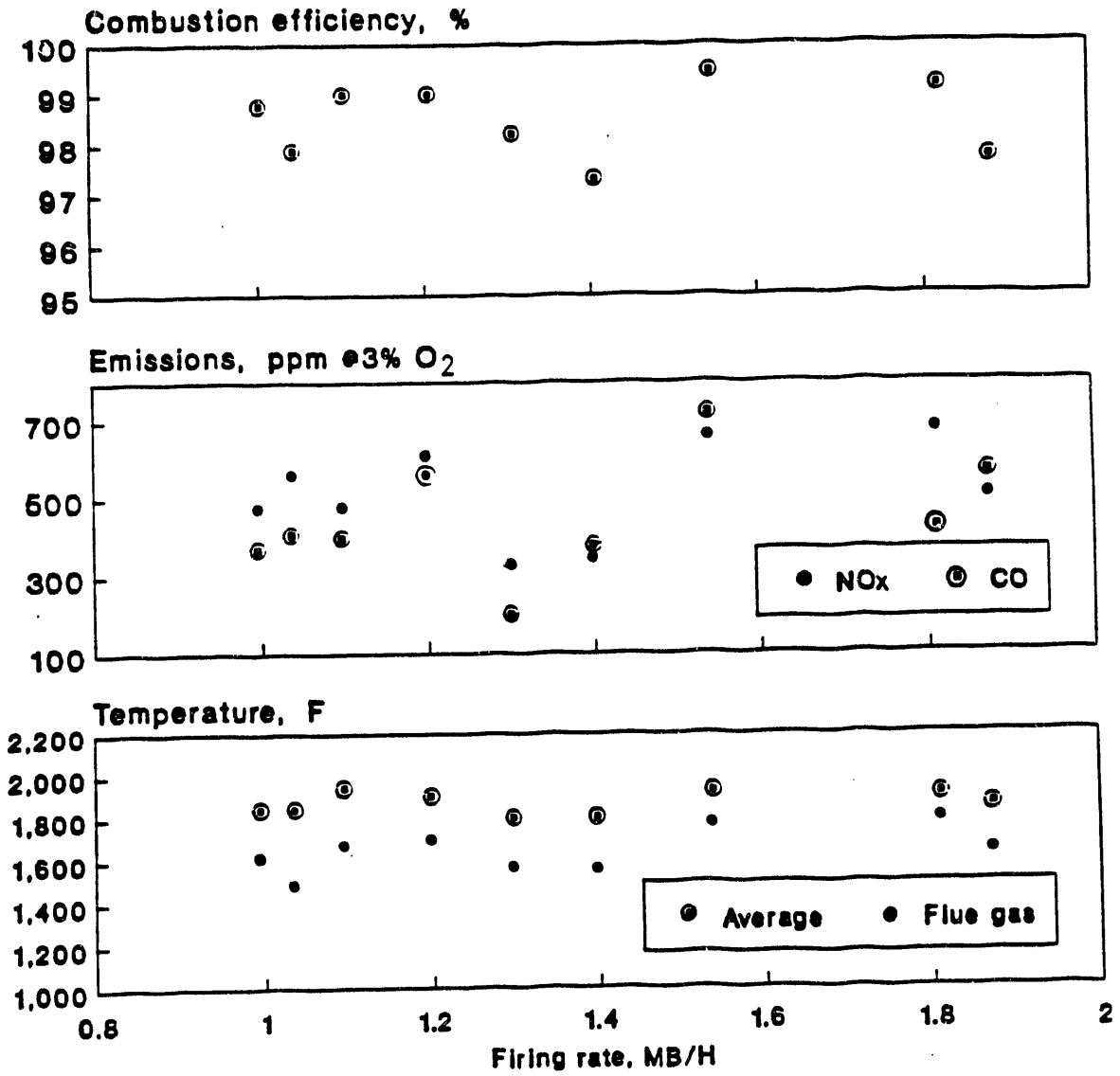


Figure 4.4 Effect of firing rate on POC VC performance firing CWF.

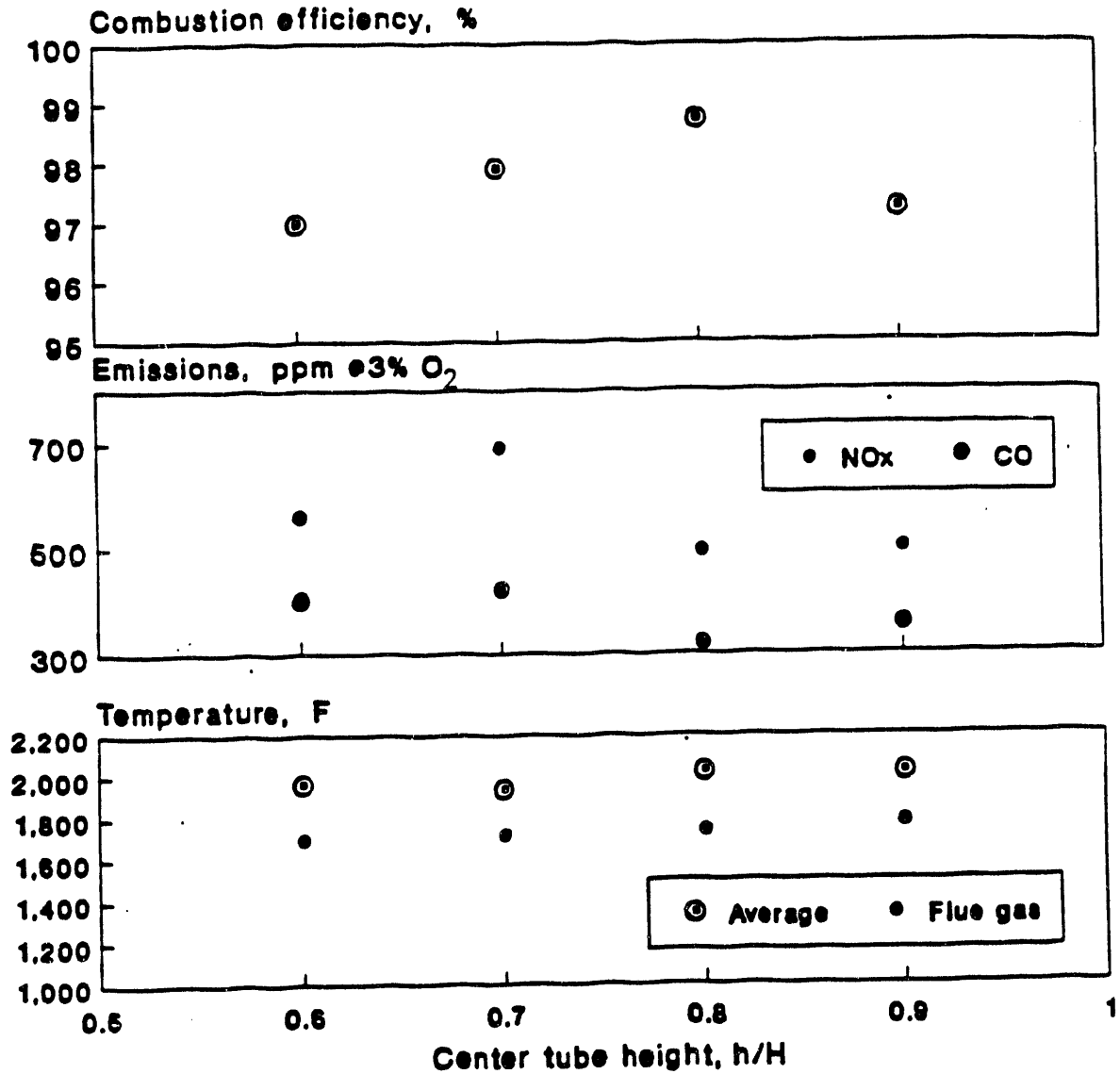


Figure 4.5 Effect of center tube height on POC VC performance firing CWF.

average and flue gas temperatures (within 100°F).

4. Effect of Inlet Configuration of Center Tube

The inlet configuration of the center tube may directly affect the local gas flow field, particle trajectory, and residence time, which in turn, affect the combustion performance. Exploratory studies with different configurations at the center tube inlet have been conducted. The results presented in Figure 4.6 show the comparison between a plain tube (original) and one with a flange at the lip (improved). A great improvement of combustion efficiency (~2%) was found with the flanged configuration. The effect of flange on NO_x level was not clear. It is very effective in reducing the CO levels, however, which suggests a substantial improvement of gas-gas mixing in the burnout zone with a flanged tube. At 25% excess air, a 3-fold improvement on CO emission (about 400 ppm reduction) was achieved with the flange. The average gas temperature in the combustor was about 100 °F lower, a result also of the presence of the flange on the center tube.

5. Effect of Refractory Liner

In order to improve the thermal environment for CWF ignition and burnout, the fraction of refractory-lined walls to total water-cooled walls was increased from 25% to 90%. This liner affects the local temperature, the combustion, and the heat removal capability. Figure 4.7 shows that the combustion efficiency was raised by about 0.5% when the refractory-lined area was enlarged from 25% to 90%. The average gas temperature increased by almost 200°F, as expected. NO_x emission was found to

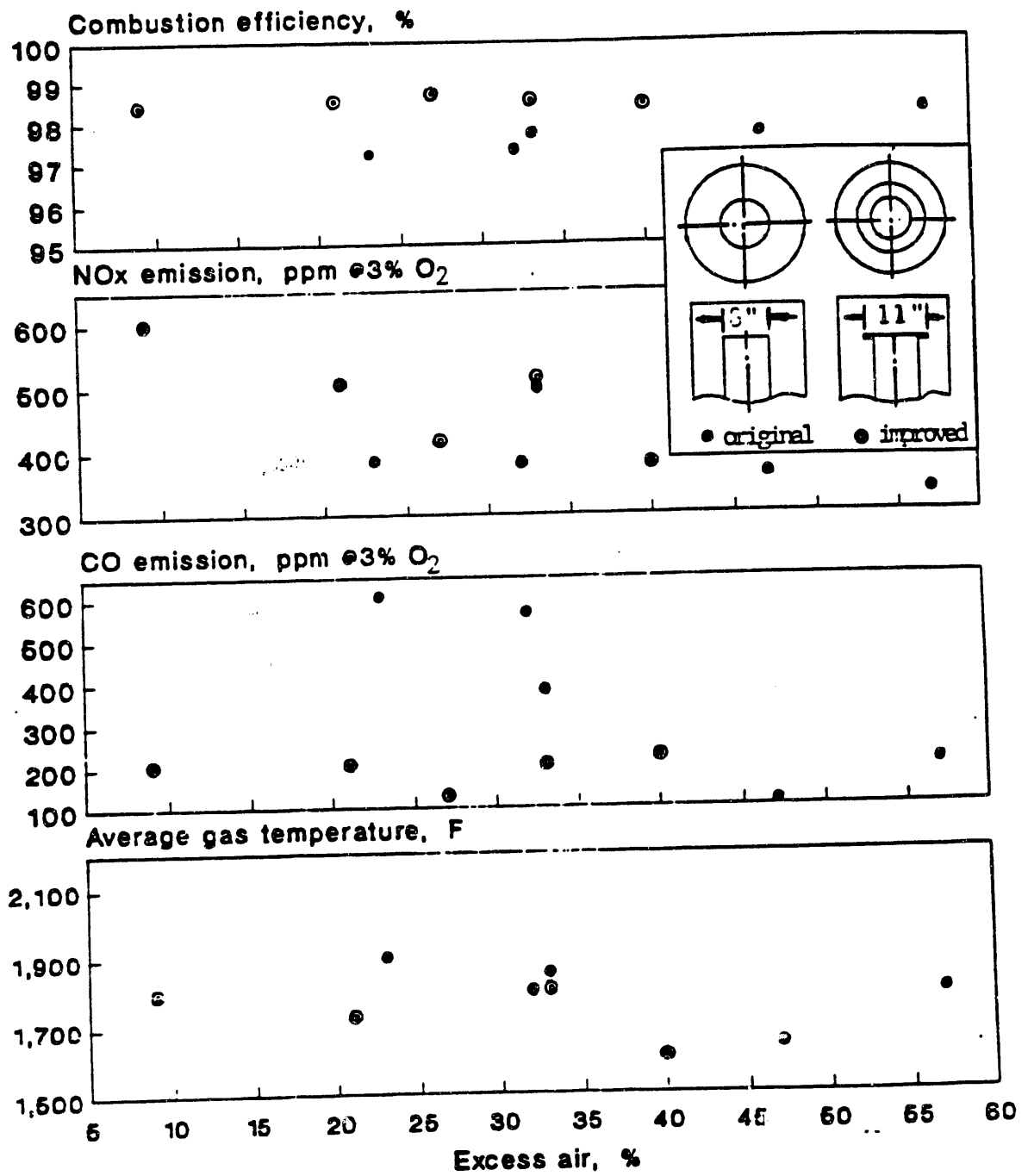


Figure 4.6 Effect of center tube inlet configuration on POC VC performance firing CWF.

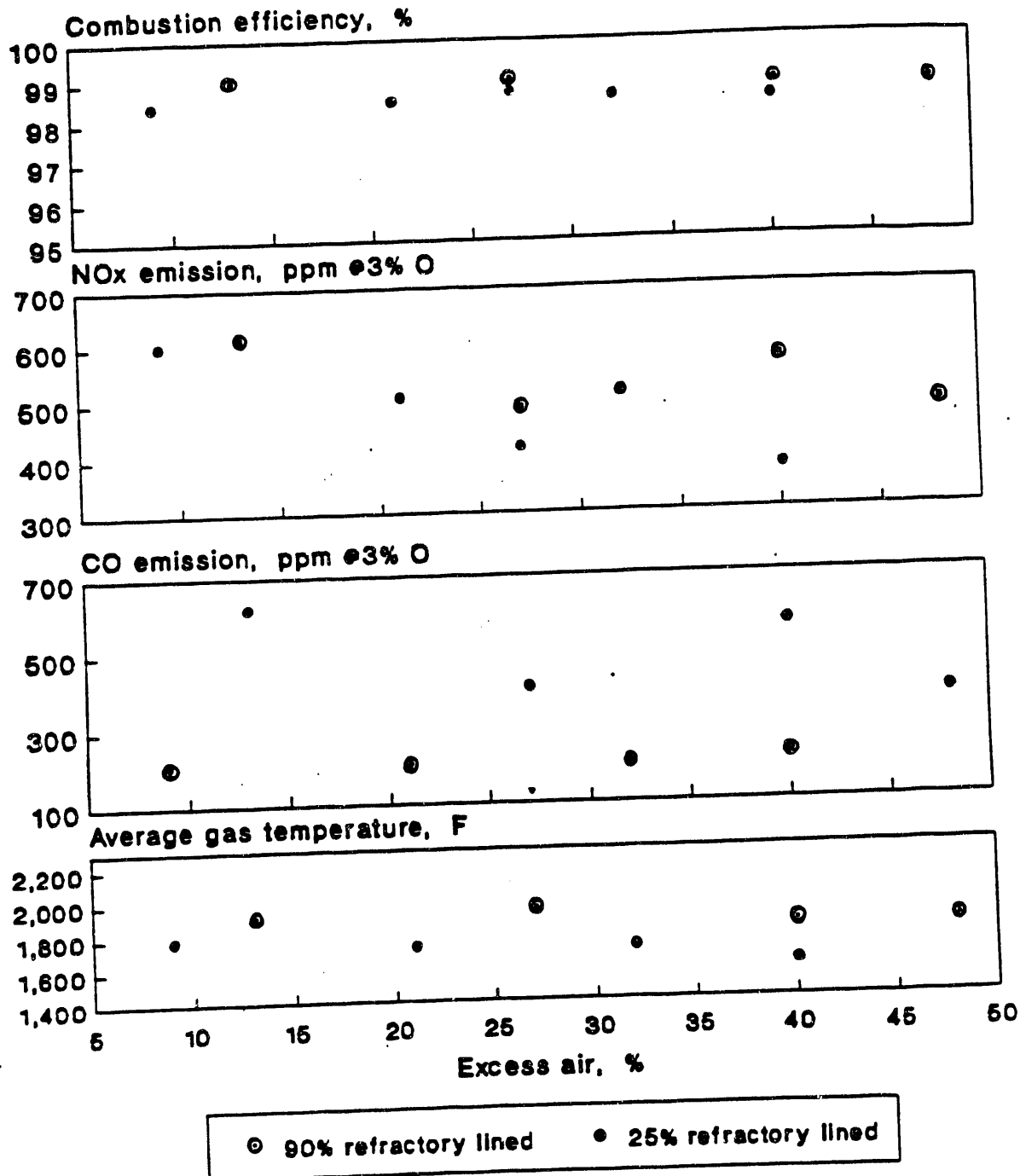


Figure 4.7 Effect of refractory liner on POC VC performance firing CWF.

increase by about 100 ppm and CO emission decreases by about 250 ppm. This is caused primarily by the higher temperature which promotes the formation of thermal NO_x .

4.3 DUC Test Results

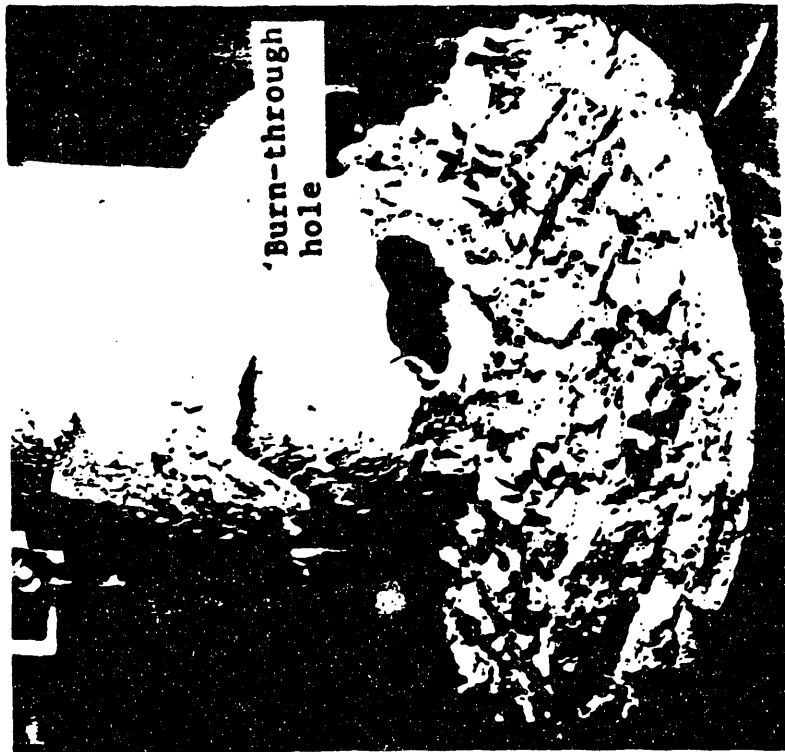
About 50 hours of combustion tests have been conducted in firing DUC. The systematic measurements and observations conducted are given in Table 4.1. Table 4.3 summarizes some of the major test results.

Performance Comparison of DUC and CWF

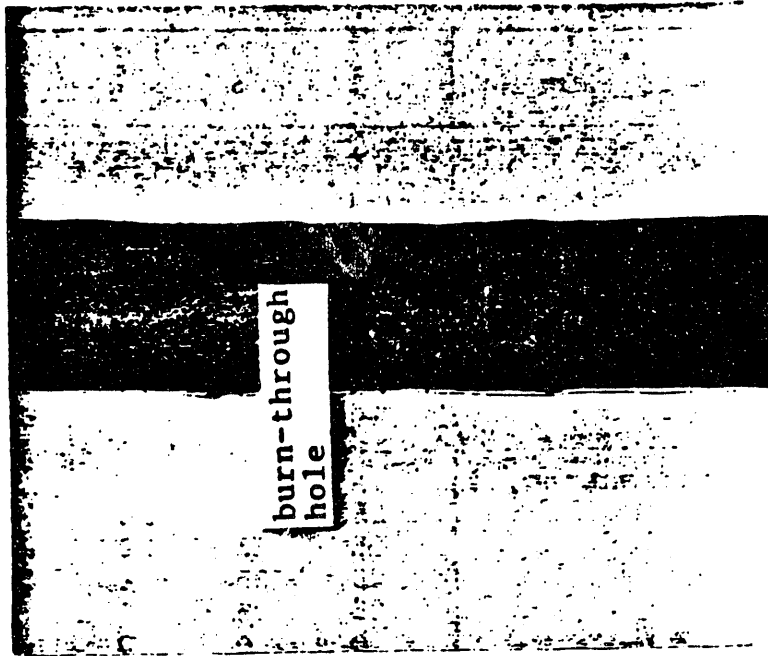
The major difference between DUC and CWF is their ignition characteristics. DUC contains less than 2% of moisture which will not cause delay or other problems as there will be for CWF in ignition. The average diameter of DUC ($12 \mu\text{m}$) is only $1/9$ that of the average CWF droplets ($106 \mu\text{m}$). This means that their particle masses or volumes may differ by 3 orders of magnitude. DUC can be ignited almost as soon as it enters the combustion chamber and burned very fast, resulting in a high temperature zone near the combustor bottom. The excellent ignition and combustion characteristics of DUC should present no difficulty in general in VC design and operation. However, since the POC VC model was designed for CWF firing, we encountered some difficulties in controlling the DUC combustion process under the same design configuration as for CWF. Higher temperatures can damage the combustor even in a few hours. Figure 4.8(a) shows a melted center tube made of $3/8$ " thick low carbon steel after a 6-hour continuous test of DUC at 1.5 MB/H. To contrast, Figure 4.8(b)

Table 4.3 Major results of POC VC firing DUC.

Parameter	Run No.	1	6	7	8	22	23
Firing rate, MB/H		1.36	2.02	0.65	1.52	1.13	0.81
Center tube height, h/H		0.9	0.9	0.9	0.9	0.8	0.8
Excess air, %		47	27	40	9	26	37
Total air distribution, %							
Primary		30	12	29	12	23	23
Secondary		70	88	71	88	77	77
Secondary air distribution, %							
Nozzle L		25	25	80	70	70	70
Nozzle ML		25	25	20	20	20	20
Nozzle M		25	25	0	10	10	10
Nozzle MH		25	25	0	0	0	0
Nozzle H		0	0	0	0	0	0
Gas temperatures, °F							
Bottom		2017	2669	2304	2264	2012	2338
Middle		1890	2205	1627	2003	2435	1913
Top		1477	1836	1429	1720	2097	1643
Exit		1231	1929	1152	1256	1879	1645
Average		1641	2144	1605	1795	2111	1871
Heat removal, %							
By water		40	47	51	56	46	54
By flue gas		42	49	28	30	44	40
Emissions, ppm @ 3% O ₂							
NO _x		378	500	455	600	578	567
SO _x		69	196	312	320	175	296
CO		109	153	266	203	571	453
Thermal efficiency, %		80	86	83	84	89	89
Firing intensity, MB/Hft ³		0.20	0.30	0.10	0.23	0.17	0.12
Combustion efficiency, %		97.6	98.7	98.4	98.4	98.3	99.0



(a) After 6 hours of tests (POC VC model)



(b) After 30 hours of tests (PEXP VC model)

Figure 4.8 Comparison of the burned-through center tubes firing DUC.

shows the burn-through hole in the center tube of the PExp model after 30 hours of tests.

Two measures were taken to resolve this problem: (1) a novel "fuel disperser" (similar to the "spray shaper" in CWF firing) was used to more evenly distribute the DUC in the combustor and consequently, the temperature in the ignition zone; (2) The amount of primary air and the distribution of secondary air were adjusted to delay the ignition and slow down the combustion. Tests showed that with these two measures the bottom "hot spot" was successfully eliminated and the combustor performance improved.

Test Results

1. Effect of Excess Air

Figure 4.9 shows the effect of excess air on combustion performance. The combustion efficiencies were all above 97%, and changed very little over the whole range of 6-47% excess air tested, indicating a stable combustion performance over a large operating range. The calculated thermal efficiencies follow the same trend and are around 85%. CO levels range from 150 to 300 ppm. Excess air in the range of 25-30% was found to give the best combustion efficiency (>99%) and thermal efficiency (>85%). Within the excess air range of 6-47%, NO_x levels range from 200 to 550 ppm, which is the case with no special efforts to fine tune the combustor for NO_x reduction. It is believed that less than 200 ppm NO_x level can be achieved if a nominal research effort is made. Figure 4.9 also shows the peak values of average gas and flue gas temperature occurring near 27% excess air.

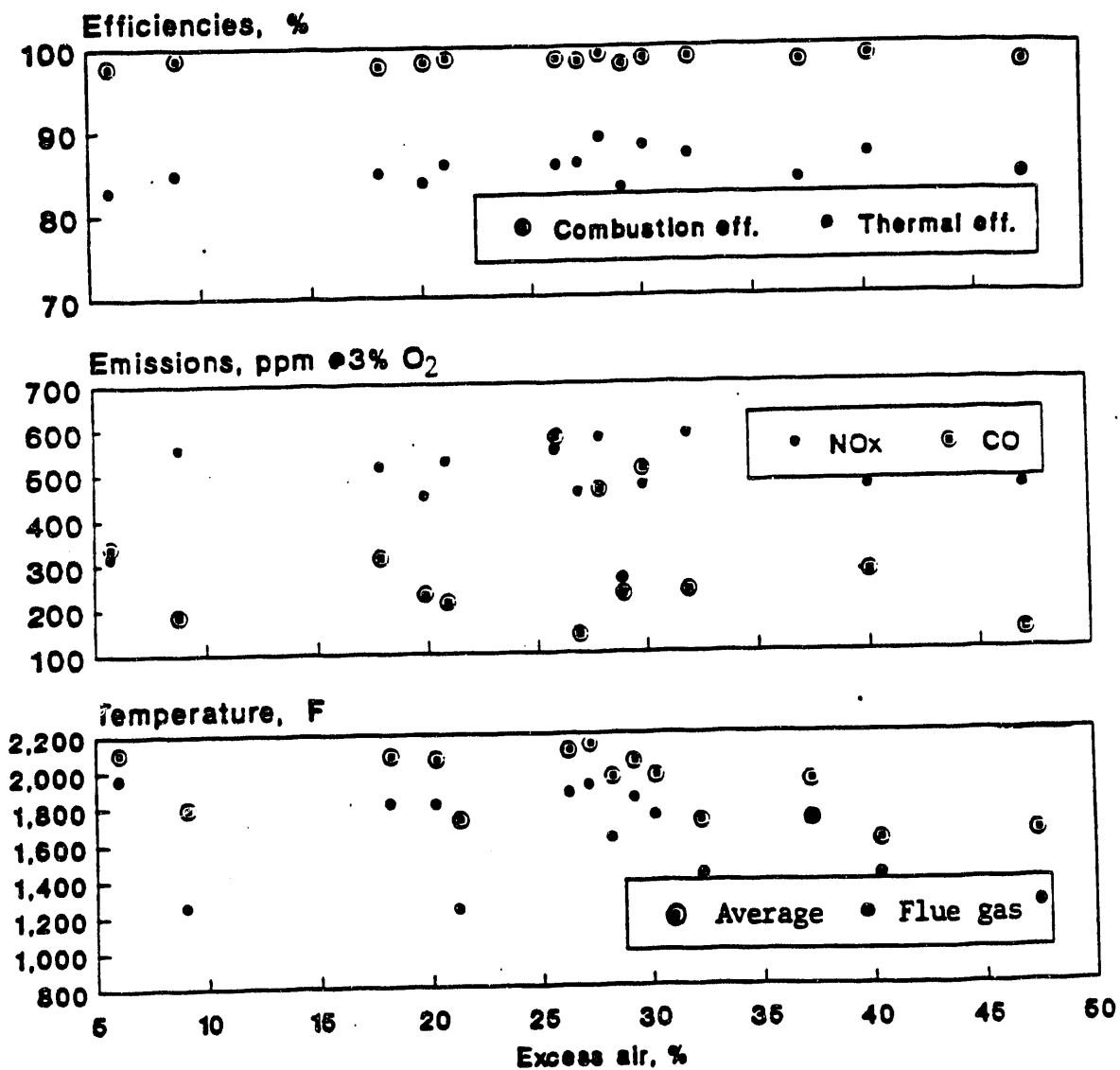


Figure 4.9 Effect of excess air on performance of POC VC firing DUC.

2. Effect of Firing Rate

Figure 4.10 shows the results of firing DUC in the range from 0.6 to 2.0 MB/H. The combustion efficiencies range from 97.4% to 99.1%. In the optimal firing range (1.3-1.5 MB/H), the combustion efficiencies were all above 99%. Results also show that the combustion efficiency doesn't seem to be adversely affected by the firing rates in the three-to-one turndown range. Little effect of firing rate was found on emission levels either. NO_x and CO levels are all within 550 ppm. Different from what was concluded for CWF combustion, the average gas temperature in DUC combustion increases consistently with the firing rate, as expected.

3. Effect of Primary/Secondary Air

The amount of primary air directly affects the ignition and temperature near the combustor bottom. Secondary air will affect the ignition, combustion, and burnout of the fuel through swirl intensity, particle flow control, timing of oxygen supply, and local mixing of fuel and air in the combustor. As shown in Figure 4.11, for primary air ranging from 10% to 30%, the combustion efficiencies are all above 97%. At 23% primary air, the combustion efficiency exceeds 99%. The available secondary air fraction of 77% for this case is considered adequate for combustion performance adjustments. As the primary air increases, the level of CO increases and the level of NO_x decreases, a result believed to be due to the decrease in gas temperature. The average temperature drops about 400 °F when primary air increases from 10% to 30%.

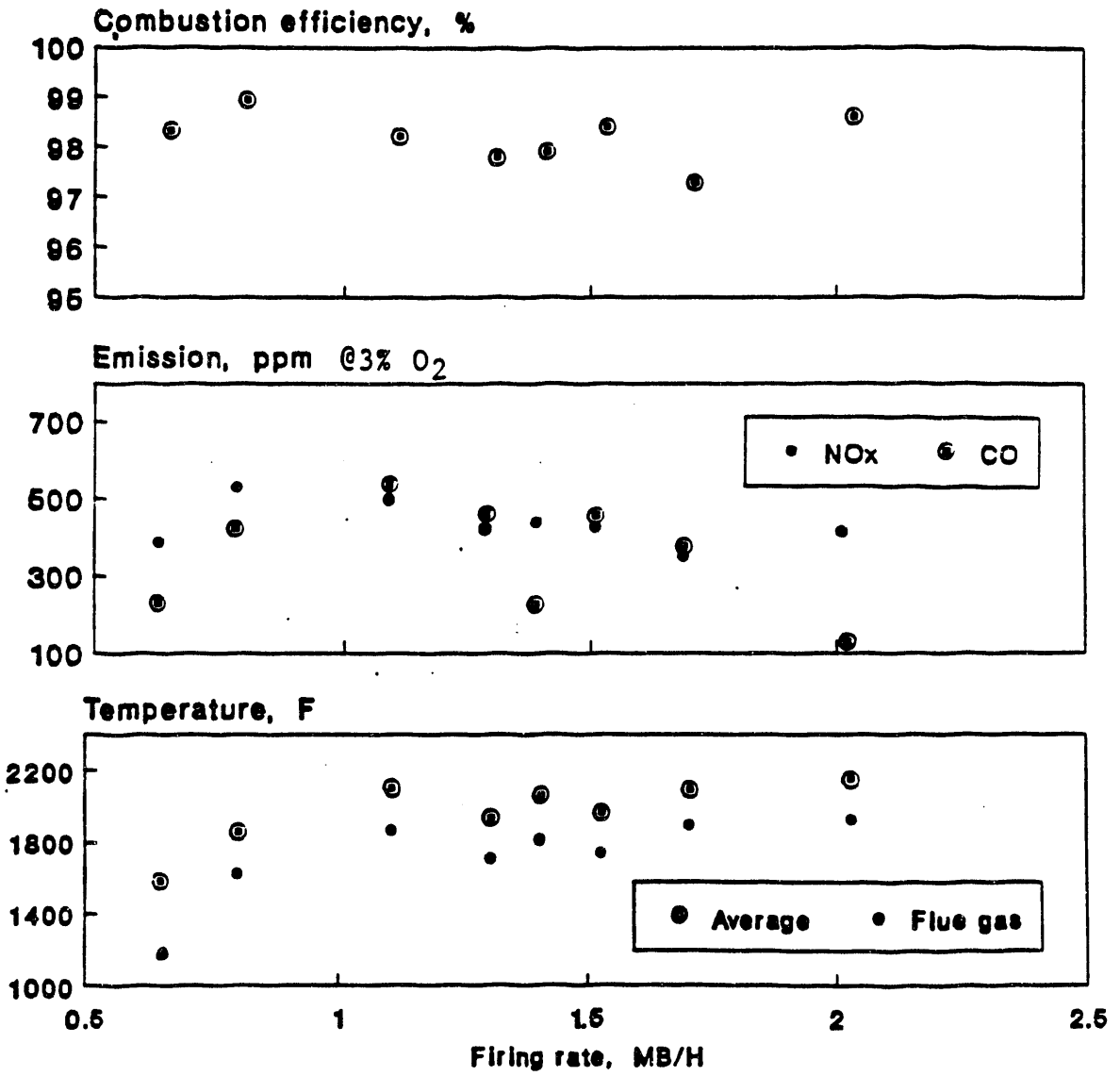


Figure 4.10 Effect of firing rate on POC VC performance firing DUC.

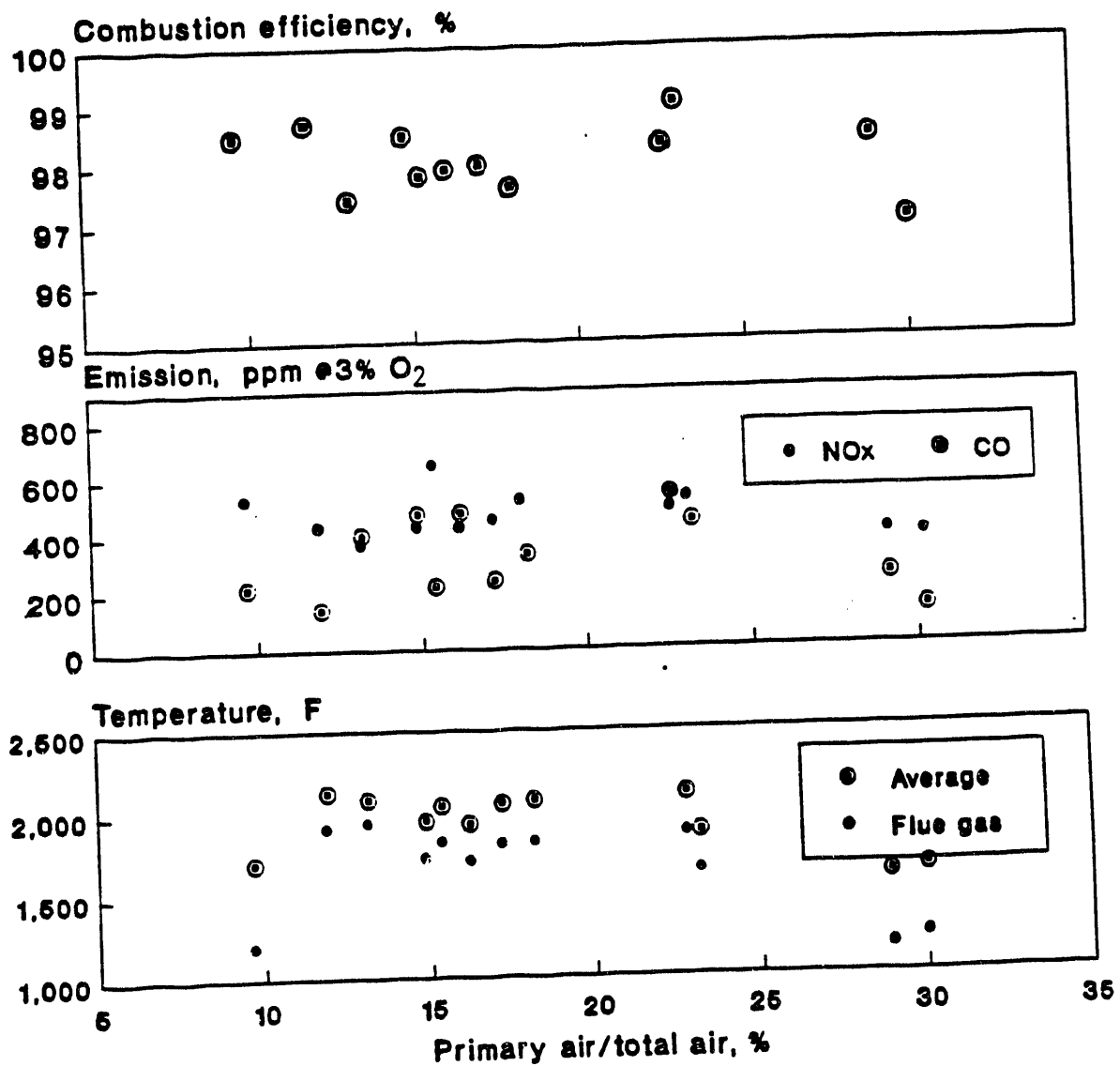


Figure 4.11 Effect of primary air on performance of POC VC firing DUC.

As also was observed in Exp VC model tests that the secondary air injection in POC VC model has a noticeable impact on combustor performance. It can control, to some extent, the uniformity of combustion temperature and particle elutriation (or residence time). The use of multiple air nozzles and the center tube enables the temperature distribution largely controllable by secondary air injection. Combined with heat transfer surface adjustments, a large degree of flexibility in combustion control may be realized in a VC.

4.4 PC Test Results

Combustion tests with PC were conducted to further evaluate the fuel flexibility of the POC VC model. As mentioned in Chapter 2, PC differs from DUC only in particle size. The mass or volume of an average PC particle (30 μm) is 17 times larger than an average DUC particle (11.7 μm). The controllability and flexibility in firing different size particles in VC have been studied in the POC VC model. Table 4.4 summarizes the major results.

Performance Comparison of PC and DUC

Larger fuel particles need longer times to completely burn. Compared with DUC, PC was expected to have a lower combustion efficiency under the same operating conditions. It was quite astonishing to find that combustion efficiency as high as 98.7% was achieved for PC, being almost the same as DUC. Our results further demonstrate the superior performance of the VC concept in

Table 4.4 Major results of POC VC firing PC.

Parameter	Run No.	12	13	14	15	16
Firing rate, MB/H		1.53	1.53	1.53	1.53	1.53
Center tube height, h/H		0.9	0.8	0.6	0.9	0.8
Excess air, %		49	28	28	31	10
Total air distribution, %						
Primary		12	18	14	16	17
Secondary		88	82	86	84	83
Secondary air distribution, %						
Nozzle L		90	90	90	90	90
Nozzle ML		5	5	5	5	5
Nozzle M		5	5	5	5	5
Nozzle MH		0	0	0	0	0
Nozzle H		0	0	0	0	0
Gas temperatures, °F						
Bottom		2084	2455	2516	2476	2446
Middle		2062	2100	1789	2071	1956
Top		1641	1843	1692	1798	1681
Exit		1382	1735	1900	1778	1717
Average		1782	2020	1958	2017	1934
Heat removal, %						
By water		44	46	53	47	56
By flue gas		42	43	38	42	32
Emissions, ppm @ 3% O ₂						
NO _x		718	540	485	552	656
SO _x		532	357	97	98	310
CO		607	344	614	391	398
Thermal efficiency, %		83	88	89	85	85
Firing intensity, MB/Hft ³		0.23	0.23	0.23	0.23	0.23
Combustion efficiency, %		97.2	98.7	97.1	97.2	97.1

fuel flexibility. Compared with DUC, the only differences found in PC combustion tests are: it is easier to clinker and inferior in ignition characteristics. Understandably, the ignition of PC is a longer process. Because of the centrifugal force, PC particles tend to slide or rotate on the combustor wall, and collide with each other and form clinker on the wall. During the devolatilization processes, viscous soot may also be produced which promotes agglomeration and clinker formation.

Adjustment of combustion air distribution was used during the tests to prevent clinker formation. More air was injected into the lower portion of the combustor so that a vigorous turbulent flow and a more oxygen-rich atmosphere were produced in the ignition zone which accelerated PC devolatilization and combustion of volatiles, and reduced the formation of viscous soot. In this way, clinker was prevented and the operations became satisfactory.

Test Results

Systematic tests of the effect of excess air on PC combustion in POC VC model were conducted for a total of 20 hours. Figure 4.12 shows the results (see also Table 4.4). For excess air ranging from 10% to 50%, the combustion efficiencies were higher than 97%. The optimal range of excess air was 25-30%, the same as for DUC and CWF firing. The highest combustion efficiency was 98.7%, slightly lower than those from DUC and CWF firing. NO_x and CO levels range from 500 to 650 ppm and 350 to 600 ppm, respectively. As excess air increases, both levels reduce slightly. The average gas and flue gas temperatures decrease

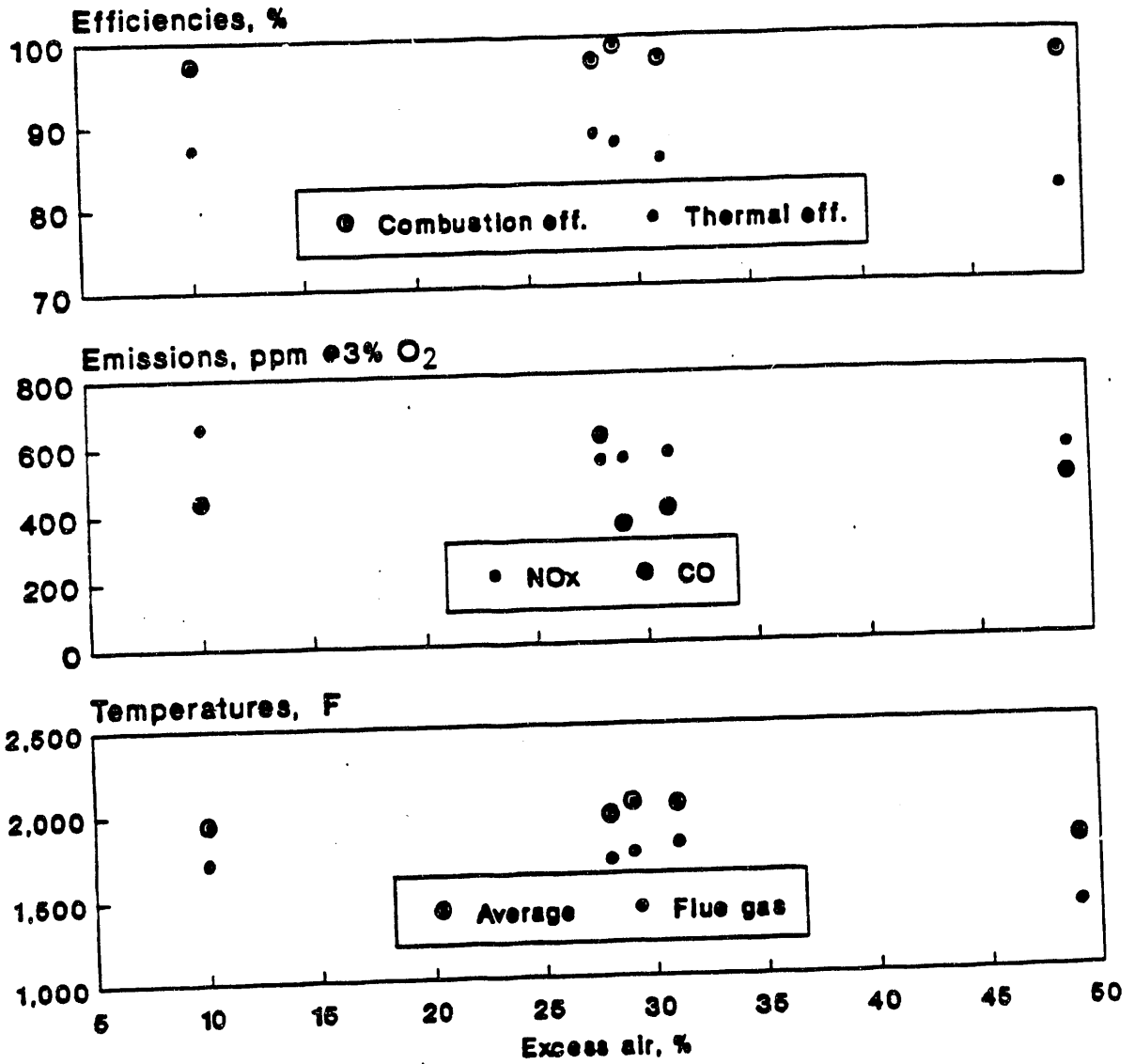


Figure 4.12 Effect of excess air on performance of POC VC firing PC.

with the increase of excess air. The temperature drops about 200°F when excess air changes from 10% to 50%. The average gas temperature was about 2,000°F in the optimal excess air range of 25-30%.

4.5 Discussions

The combustion of coal fuels may be considered roughly in three overlapping stages: water evaporation, devolatilization and ignition, and homogeneous combustion of volatiles and heterogeneous combustion of char. Different water contents and fuel particle sizes normally will require different design and operational adjustments of the combustor to ensure stable and complete combustion. Large water content may delay the ignition and slow down the early-stage combustion processes because of the low surrounding temperature and high water vapor concentration (or dilute oxygen distribution). Fuel particle size is critical for ignition and burnout. In most traditional designs of coal combustors or burners, little flexibility on fuel properties and particle sizes can be tolerated because they significantly affect the performance of flame stability, temperature distribution, boiler rating, and combustion efficiency. The test results presented in this chapter, strengthened by our cold model results [11], have conclusively demonstrated the superiority of the VC concept in high combustion efficiency, good operational performance, and fuel flexibility, a significant stride in coal combustion technology.

With regard to fuel flexibility, the POC VC model has demonstrated its potential to burn both dry powdered coals and coal-water slurries as illustrated in Figure 4.13. When burning these fuels: DUC (12 μm mean diameter), PC (30 μm mean diameter), and CWF (106 μm mean droplet diameter), on-time ignition, stable flame, intense combustion, and high combustion efficiency (>98.7%) have all been achieved. It should be noted that many large particles with diameters above 300 μm could exist in the combustor when burning either PC or CWF with poor atomization and aggravated agglomeration. The POC VC model can ignite and effectively burn these fuel particles to completion. This performance of fuel flexibility is attributed to the inherent superiority of the VC concept: long and controllable residence time, vigorous recirculations, intense turbulent mixing, and large gas-particle slip motion.

Figure 4.14 illustrates the advantage of the VC on fuel particle residence time. Assuming perfect mixing, the burnout time needed for coal particles increases almost linearly with particle diameter with the slopes depending on the average combustion temperature. The residence time, however, increases rapidly with particle diameter due to the interaction of strong centrifugal force and gravity. It is seen also that the particle residence time is always longer than the needed burnout time in a VC, a fact especially prominent for large particles. It should be noted that both particle residence time and burnout time may be sensitively affected by the aerodynamic structure of the

	DUC		PC	CWF	
Firing rate, MB/H	2.02	0.8	1.53	1.1	1.54
Excess air, %	27	27	28	27	26
Average temp., °F	2180	1884	2133	1951	1917
Combustion eff., %	98.7	99.0	98.7	99.1	99.4
Thermal eff., %	86	88	86	88	88

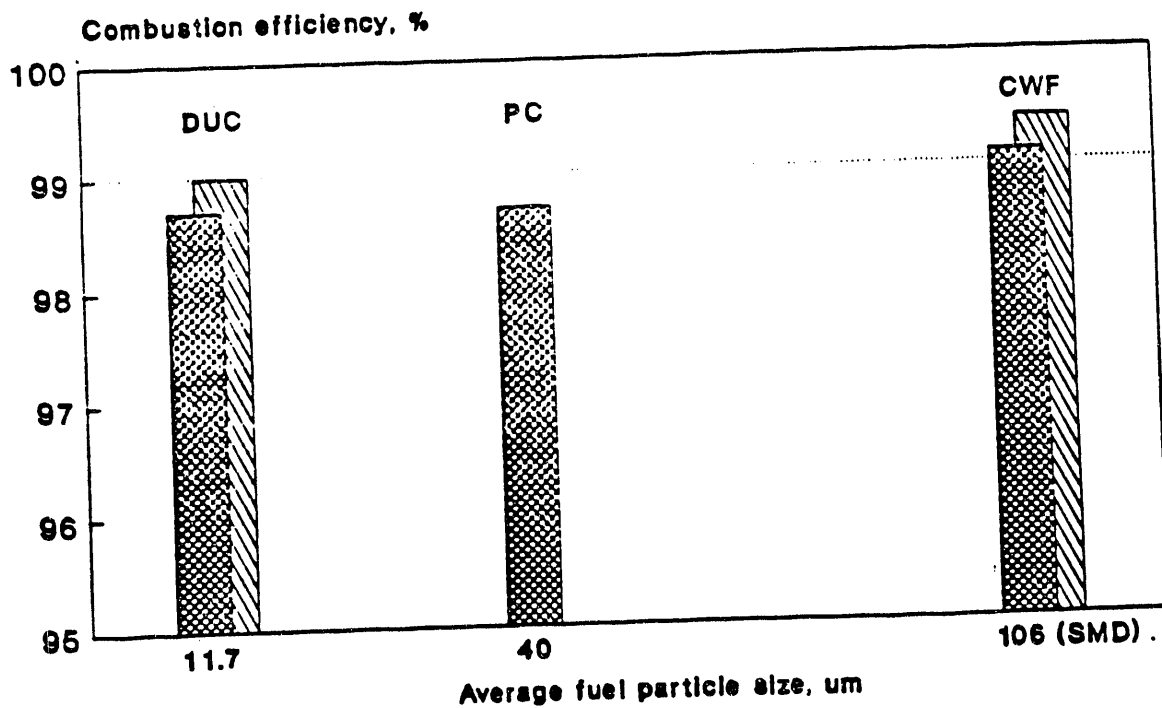


Figure 4.13 Fuel flexibility of POC VC model.

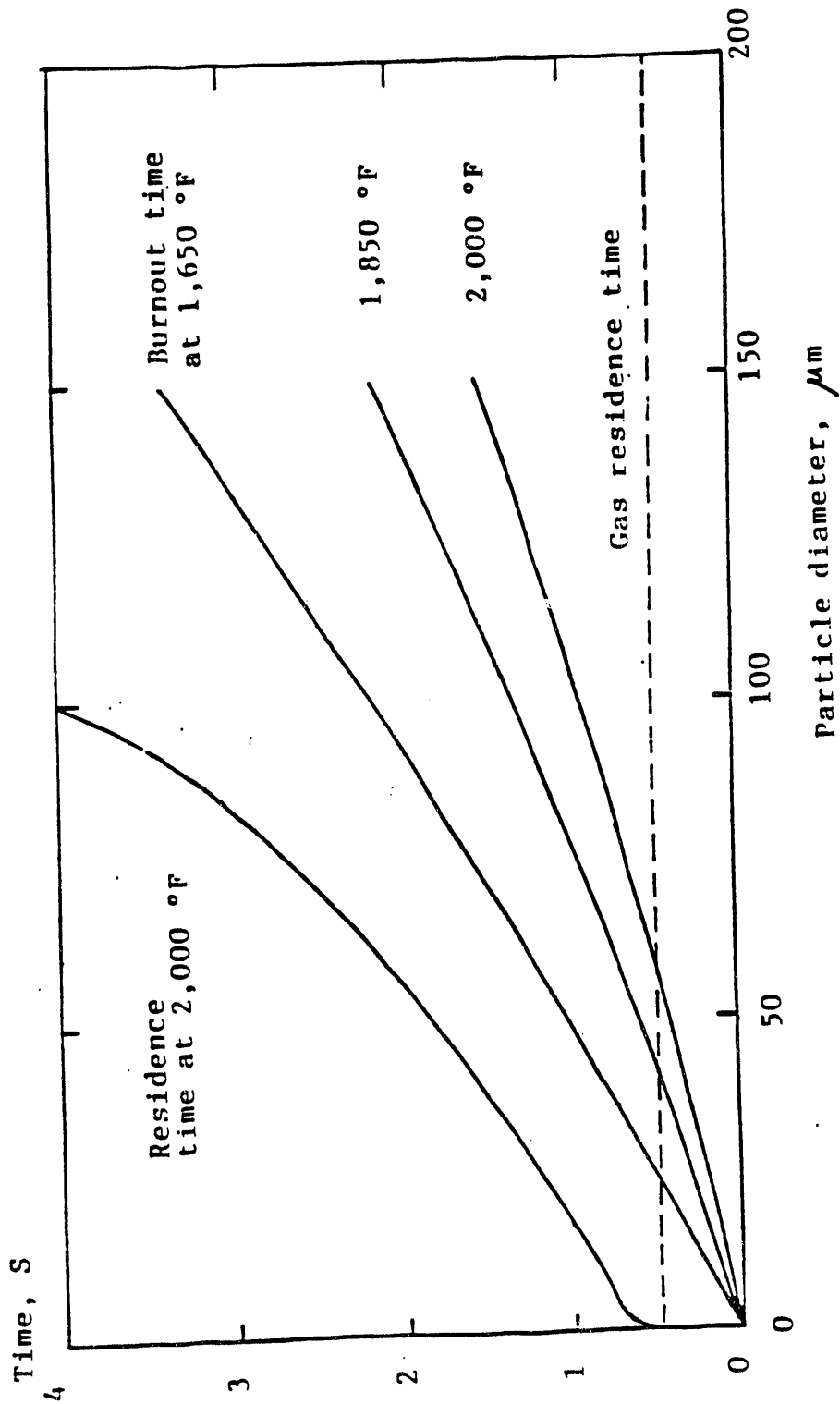


Figure 4.14 Particle residence time in a VC.

combustor which can be effectively controlled by means of secondary air injection. This feature of VC helps achieve high combustion efficiency, burning lower grade fuels, suppressing particle elutriation, and reducing pollutant emissions.

CHAPTER 5

ECONOMIC ANALYSIS AND NUMERICAL CALCULATIONS

5.1 Operational Concept

The operation and maintenance (O&M) costs, extent of system automation, and fuel supply/ash removal network for small coal-fueled boilers can significantly impact the overall economics, serviceability, and maintainability. Conventional practice using dedicated O&M crew for small coal-fueled boilers can hardly compete with oil- or gas-fired boilers of equivalent capacity.

Because of the simplicity in design and operation, it is possible to operate VC systems unattended using automatic controls. A centralized O&M concept serving a group of VCs is proposed here. This centrally located service center will, on a regular basis, deliver the fuel and collect and dispose of the ash, conduct scheduled maintenance and unexpected repairs, etc.. Figure 5.1 is a schematic showing this concept where a center of about 30 persons will serve about 100 VC systems. The operations between the center and satellite VC systems will be monitored and controlled via Energy Management Control System (EMCS). In this fashion, dedicated operators are eliminated and O&M costs greatly reduced.

The VC and the required various auxiliary subsystems can be easily packaged into a turnkey steam or hot water generating system made up of individual functional modules such as: the

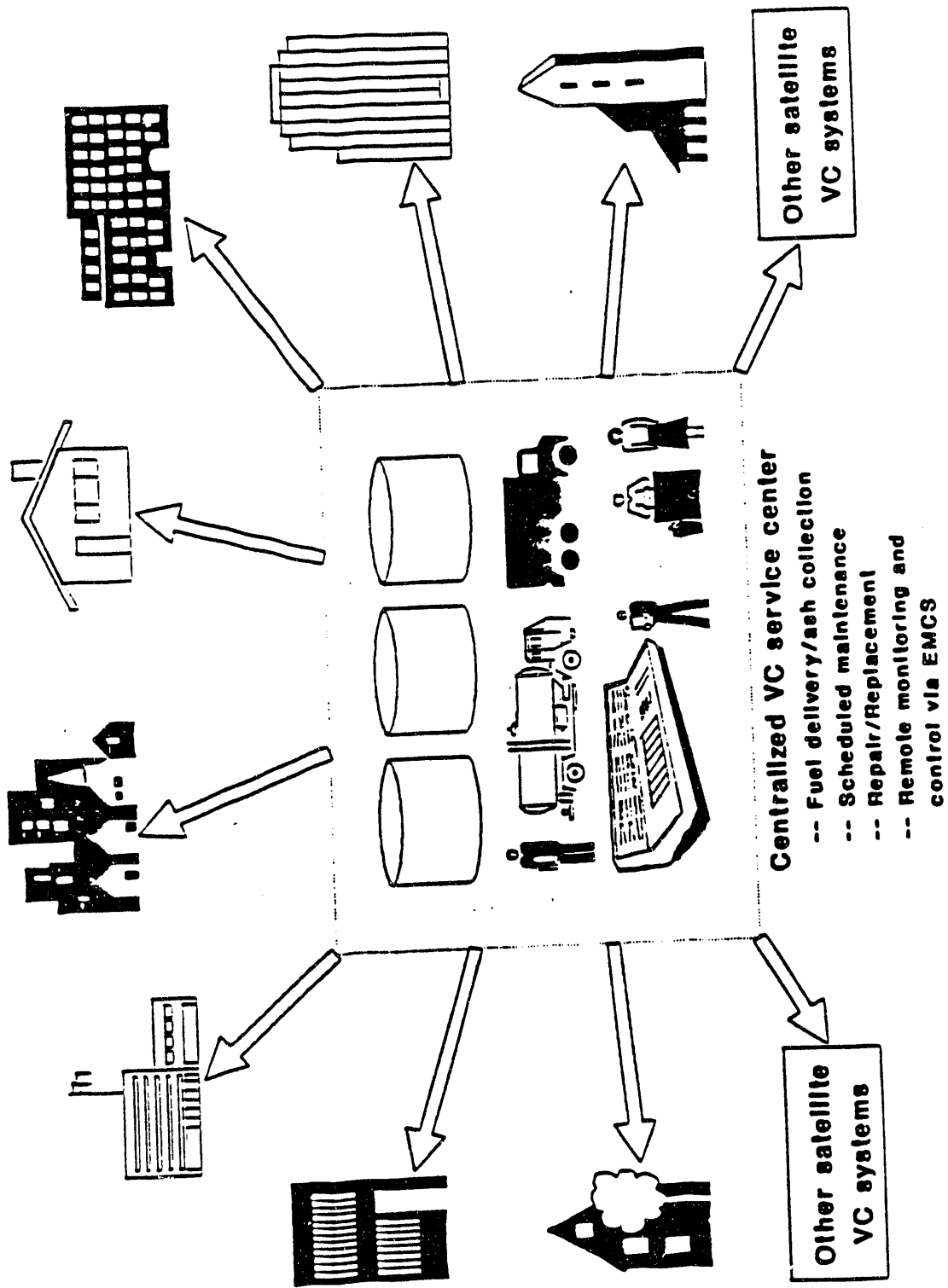


Figure 5.1 Centralized O & M concept to serve a group of satellite VCs.

combustor itself, steam/hot water generator, baghouse/ash collector, fuel/air supplies, flue gas exhaust, controls, etc. These will be completely shop-assembled, packaged, and tested. The complete VC system will fit into the envelope of a standard 8'x8'x20' shipping container for easy shipment and fast installation. The system will be automatically controlled and operated unattended. All scheduled routine inspection and servicing and unscheduled repairs will be conducted by technicians from the service center.

5.2 Basis of Economic Analysis

The development of CWF has provided the industry with a new fuel option. In general, retrofit of existing oil firing boilers to CWF firing may encounter problems such as boiler derating, space limitation on auxiliary equipment, fouling and erosion/corrosion of heat transfer surface, high modification costs, and high O&M costs. Thus, retrofitting oil-fired boilers to CWF firing is unlikely to be economically attractive at the present time, especially for the small and medium size boilers concerned here.

The economic analysis, therefore, is based only on a new, prepackaged, turnkey unit of VC space/water heating system firing CWF. It includes capital investment, operating cost estimates, and related sensitivity analysis. The firing rate of the VC heating system considered here is 4 MB/H (producing 2,800 lb/H saturated steam at 120 psig or equivalent amount of hot water) at a system thermal efficiency of 85%. The annual capacity factor is assumed to be 80% typical for heating applications in hospi-

tals or other commercial buildings in mid-Atlantic states. Major assumptions and data used in the economic analysis are given in Table 5.1 below.

Table 5.1 Major data used in economic analysis.

DESIGN CONDITIONS:		
Fuel	Deep-cleaned CWF	
Atomization medium	Compressed air	
Combustion efficiency, %	99	
Energy input, MB/H	4	
Steam output, lb/H (MB/H)	2,800 (3.4)	
Steam pressure, psig	120	
Steam temperature (saturated), °F	341	
Feedwater temperature, °F	68	
Air temperature, °F	68	
Excess air, %	20	
Dimension of system, LxWxH, ft	8x8x20	
Annual capacity factor	0.8	
FUEL PROPERTIES:		
Fuel price, \$/MB	4.1	
Mean parent coal size, μm	15	
Ash content, wt%	1.0	
Sulfur content, wt%	0.42	
Moisture, wt%	34.5	
Solid loading, wt%	65.5	
Heating value, Btu/lb	9,740	
MATERIAL CONSUMPTIONS:		
	<u>Hourly</u>	<u>Annually</u>
CWF	411 lb	1439 ton
Air	39,060 Nft ³	274 MNft ³
Limestone	(optional)	
Makeup water	280 lb	981 ton
Electricity	21 kw	147,000 kWh
Chemicals	(optional)	--
WASTE GENERATION:		
Flue gas	51,840 Nft ³	363 MNft ³
Ash	4.1 lb	13 ton
Sulfur Dioxide (max.)	0.006 lb	42 lb
Nitrogen oxides (@200 ppm)	1.17 lb	8,190 lb
Waste water	140 lb	491 ton

5.3 Cost Estimates

The primary criteria for selecting a heating system are minimal initial and operating costs so that the steam or hot water may be supplied to the consumers at the lowest possible price. In general, a number of factors, such as energy policy, zoning regulations, maturity of the technology, capital costs, fuel prices, prevailing interest rate, and inflation index would affect the "bottom-line" economics of a heating system and its performance trade off. Here we shall simply consider the capital investment and operating cost of a 4 MB/H VC heating plant firing CWF.

Equipment Costs

There are several commonly used capital cost estimating methods which vary in accuracy depending on the stage of development of the project. The method of purchased cost factors is used here because it considers certain cost categories in a turnkey project, such as installation costs, freight and taxes, etc. as a fixed percentage of the equipment costs. This method is useful for determining whether the heating system merits further consideration and for comparing with other alternative designs [31,32].

Table 5.2 summarizes the costs of major equipment of a shop-assembled, packaged VC heating system. The costs of individual equipment is given on an FOB basis. These costs were obtained either directly from quotations of equipment vendors, or using conventional engineering practice, or based on our experience accumulated from this research. All cost data are converted to

Table 5.2 Cost estimates of a 4 MB/H packaged, CWF-fired VC heating system.

Item/Equipment	Specification	Cost, \$	Cost, %
1. CWF storage/handling:			
Main storage tank	2,000 gal, with heating coil and agitator, carbon steel	10,260	
Day tank	150 gal, carbon steel with filter	3,270	
Transfer pump	Rotary pump, 0.2 cfm, 1.5 hp	850	
Feed pump x 2	Progressive cavity pump, speed adjustable, 120 psi, 0.1 cfm	4,050	
Compressor	120 psi, 60 cfm, 1 hp	<u>900</u>	
		19,330	19.6
2. Combustor and boiler:			
Boiler	Fire tube boiler, 158L x 2D 100 tubes, vortex combustor, 56H x 24D	35,000	
Forced draft fan	720 scfm, 15 hp	5,040	
Feedwater pump x 2	Centrifugal, 10 & 100 gpm, 1/2 hp	1,340	
Make-up water system	500 gal tank, stainless steel, zeolite water softener	1,200	
		<u>42,580</u>	43.1
3. Flue gas/ash system:			
Baghouse	800 ft ² filter area, 4" water	8,640	
Flyash remover x 2	Intake electrical valve	2,000	
Induced draft fan	1,200 scfm, 15 hp	<u>3,360</u>	
		14,000	14.2
4. Instruments/control:			
30% of items 1-3		22,773	23.1
5. Total equipment cost (5-8)		98,683	59.0
6. Freight, insurance, tax (8%), 10%*		9,869	5.9
7. Installation cost, 17%		16,776	10.0
8. Others direct cost, 18%		17,763	10.6
9. Total direct cost (5-8)		143,091	85.5
10. Engineering and construction, 5%		4,934	2.9
11. Total system cost (9,10)		147,025	87.9
12. Contractor's fee, 6%		5,921	3.5
13. Contingencies, (10% of item 11)		14,309	8.1
14. Total fixed-capital cost (11-13)		167,255	100.0

* Percentages of items 6-12 are based on item 5.

January 1990 dollars based on the Marshall and Swift all-industry index [33]. It is estimated that the costs of instrumentation and control devices are 30% of other equipment costs.

Fixed Capital Investment

Before an industrial system can be put into operation, fixed capital investment is needed to cover costs of shipment, erection, building renovations and additions, minor equipment, piping and installation, instrumentation, etc.. The cost breakdown for a grass-roots VC heating system is shown in Table 5.2 [31,32,34].

Brief explanations are given below:

- o Freight and taxes - The sales taxes, freight, and insurance charges of purchased equipment are estimated to be 10% of item 5 of Table 5.2 [31].
- o Installation cost - Costs for equipment installation and integration with other tie-ins at the operation site, at the cost of insulation and painting depending on the type of equipment, materials of construction, and degree of preinstallation in the fabricator's shop. The installation costs factors for each subsystem in Table 5.2 are estimated differently [31,32]. The average factor is about 17% of item 5.
- o Other direct costs - Other costs, such as electrical facilities, buildings, and site improvement are estimated to be 18% of item 5 [31,32].
- o Engineering and construction - The costs for construction design, engineering drafting, technical document preparation, project management, and start-up cannot be directly charged to equipment, materials, or labor in capital investment. It is normally considered as an indirect cost and is estimated to be 5% of items 5 [31,32].
- o Contractor's fee - The contractor's profit is estimated to be 6% of items 5 [31].
- o Contingencies - The contingency factor is to compensate for those overlooked or unanticipated elements and unpredictable expenses. It is estimated to be 10% of the total system cost [31,32].

General Cost Estimates

For lack of better information, the estimates for the 4 MB/H system presented above and the five-tenths rule below will be used as the basis to estimate the costs of VC heating systems of other capacities [32].

$$C_n = r^{0.5}C \quad (5.1)$$

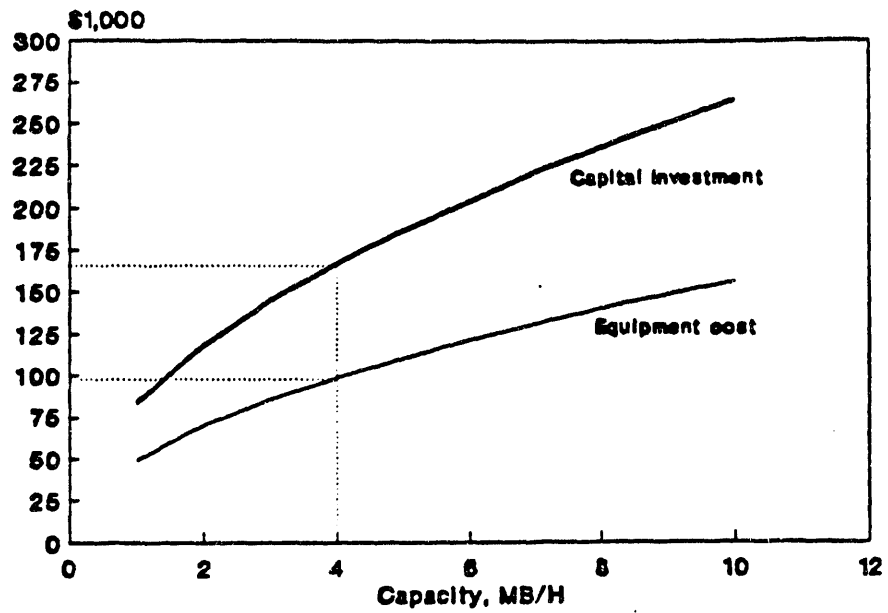
where C_n is the costs of VC system of capacity other than 4 MB/H; C the known costs of a 4 MB/H VC system; r the ratio of VC capacities.

Figure 5.2(a) shows the estimated capital investment versus design capacities of VC heating systems. It increases almost linearly with the capacity. For a 4 MB/H VC heating plant, the total capital investment for a turnkey unit is \$167,255 and the total cost of equipment is \$98,683 (item 5 in Table 5.2).

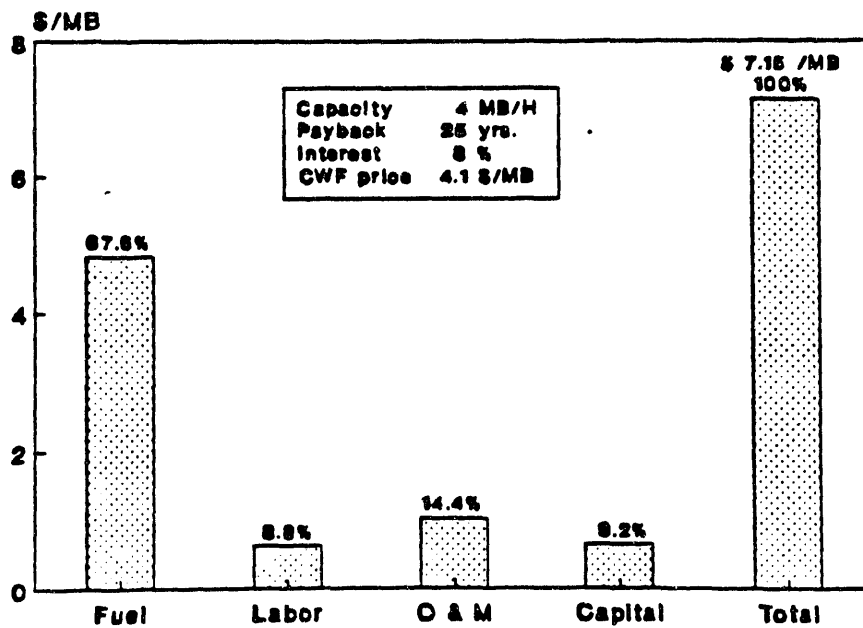
Operating Costs

The operating costs of a VC heating plant include: fuel, operating labor, utility, maintenance, overhead and supervision, and annual capital charge. These are briefly explained below:

- o Fuel cost - The CWF price is estimated to be at \$4.1/MB delivered [35]. For CWF with a heating value of 9,740 Btu/lb, the fuel price is \$0.04/lb (based on parent coal at \$50/ton).
- o Operating labor cost - Based on the centralized servicing concept discussed in section 5.1, only a small group of O&M personnel will be required to take care of many VC plants at the same time. Thus, it is possible to use only one dedicated man-hour per day and two additional man-hours per week for operating one VC system. Assuming the hourly rate of \$40 [32], the needed annual labor cost per VC system is 376 man-hours or \$15,040 which is only about 11% of the operating labor cost of the other coal fired systems requiring one dedicated full-time operator.



(a) Capital investment of VC systems



(b) Steam/hot water cost breakdown

Figure 5.2 Economics of CWF-fired VC heating plants.

- o Utility cost - The price of electricity is assumed to be \$0.065 per kWh.
- o Maintenance - The maintenance expenses include costs for labor and materials (assumed to be 3% of total direct cost [31]).
- o Overhead and supervision - this cost covers the general expenses for supporting offices, overhead, safety and protection, and laboratory fees. It is assumed to be 70% of the operating labor cost [31].
- o Annual capital charge - To recover initial investment, the total fixed-capital investment is amortized over the lifetime of the equipment at 8% interest.

Steam Production cost

Total production cost of steam or hot water is usually calculated on annual basis. The annual production cost can smooth out the effects of seasonal variations and permit a quick calculation of operating costs at partial loads. Table 5.3 shows the estimated unit production cost of steam or hot water for a 4 MB/H VC space/water heating system. For a 25-year payback, at 8% interest and \$4.1/MB CWF, the operating costs of a 4 MB/H VC system require the steam to be sold at \$7.15/MB, in which the fuel costs 67.6%, capital investment 9.2%, and others 23.2%. The cost breakdowns are also plotted in Figure 5.2(b).

Table 5.3 Production cost of steam or hot water.

	Consumption	Unit Price,\$	Annual Cost,\$	Cost,%
Fuel	1,305 ton	88.0	114,889	67.6
City water	4,220 ton	0.025	106	0.1
Electricity	147,000 kWh	0.065	9,555	5.6
Labor			15,040	8.8
Maintenance			4,293	2.5
Overhead			10,528	6.2
Subtotal			154,411	90.8
Annual capital charge			15,668	9.2
Steam/hot water cost				\$7.15/MB

Effects of Year Payback and Interest Rate

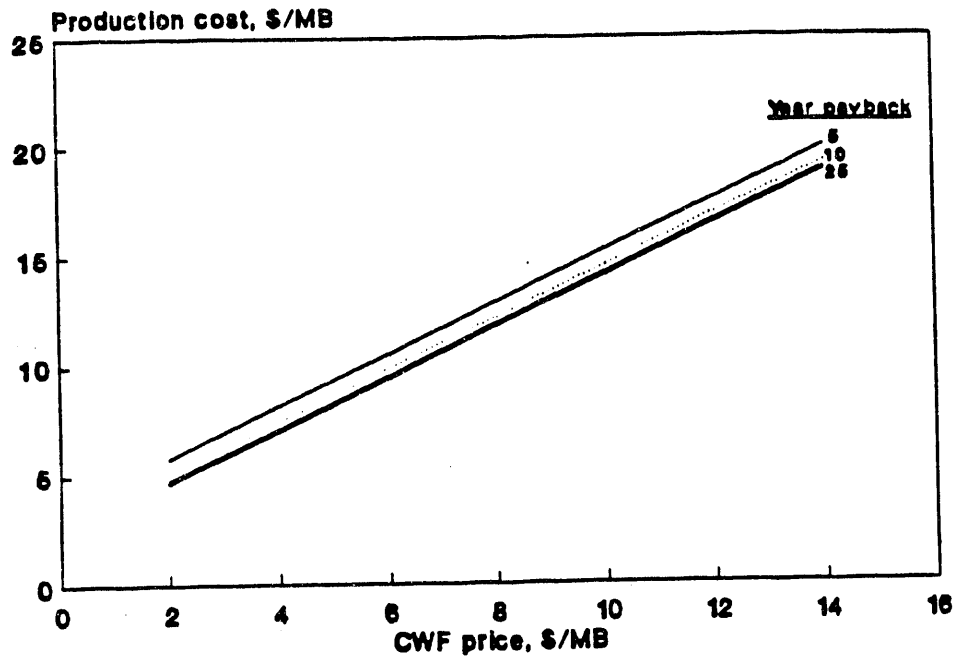
Figure 5.3 shows the effect of year payback and interest rate on the steam/hot water production costs of a 4 MB/H VC heating system. It is seen that the unit production cost decreases with the decrease of interest rate but with the increase of year payback. At the assumed CWF price of \$4.1/MB and 8% interest, steam cost is \$8.25/MB for 5 years payback, which drops to \$7.45/MB for a 10-year payback and to \$7.15/MB for a 25-year payback.

At a 25-year payback and \$4.1/MB of CWF price, the production cost drops only from \$7.91/MB (at 20% interest) to \$7.04/MB (at 6% interest). The effects of year payback and interest rate on overall economics are only very minor. This is understandable because of the minor role of total equipment costs (only 9.2%) in steam production cost.

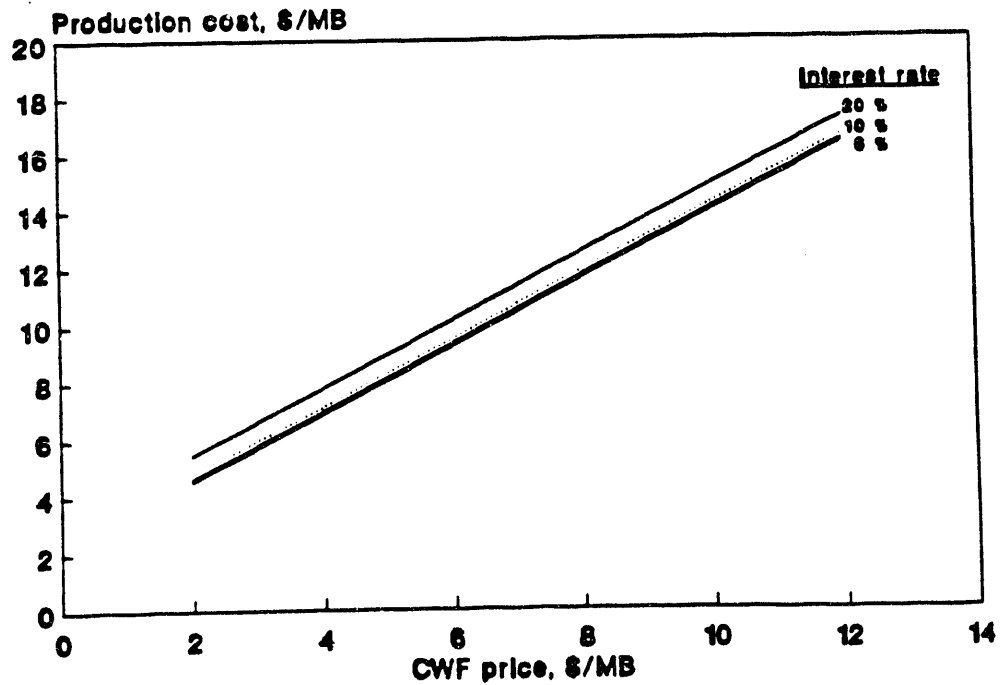
5.4 Numerical Simulation of POC VC Firing DUC

The recently developed mathematical model and computer code [7,11,36,37] were used to simulate the conditions in the POC VC firing DUC. The configurational and operational parameters corresponding to the test run to be simulated are summarized in Table 5.4. Some of the typical calculated results as shown in Figures 5.4 through 5.7 are discussed here.

Figure 5.4 shows the gas tangential and axial velocity distributions. The tangential velocity profiles show the strongly swirling flow feature, while the axial velocity profiles show the developing type of flow. Due to the presence of a center



(a) Effect of year payback (8% interest).



(b) Effect of interest rate (25 years pay back).

Figure 5.3 Sensitivity study of year payback and interest rate on steam production cost.

Table 5.4 Parameters of one test run used in numerical simulation.

Parameter	Magnitude/Arrangement
COMBUSTOR GEOMETRY	
Chamber I.D., in	19
Chamber height, in	33
Center tube O.D., in	8.5
Center tube height, in	29
HEAT REMOVAL SURFACE	
Chamber wall	Water-cooled, 1/4H refractory lined
Top	Water-cooled
Bottom	Refractory
Center tube	Mild steel
FUEL (DUC)	
Feed rate, lb/hr (MB/H)	137 (2)
Mean Diameter, μm	12
Proximate Analysis (%wt)	
Moisture	0
Volatile matter	36.9
Fixed carbon	60.8
Ash	2.3
Heating value, Btu/lb	15,049
Volatile Composition (assumed):	
Methane, %wt	68
Nitrogen, %wt	32
AIR SUPPLIES	
Overall excess air, %	26
Primary air/Secondary air	12/88
Air inlet temperature, °F	50
Primary Air	
Nozzle height, in	5
Flow rate, scfm	48.9
Velocity, ft/s	66
Secondary Air Distribution	
Nozzle height, in	5/9/13/16.5
Flow rates, scfm	91.1/91.1/91.1/91.1
Velocity, ft/s	98

Gas Axial Velocity (ft/sec) | Gas Tangential Velocity (ft/sec)

Total air flow rate: 413 scfm
 Air temperature: 50°F
 Excess air: 26%

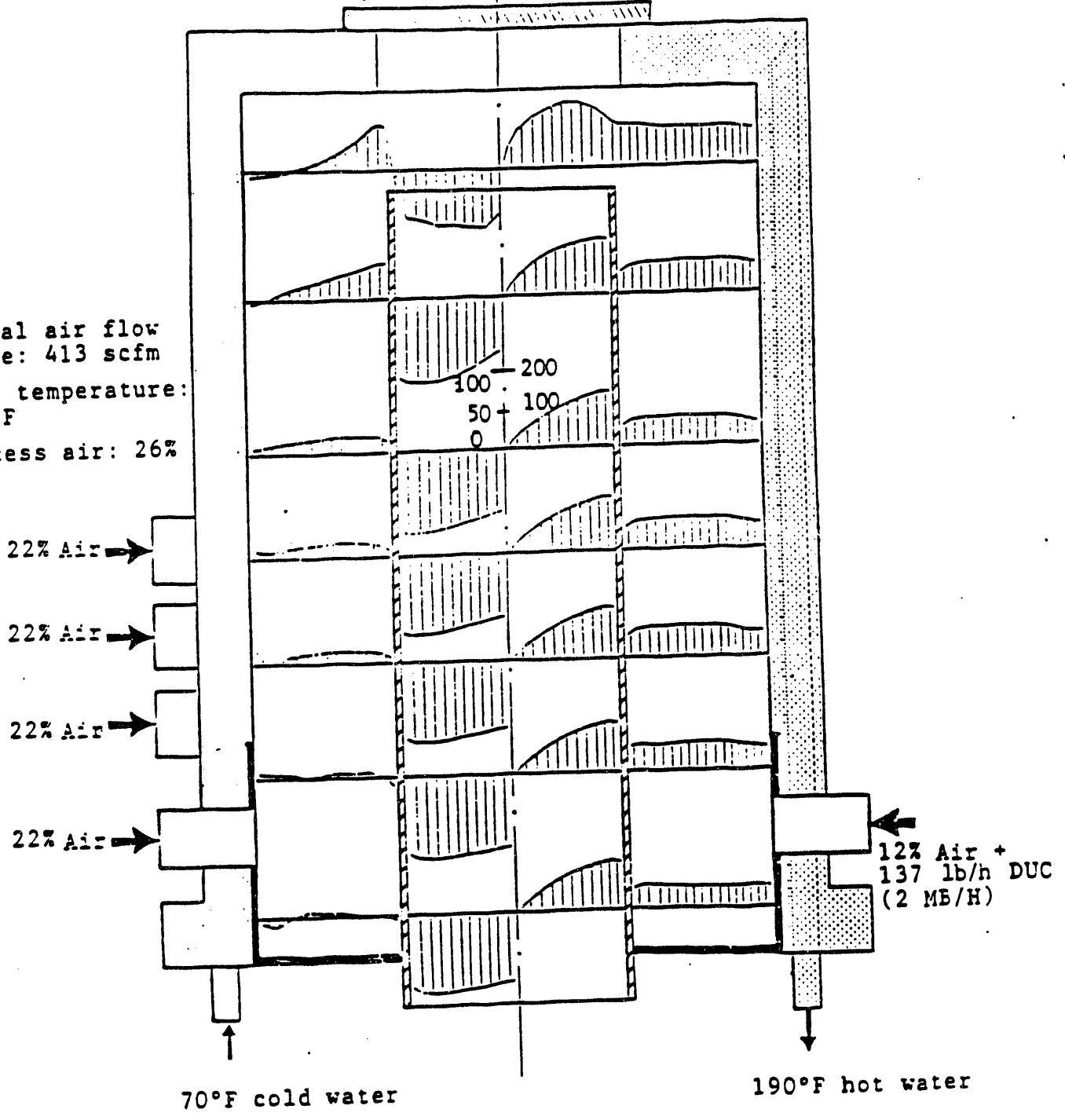


Figure 5.4 Calculated gas velocity distributions.

tube, the tangential velocities in the annular space are consistently high and relatively uniform, which is beneficial for combustion and pollutant abatement. Due to the arrangement of progressive secondary air injection along the flow direction, the gas axial velocity profiles change rapidly in the annular space. This developing type of flow can intensify gas-particle slip motion and heat/mass transfer. In the top cylindrical zone, the tangential velocity profiles exhibit the general behavior of Rankine type of flow: a rigid body in the core region surrounded by a free vortex. The axial velocities increase by three times inside the center tube due to reduced cross-sectional area of the flow.

The calculated gas streamlines in Figure 5.5 show a recirculating flow pattern in the combustor. The vigorous tori near the fuel feed port can bring the hot flue gases back to help ignite the freshly fed coal and stabilize the flame. A number of small recirculating zones near the secondary air nozzles are seen, which can promote the mixing of the injected air and ascending flue gas/particles. The sizable recirculation (or torus) near the top corner can help trap and throw the burning particles toward the chamber wall, prolong their residence times, and thus enhance the burnout.

Figure 5.5 also shows the contour of gas temperatures in the POC VC model. It is seen that the calculated gas temperatures are in rough agreement with the measured temperatures. The isotherms show a high gradient near the water-cooled walls as expected. A peak of 2,400°F was found immediately downstream of the secondary air injection, which was also observed (100°F less)

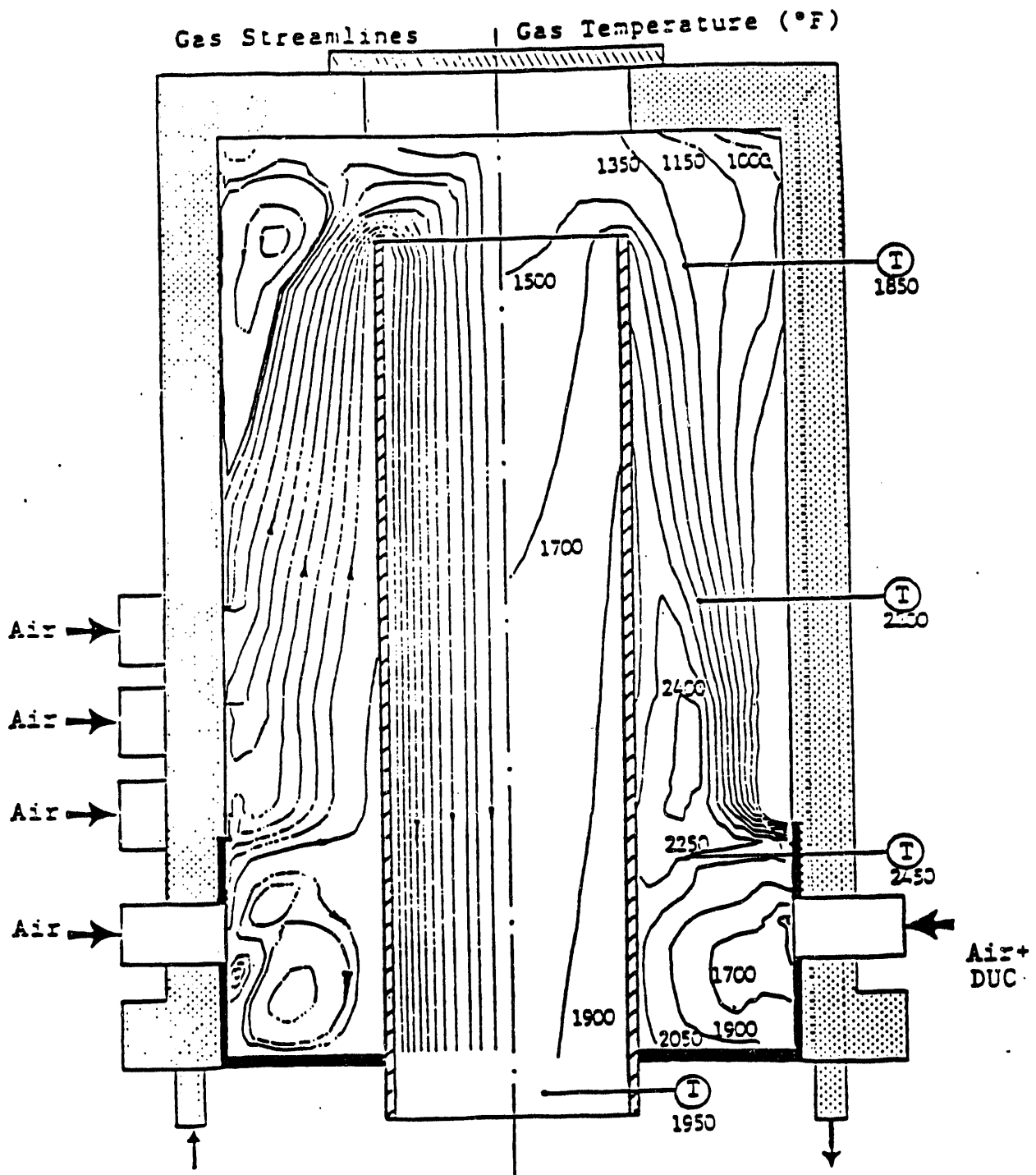


Figure 5.5 Calculated gas streamlines and temperatures.

in our combustion, a fact also consistent with our test results.

Figure 5.6 shows the calculated distributions of the gas-particle slip velocity, the vector difference between gas and particle velocities, in the VC. For particles of 12 μm average diameter, the slip velocity is quite large, being on the same order of magnitude of the exiting gas axial velocity in the center tube. This large slip velocity is caused by the unique characteristic features of strong swirling, developing, and circulating gas flow in a VC. The slip velocity near the fuel feed port is large, which is favorable for coal particles to meet with hot flue gases for drying, devolatilization, and ignition. In other parts of the annular space, the slip velocities are generally high near the chamber wall and low toward the center tube. The high gas-particle slip motion in the top cylindrical burnout zone is highly desirable; it can intensify the mixing and heat/mass transfer between gas (oxygen) and fuel (coal particles). Figure 5.6 also shows the concentrations of volatiles and oxygen. The volatile combustion process can be roughly seen from its depletion in this figure. Most volatiles were found close to the center tube where oxygen concentration is the lowest (i.e., consumed).

Figure 5.7 shows the calculated active zones of coal devolatilization, volatile combustion, and char reaction. It is shown that the char reaction zone basically coincides with the volatile combustion zone suggesting that volatile combustion and char combustion tend to take place simultaneously rather than sequentially in the VC. Char reaction zone in the annular space is close to the center tube. This is believed to be due to the

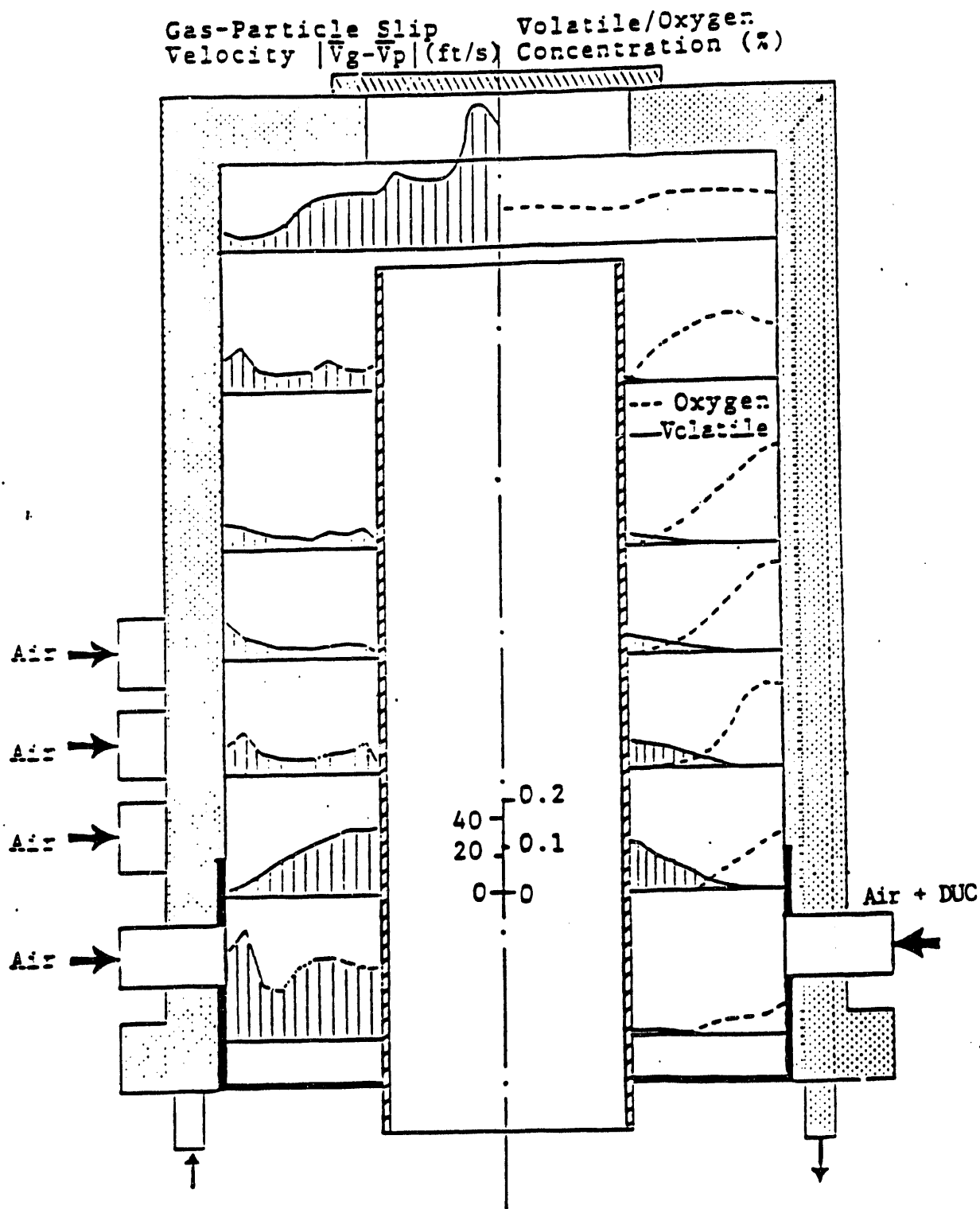


Figure 5.6 Calculated gas-particle slip velocity and oxygen/volatile concentrations.

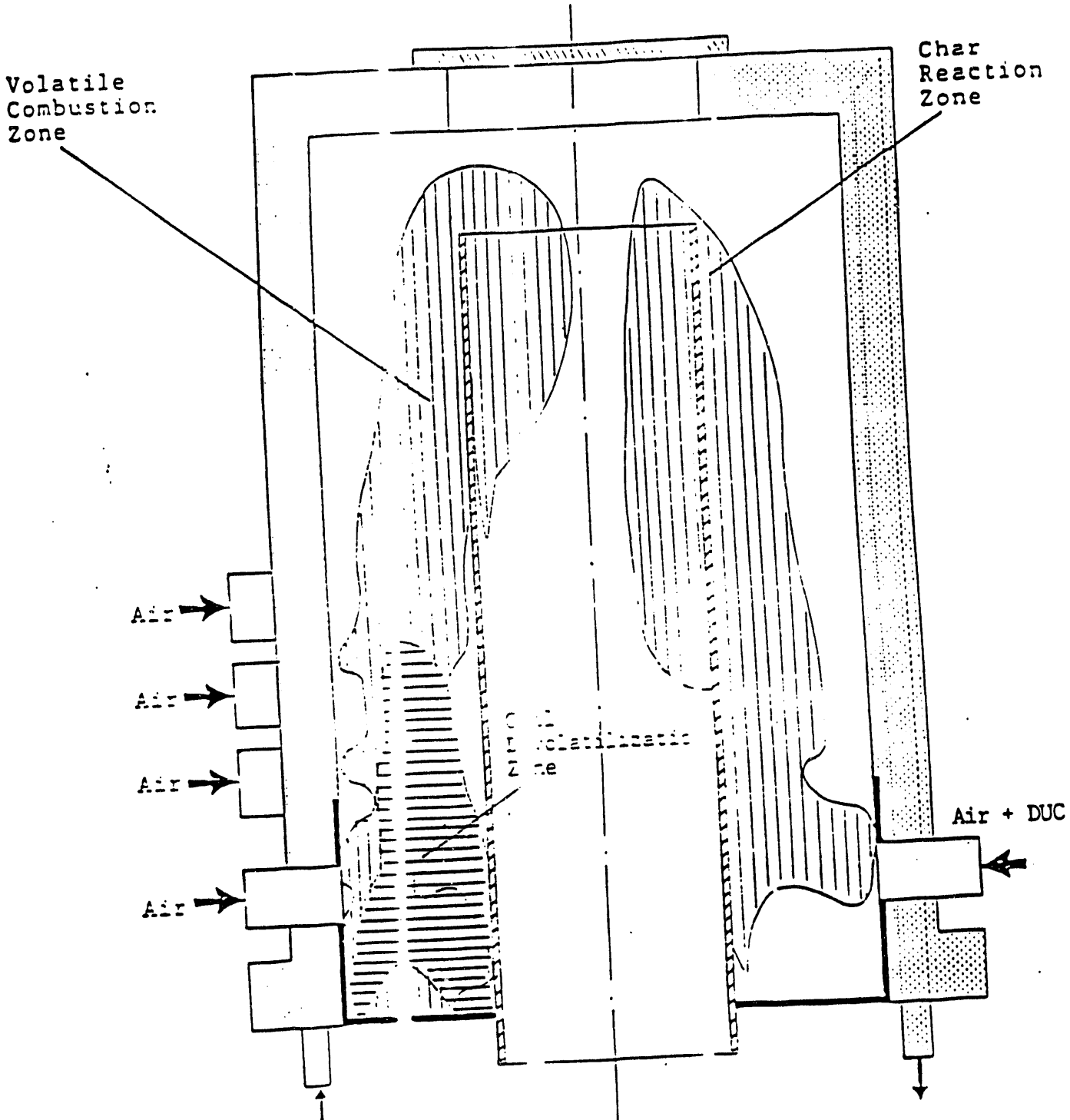


Figure 5.7 Active zones of coal devolatilization, volatile combustion, and char reaction.

depletion of coal mass (or shrinking fuel particle sizes) making it easier for the fuel particles to follow the gas flow. Figure 5.7 also depicts the calculated coal devolatilization zone in the VC. The devolatilization process takes place primarily near the combustor bottom due to the local high temperature. This is desirable since quick release of volatiles from freshly fed coal is helpful for ignition and flame stability. The calculated volatile combustion zone in the VC is also shown in this figure. The volume of the volatile combustion zone is much larger than the devolatilization zone. It even extends into the center tube similar to the char reaction zone. Comparing the temperature and species distributions (see Figures 5.4 and 5.6), it is significant that the volatile combustion zone almost coincides with the high temperature and low oxygen zones. These results demonstrate the strong linkage among the different variables in the VC combustion processes.

The above detailed results of combustor performance illustrate the unique gas-particle flow and combustion features of the VC: strong swirling, developing, and recirculating flow, vigorous mixing and slip motion between two phases, on-time stable ignition, relatively uniform and low combustion temperature, and good char burnout environment. These features have all been verified by our cold flow study [11] and the combustion tests reported here and earlier [27,28,38-40].

CHAPTER 6

CONCLUSIONS

This 36-month research program for the development of a proof-of-concept, non-slugging vortex combustor for commercial space/water heating applications has been successfully completed.

The major accomplishments are summarized below:

- o The VC concept has been refined and used to guide the design of two exploratory subscale models (0.15 MB/H PExp and 0.3 MB/H Exp VCs) and one preliminary full-scale model (3 MB/H PPOC VC). The auxiliary subsystems and measuring devices for testing these VC models have been successfully developed.
- o A total of 250 hours of combustion tests of CWF, DUC, PC, No. 2 heating oil, and propane have been conducted on the above three VC models. Systematic evaluations of these VC models have also been conducted on the combustion characteristics with regard to temperature variation, combustion efficiency, emission levels, heat transfer, and average firing intensity, and on the operational characteristics in terms of cold start, load variation, hot restart, turndown, and shutdown. A preliminary data base on the design and operation of a VC was established.
- o Two types of CWF nozzles and a special atomizing technique compatible with the VC configuration and applications have been designed, fabricated, and successfully demonstrated.
- o A 2 MB/H POC VC capable of firing CWF, PC, and DUC has been successfully demonstrated to PETC and Navy sponsors and guests. A total of 140 hours of systematic combustion tests have been conducted.
- o The VC concept has been demonstrated to be a superior multiple fuel combustion device for small boilers. Unlike some coal combustors which rely on a combination of precombustion, post combustion, and preheating combustion air and fuel, the burning of fuel in a VC is totally completed in the combustor itself without the requirements of preheating either the air or the fuel.

The test results of POC VC have been demonstrated to meet the PRDA's performance requirements. The advantages of the VC technology as previously claimed in our 1986 proposal have all been verified both experimentally and theoretically. Because of the strong swirl, low temperature, and unique configuration, the coal-fired VC technology is ideally suited for small- and medium-scale boiler heating applications. The advantages inherent with the VC can be summarized as follows:

- o Working concept and scaling - The VC concept has been brought into reality for a wide range of sizes (0.1 - 3 MB/H). No adverse impacts on technical performance were noted. Potential for up-scaling still exists.
- o High combustion efficiency - Consistently greater than 99% for firing both DUC and CWF can be achieved. The thermal efficiencies are also high ranging from 82% to 89%.
- o High average firing intensity - 0.1 - 0.45 MB/Hft³ (an order of magnitude higher than typical pulverized coal-fired utility boilers). This enables the VC to be made very compact.
- o Large turndown capability - greater than 3:1.
- o Fast, on-time ignition - Less than 15 minutes from cold to full load operation.
- o Broad fuel flexibility:
 - Fuel type - dry powdered coals, coal slurries, heating oil, and gas fuel;
 - Particle size - DUC (12 μ m), PC (40 μ m), and CWF (120 μ m).
- o NO_x and SO_x levels are respectively around 400 ppm and 300 ppm (at 3% O₂) although no special effort was made to reduce them, indicating a great potential in reaching very low emission levels when pollution abatement techniques are used.
- o No preheating - No air/fuel preheating is needed for all fuels to achieve high combustion performance.
- o Controllable combustion temperature - The temperature level is controllable and can be maintained low (1,600-2,200 °F) to facilitate pollution abatement and non-slagging/dry ash removal.

- o Controllable particle behavior - Fuel particle residence time can be controlled to ensure complete burnout of the fuel.
- o Simple construction and stable performance - High level of safety and reliability.

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