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ANNULAR VORTEX COMBUSTOR (AVC) DEVELOPMENT FOR SPACE/WATER HEATING APPLICATIONS

ABSTRACT This is the final report for Annular Vortex Combustor (AVC) development for commercial applications. The work culminated in the successful demonstration of a 2-MB/H proof-of-concept (POC) model firing coal-water slurry fuel (CWF) and dry pulverized coals. This development was concerned with a new concept in combustion for which there was a general lack of relevant information. The work began with a cold flow modeling study and 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 AVC can be fired on several coal fuels (CWF, dry ultrafine coal, utility grind pulverized coal) at high combustion efficiency (>99 percent), high firing intensity (up to 0.44 MB/H-ft^3), and at temperatures sufficiently low for dry ash removal and in-situ pollution abatement. The combustion process is completed totally inside the combustor. Conventional combustion enhancement techniques such as preheating (air and/or fuel), precombustion, and post-combustion are not needed.

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CONTENTS

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In the early 1970s, the increase in oil prices and the potential oil shortage 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 (Ref 1). In recent decades, coal has rarely been used 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 hotels, institutions, warehouses, industrial plants, apartment buildings, hospitals, and office complexes (Ref 2).

Small-scale coal-fueled heating units are inconvenient to operate due to the lack of: (1) automatic control; (2) fuel delivery, storage, and ash removal infrastructure; and (3) capability 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 success in large-scale applications. Their potential for commercial heating applications in an environmentally and socially acceptable way remain an uncertainty. Therefore, novel coal combustion technologies engineered for small- and medium-scale boiler applications are needed.

In 1986, the Pittsburgh Energy Technology Center (PETC), U.S. Department of Energy, issued a Program Research and Development Announcement (PRDA) (Ref 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 annular vortex combustor (AVC) concept was proposed to fire both CWF and DUC for commercial space/water heating applications. The developmental work of the AVC was awarded to the Naval Civil Engineering Laboratory (NCEL) for the combustion tests, and to the Catholic University of America (CUA) for the cold flow modeling study. This is the final report on the results of AVC combustion tests, a 36-month research effort starting on October 1, 1987 (Ref 4).

1.2 PROJECT OBJECTIVE AND REQUIREMENTS

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

1.3 AVC CONCEPT

The AVC concept evolved from the basic understanding of swirling multiphase flows and combustion in vortex chambers (Refs 5, 6, 7, 8). It is characterized by a strong swirl, low temperature combustion environment, which integrates the advantages of cyclone combustor, swirl burner, multistage combustion, and fluidized-bed combustor, while eliminating some of their inherent disadvantages. As shown in Figure 1.1, the AVC 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 the water jacket, are provided to remove the excess heat and control the temperature of combustion products to be 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 AVC, 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 AVC, therefore, may be reduced to one of particulate matter removal only.

The benefits of swirl in both nonreactive and reactive flow systems have been recognized for many years (Refs 9, 10). Swirl flows occur in a very wide range of applications. In nonreacting 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 (Ref 9).

Two types of conventional swirl combustors are widely used: swirl burners and cyclone combustors. With a 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. 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 a 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 AVC and distributed injection of combustion air warrant the above desired improvement (Ref 11). From the standpoint of gas-particle flow, AVC 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, AVC is unique in its low, nonslagging combustion temperature which is beneficial in pollution abatement and system operation.

1.4 TECHNICAL APPROACH

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

Figure 1.2 depicts the technical approach adopted for the development and demonstration of a POC AVC and for the establishment of the needed technical data base for AVC 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) was designed and tested. The purpose of this PExp AVC was to reduce the AVC 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 AVC.

The CWF nozzles needed to match the unique AVC configuration were developed. The nozzle atomization and compatibility tests were conducted. A full-scale preliminary POC (PPOC) AVC hot model (~3 MB/H) was designed and built utilizing the experience and data obtained from the PExp AVC. The purpose of this PPOC AVC was 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 AVC.

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

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

In order to explore the detailed characteristics of the AVC performance and to help in any possible design modifications, numerical calculations were pursued simultaneously with the combustion tests of the POC AVC. These calculations are a meaningful continuation of the cold modeling study (Ref 11) into practical applications.

Table 1.1 Performance Requirements and Design Goals for the AVC

Basic Requirements (PRDA Specifications)	
Thermal input capacity	2 to 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 (AVC Features)	
Combustion temperature	1,600 to 2,200°F (870 to 1,200°C)
Ash removal	Nonslagging (dry flyash)
Flow field in combustor	Swirling, recirculating, and developing
Combustion air preheating	Not needed

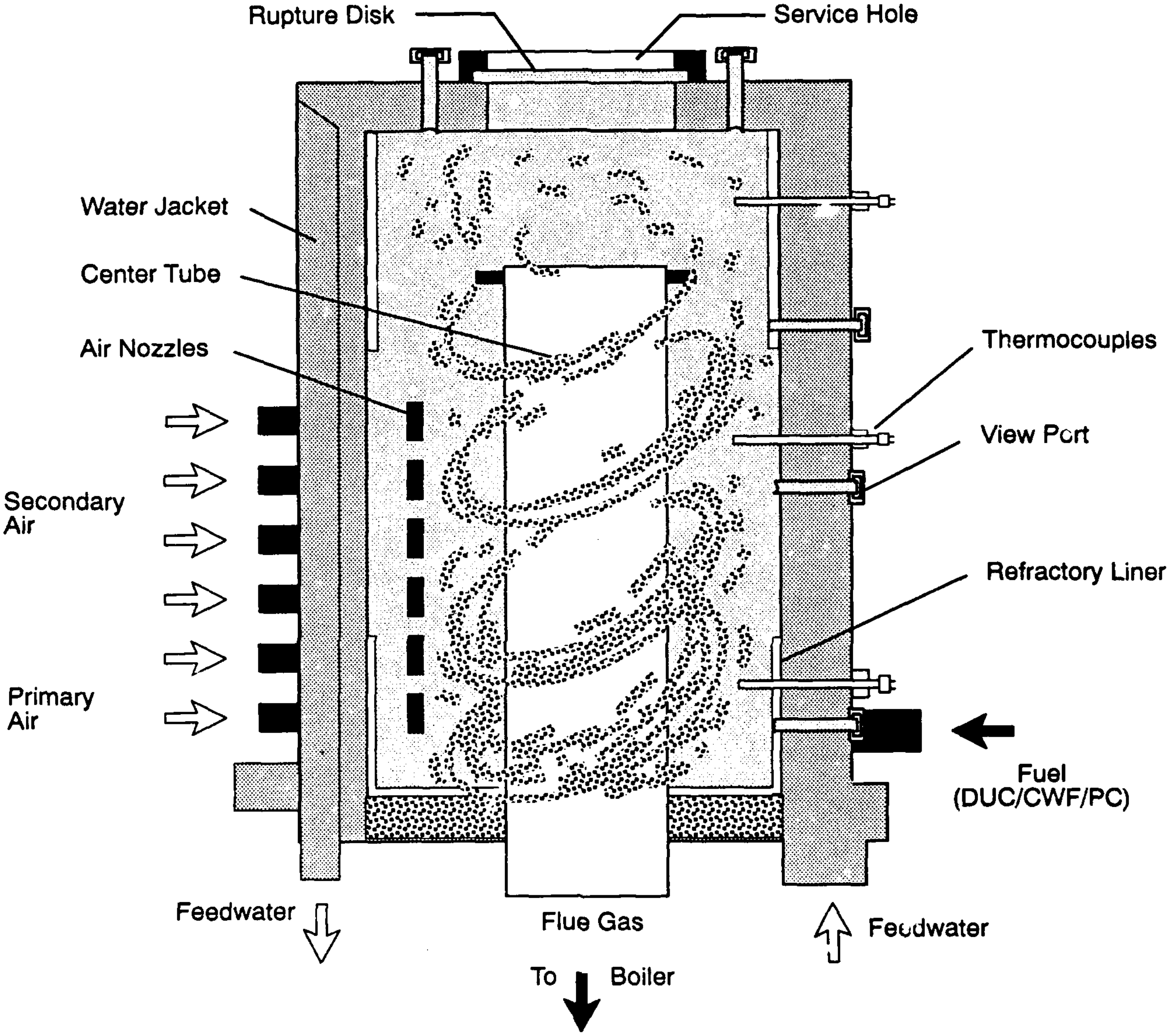


Figure 1.1 Conceptual design of the annular vortex combustor.

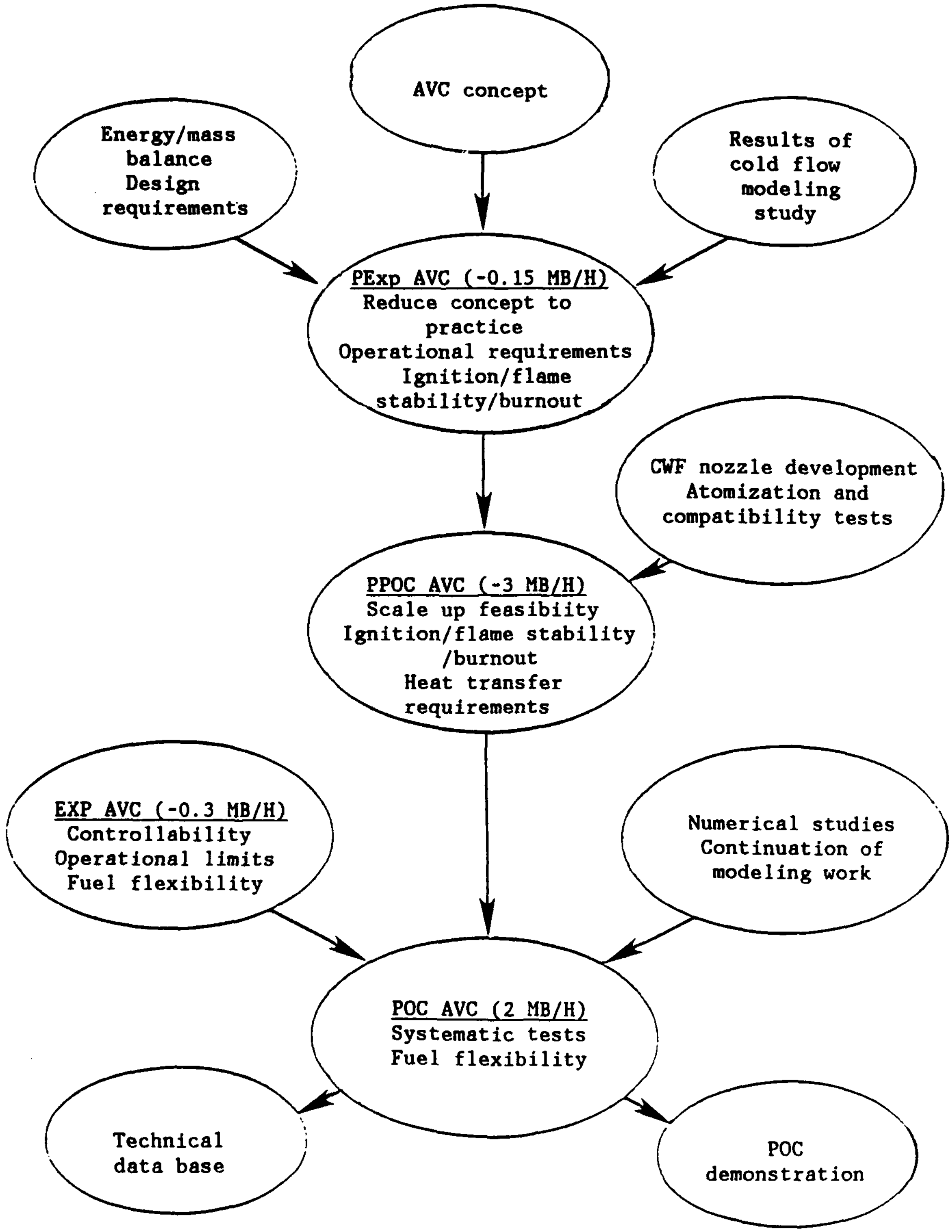


Figure 1.2 Technical approach for the development and demonstration of a POC AVC.

CHAPTER 2

AUXILIARY SYSTEMS, INSTRUMENTATION, AND TEST FUELS

In this chapter, the auxiliary systems of AVC 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 the full-scale PPOC and POC AVC models. The auxiliary systems include air supply, water supply, fuel supply, flue gas exhaust, ash collection, and ignition. The fuel supply systems are described in Section 2.1 and other auxiliary systems in Section 2.2. Figure 2.2 is a schematic diagram of the test setup for subscale PExp and Exp AVC 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 including CWF, DUC, PC, No. 2 heating oil, and propane gas. The performance of CWF nozzles specially developed for the AVC tests is also presented.

2.1 FUEL SUPPLY SYSTEMS

Since the AVCs are designed to burn both dry powdered coals (DUC and PC) and their water slurries (CWF), two separate fuel storage, handling, and feeding systems were installed for the combustion tests. In order to ensure that CWF can be properly atomized and burned in the AVC, a separate CWF atomization test system was also built to study nozzle atomization characteristics.

2.1.1 DUC/PC Supply System

The dry powdered coal supply shown in Figure 2.1 is basically a screw feeding and pneumatic conveying system. It consists of a 20-ft^3 coal hopper, a Vibra Screw coal feeder with a vibrating bottom, a feed rate control box (0 to 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-horsepower blower is used to provide primary air up to 30 percent of the total combustion air. Coal-air mixture is then injected tangentially into the AVC bottom by 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 a 2-MB/H load. When testing CWF, this system is used to supply only the primary air. For the PExp and Exp AVC model tests, a similar DUC/PC supply system with smaller capacity components was used, as shown in Figure 2.2.

One of the problems encountered in the combustion tests was the fluctuation of coal feed rates at low loads, which often results in unstable ignition and combustion. Several attempts were 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 was injected into the conveying pipeline.

2.1.2 CWF Supply/Atomization System

As shown in Figure 2.3, the CWF supply/atomization system 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 were 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 stirs 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 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- by 29- by 28-inch enclosure made of Plexiglas to facilitate spray visualization and measurements. In the CWF atomization tests, the spray cone angle, droplet size and spatial distributions, CWF flow rate distribution, and other atomization characteristics were either observed or measured in this test chamber or via a camera-assisted microscopic examination scheme (Refs 12, 13).

The atomization quality of the CWF nozzle and flow rate of each supply line can be independently adjusted, a feature essential for achieving stable CWF combustion, particularly at high firing rates.

2.2 AUXILIARY SYSTEMS

2.2.1 Air Supply System

The primary air for each AVC 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 horsepower, 1,300 scfm, 47 inches of water static head). This blower (the F.D. fan) is connected to the AVC models by several 2-inch PVC pipes via a 4-inch or 6-inch header pipe. The flow rates are conveniently controlled by seven valves at strategic locations and monitored by six miniature Pitot tube type flowmeters. A photograph of the POC AVC and its various auxiliary systems is shown in Figure 2.4.

2.2.2 Water Supply System

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

2.2.3 Flue Gas Exhaust and Cleaning System

This system, as 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-foot stack, and 14-inch connecting ducts (Ref 14). The 5-foot-diameter by 15-foot-tall stainless steel cyclone separator is also equipped with an internal water spray for wet scrubbing. The particulate concentration of the flue gas discharged into the atmosphere was found in most tests to be around 250 mg/Nm^3. 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 stack downstream. The dampers and cold fresh air inlets were used to adjust the draft in the combustor. This exhaust gas system and the performance of the AVC models were reviewed by the environmental control officers in Washington DC. A certificate on environmental control was granted permitting NCEL to conduct coal combustion tests.

2.2.4 Ignition System

Propane gas was used as the starting fuel. As shown in Figures 2.1 and 2.2, the major components of this system consist of two 100-pound 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 was injected immediately after the propane was ignited. Both fuels were fired simultaneously for about 10 to 15 minutes to achieve a stable combustion. The propane was then cut off and self-sustained combustion was usually established at this point.

2.3 INSTRUMENTATION

A computer-assisted data acquisition system was developed to accelerate the data taking process and to eliminate human errors. Four major types of instrumentation were used: 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.

2.3.1 Temperature Measurements and Data Acquisition System

Both K- and R-type thermocouples were used for temperature measurements. They were 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) (Ref 15), and two 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 eight channels were enabled: five 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 AVC tests, a total of 28 thermocouples were installed and linked with the data acquisition system for monitoring various temperatures. Real time temperature data was displayed on a computer monitor, printed, and stored on floppy disks for later processing. The errors of temperature measurements were about ±0.3 percent of the readings.

2.3.2 Flow Measurements

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

Dry powdered coal, either DUC or PC, was fed by the AccuRate screw feeder with a feed rate control box into a pneumatic pipeline. The primary air from a centrifugal blower carried and injected the coal into the AVC model through feed nozzles. The feed rate was determined by the precalibrated rotating speed of the screw of the feeder. The feed rate data from the control box was linked to the data acquisition system for display and automatic recording. (DUC and PC require different conversion factors for feed rates.) The measurement errors were ±2 percent in the range of 0 to 300 lb/hr.

The flow rate of CWF was measured by an electromagnetic flowmeter with an operating range of 0.075 to 0.75 gpm. A Taylor Instrument 1100 TB Mag-pipe transmitter was used to amplify the AC signals generated from the sensing head and convert them to a 4- to 20-mA DC output which was directly proportional to the CWF flow rate. The converted signals were forwarded to the data acquisition system for display and recording. The measurement errors were ±2 percent 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 AVC model was monitored by a flowmeter and frequently calibrated by a stop watch/graduated container arrangement. The pressures in the combustor and auxiliary components were monitored by various manometers and gauges.

2.3.3 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 (Ref 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) (Ref 17) was also used to cross check the flue gas composition readings. These flue gas analysis systems are shown in Figure 2.7.

Measurements of combustion products by the KVB console started at the sampling probe which was inserted into the outlet of the center exhaust tube of the AVC. The construction of this probe is shown in Figure 2.8(a). The sampled flue gases were transported via a heated sample line to the console. This line maintained 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 was 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 was then connected to the automated valving system and distributed for the following analyses:

1. Carbon Monoxide (CO). A 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 (Ref 16). Two equal energy infrared beams were directed through two optical cells: the sample cell that the conditioned gas sample flows through and a sealed reference cell. Solid state electronic circuitry continuously measured the difference between the amount of infrared energy absorbed in the two cells. This difference indicated the concentration of CO in the flue gas through the sample cell. The measurement range of CO was 0 to 2,500 ppm with measurement errors of ±6 percent of the readings.

2. Oxides of Nitrogen (NO_x). A 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 + NO_2) in the sampled flue gas. This instrument utilizes the chemiluminescence principle to continuously measure NO and NO_x in eight linear, full-scale ranges from 2.5 to 10,000 ppm. The measurement error was ±4 percent of the readings (Ref 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 the ultraviolet absorption principle. The measurement range of SO_2 was 0 to 500 ppm with measurement errors of ±4 percent of the readings (Ref 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 (Ref 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 was 0 to 25 percent with ±1 percent measurement error.

2.3.4 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 was dried first at about 226°F in a Fisher Scientific model 510 Isotemp oven for 1 hour and the mass measured by a digital balance. The dried flyash was then heated again in a Fisher Scientific model 2000 muffle oven at 1,830°F for 3 hours. The weight loss of the flyash sample in the oven represented the unburned combustible residues in the ash (basically carbon), and was used to determine the combustion efficiency. The measurement errors were estimated to be ±3 percent.

2.3.5 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 to 100 mV is connected to the computer-assisted data acquisition system as shown in Figure 2.6. Typical results of the combustible gas concentrations were about 500 ppm during DUC tests and 120 to 200 ppm during CWF tests. This low level of unburned combustible gases did not noticeably affect the combustion efficiency calculations. It did give indications of the extent of gas-gas and gas-particle mixing in the combustor, however. The instrument error was ±2 percent of the readings.

2.4 TEST FUELS AND CWF ATOMIZATION TESTS

One of the potential advantages of the AVC concept is that different fuels (types, properties, and sizes) may be burned in it with high combustion efficiency by only adjusting the operating conditions rather than the hardware or the design. To demonstrate this important feature of AVC, five types of fuels (propane, No. 2 fuel oil, CWF, DUC, and PC) were tested. It should be noted here that when burning heating oil, the same CWF supply/atomization system can be used without any operation and compatibility problems.

2.4.1 Fuel Properties

The DUC, PC, and CWF used for combustion tests were 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 percent and sulfur content less than 0.7 percent. Analyses of the fuels used are summarized in Table 2.2.

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

2.4.2 CWF Nozzles and Atomization Tests

The atomization quality of a CWF nozzle directly affects the ignitability, flame stability, and combustion efficiency of CWF (Refs 20, 21). Ideally, the droplets in a CWF spray should be sufficiently fine and have a maximum specific surface area for rapid evaporation and devolatilization (Ref 12). Equally important is that the droplets must be properly dispersed in the ignition zone to ensure intimate fuel-oxygen mixing for complete combustion (Ref 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 (Ref 23). It must be pointed out that the unique configuration of the AVC posed a great challenge to the CWF nozzle development. Based on the above considerations, two types of air-assisted CWF nozzles were developed for AVC applications:

Type A: 20 lb/hr, internal mixing (Figure 2.9(a))

Type B: 250 lb/hr, internal-external mixing (Figure 2.9(b))

The Type A nozzles were for exploratory tests in subscale AVC models. The Type B nozzles were for tests in full-scale AVC 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 an AVC, the CWF nozzles were designed with small cone angles to minimize spray impingement on adjacent combustor walls. A typical pattern of CWF spray from Type A nozzles (32-degree cone angle) is shown in Figure 2.9(c).

CWF atomization tests with both Type A and B nozzles were conducted in the atomization test chamber explained earlier. 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 this case, this ratio was 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 diameter) 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 a 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 AVC models. Type B nozzle spray has a relatively flat spatial dispersion 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 (Refs 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 was satisfactory for AVC combustion tests within the range of applications.

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 flow rate, 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 flow rate, 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	0-10000 (±4%)
SO_2, ppm	Ultraviolet absorption	Western Research model 721A	0-500 (±4%)
HC, ppm	Combustible gas analyzer	United Tech. TLV/FM Sniffer	0-10000 (±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%)

Table 2.2 Typical Analyses of the DUC, PC, and CWF Used in Combustion Tests

PROPERTIES OF PARENT COAL

I.D.#: UE3-191-PCO-E   Bed: West Virginia Upper Elkhorn #3

Proximate Analysis (% wt):		Ultimate Analysis (% wt):	
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 @ 6[illegible] °F	1.2	SMD of droplets	106 μm
Heating value, Btu/lb	9.930	Average droplet size	75 μm

Table 2.3 Typical Results of CWF Nozzle Tests

Parameter/ Flow Rate (lb/hr)	Type A Nozzle		Type B Nozzle	
	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

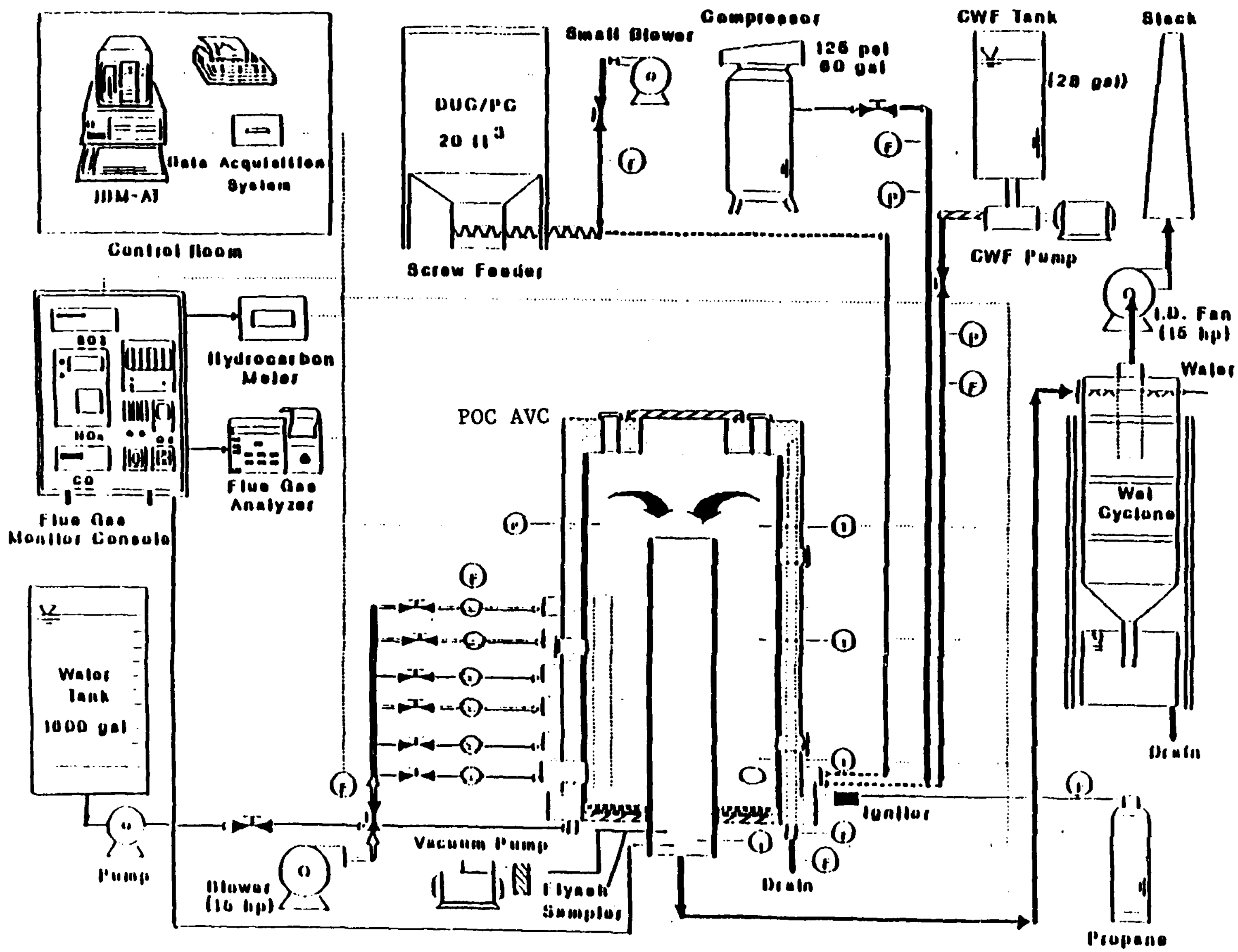


Figure 2.1 Schematic diagram of PPOC and POC AVC test setup.

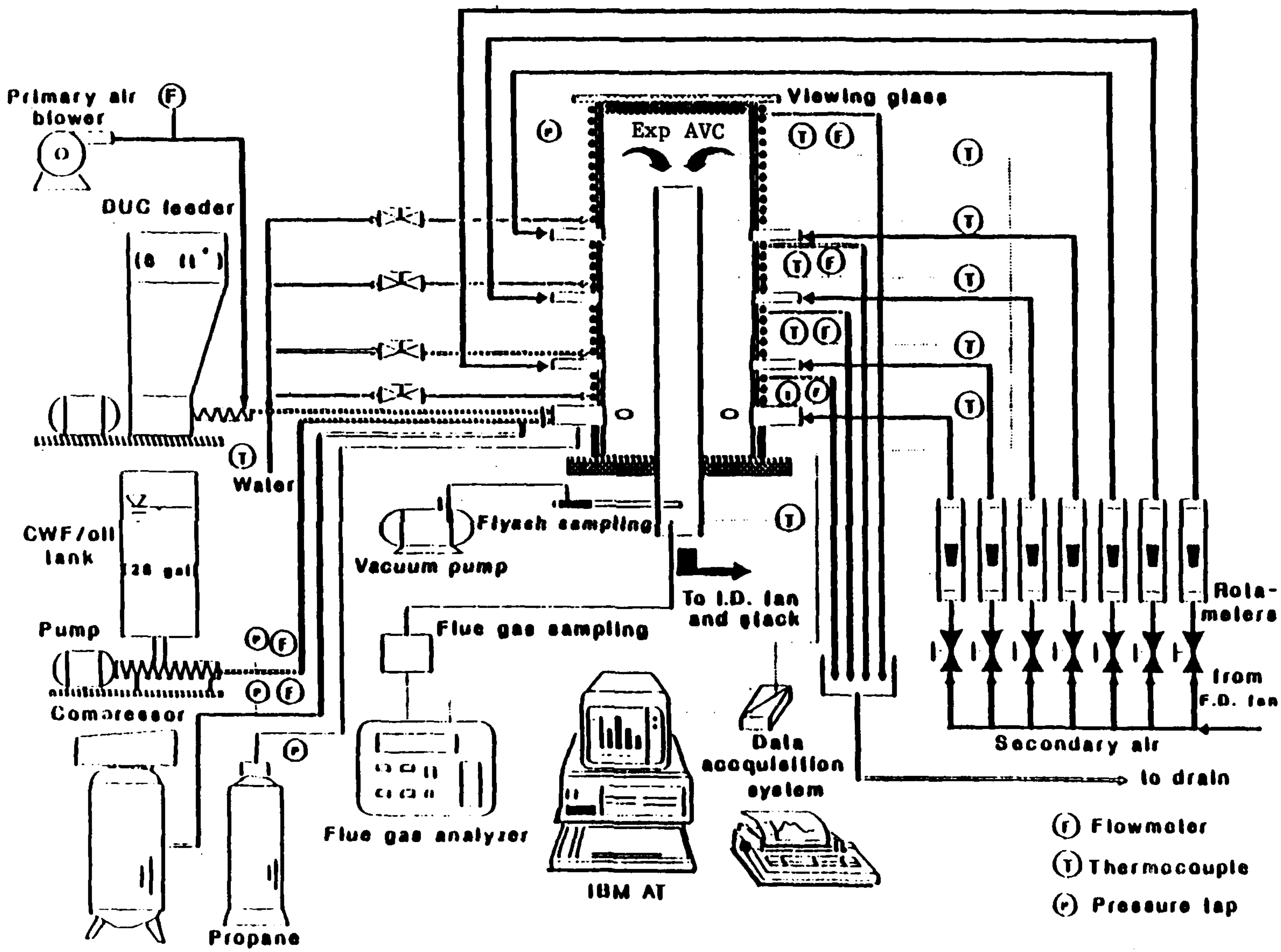


Figure 2.2 Schematic diagram of PExp and AVC test setup.

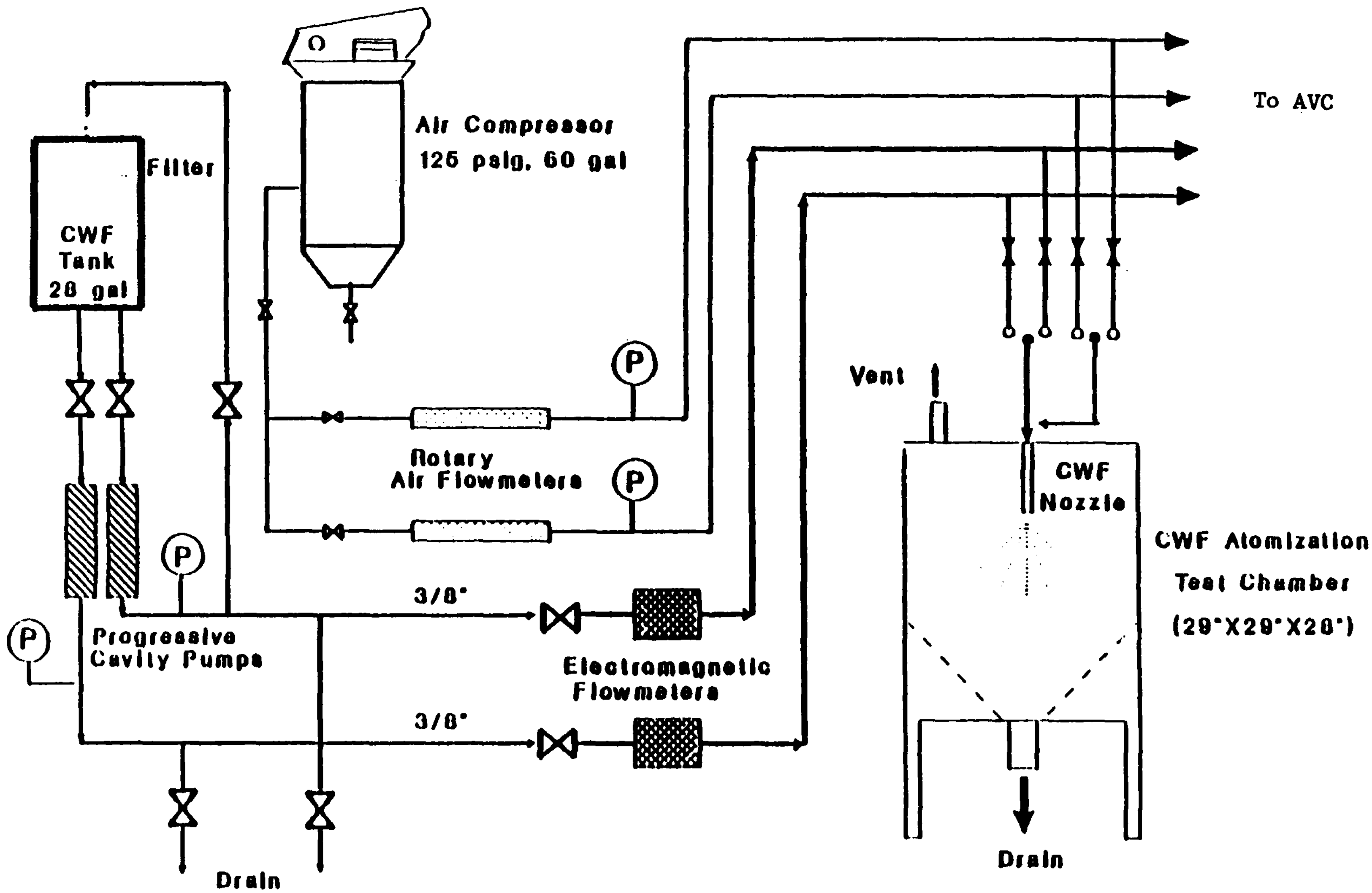


Figure 2.3 CWF supply system and atomization test chamber.

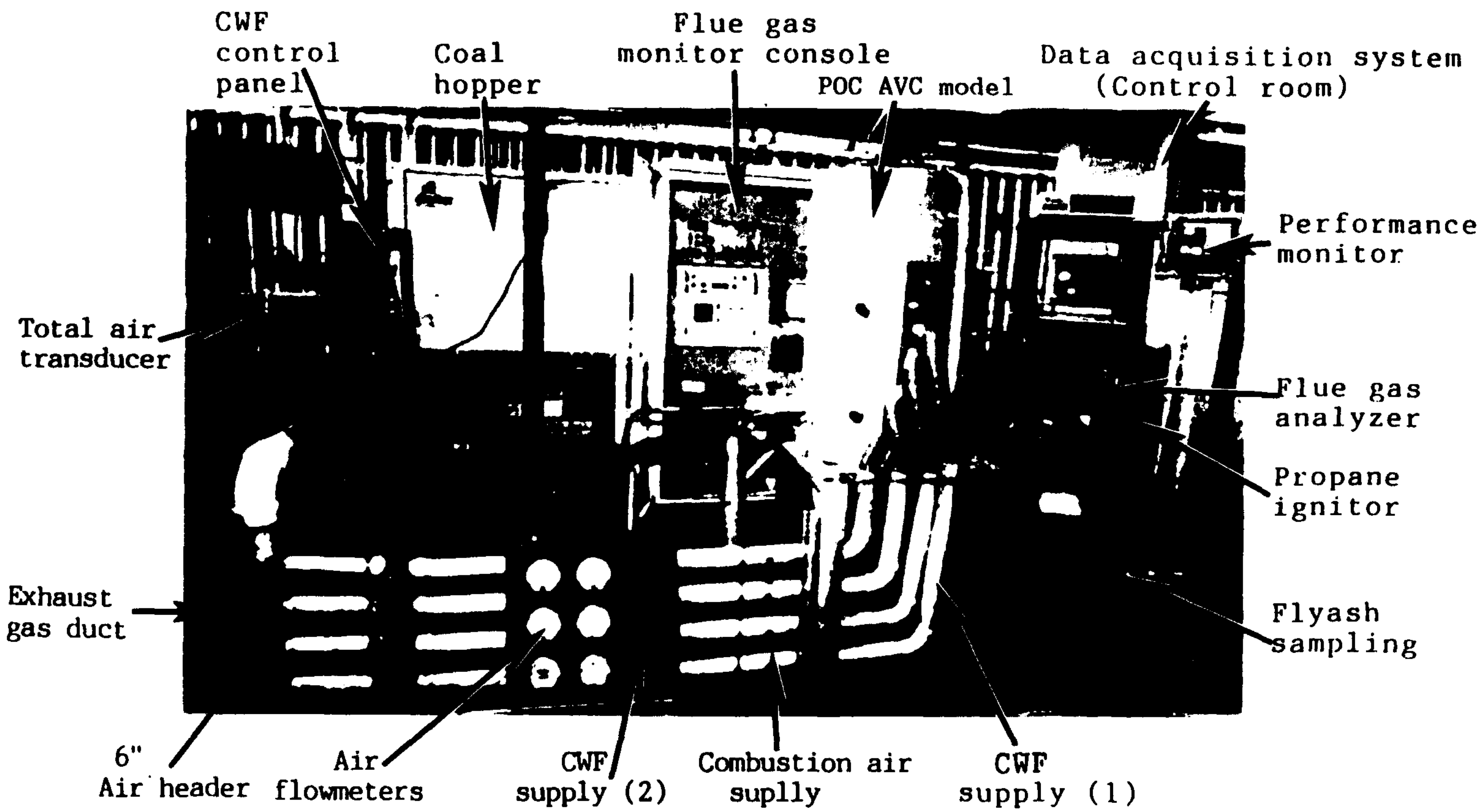


Figure 2.4 POC AVC model test facility.

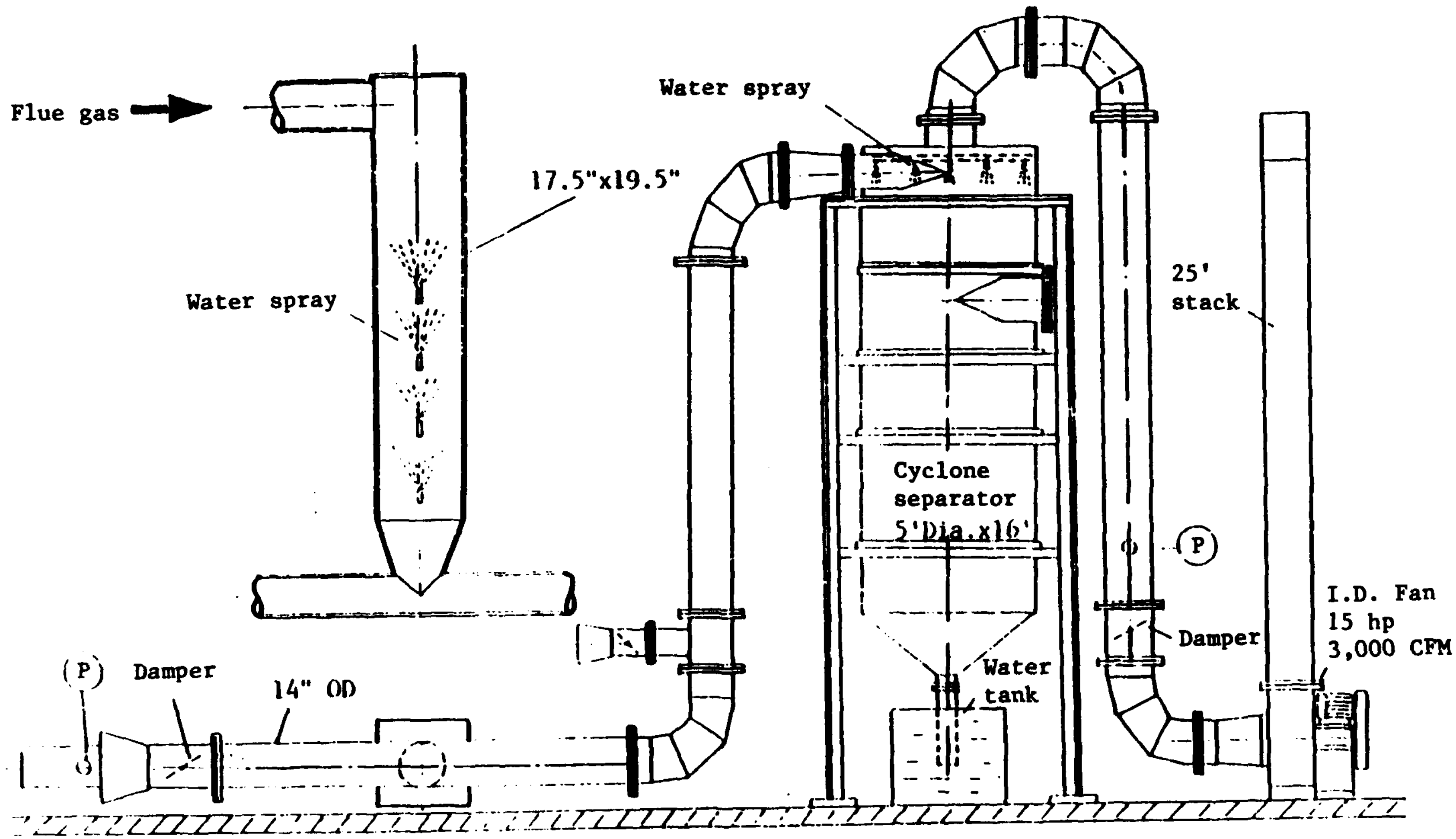


Figure 2.5 Flue gas exhaust and cleaning system.

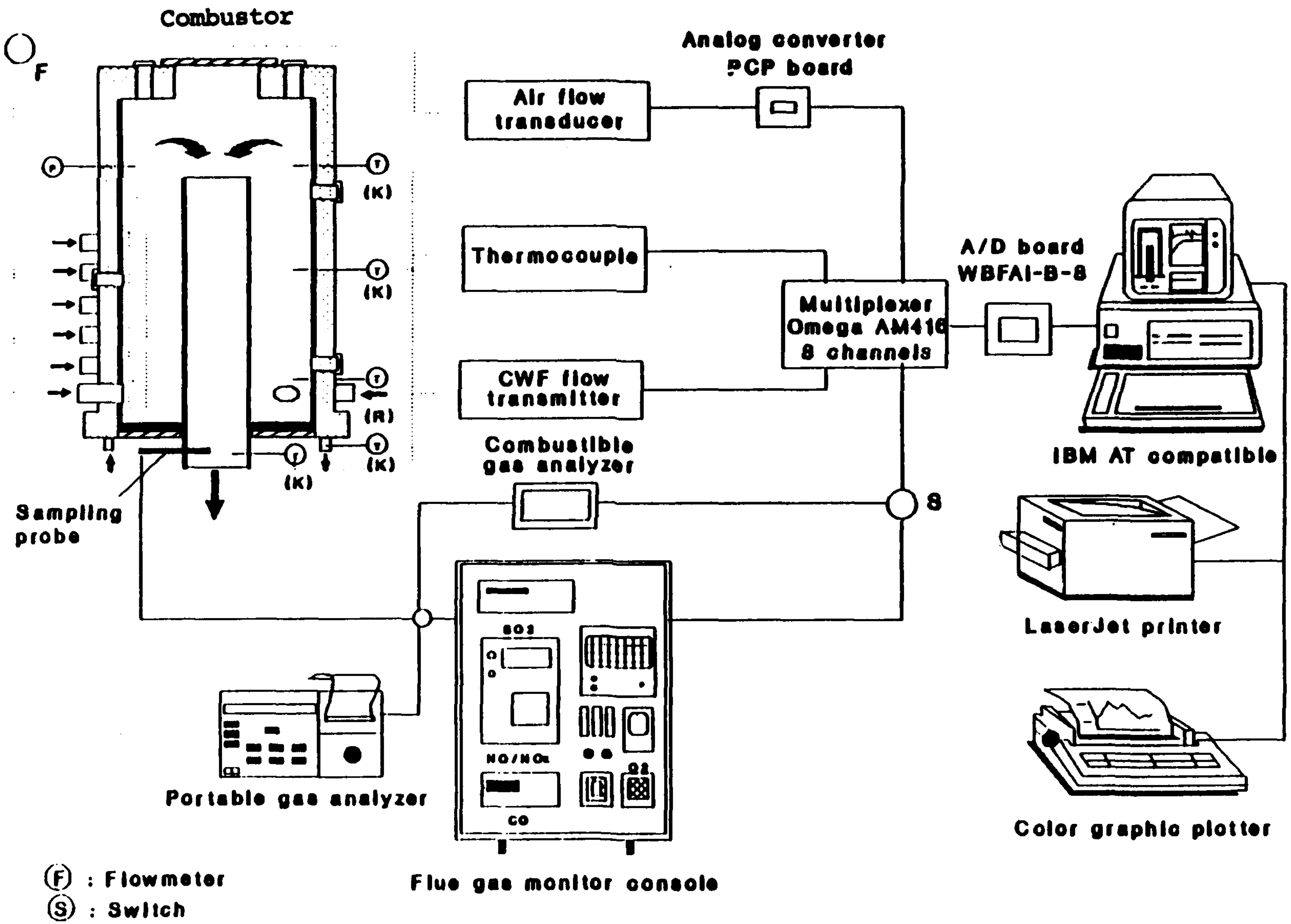
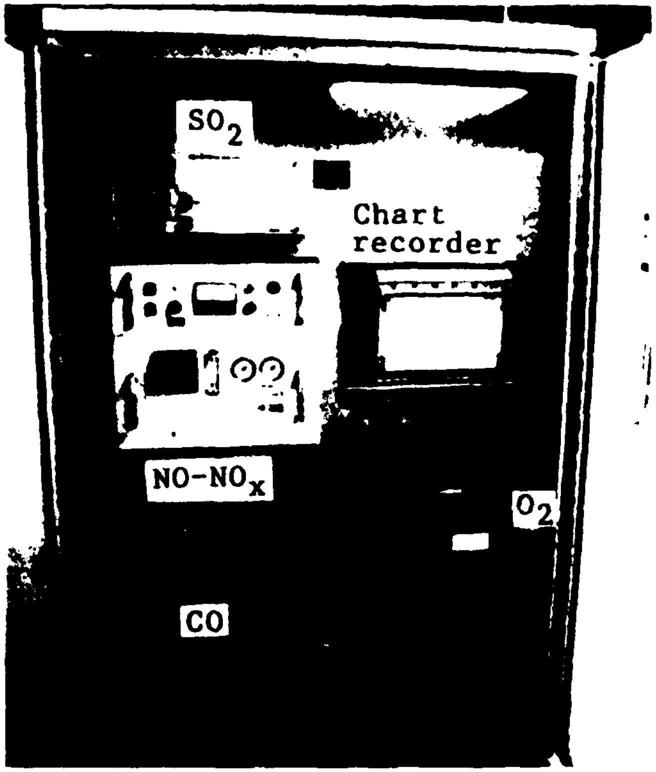
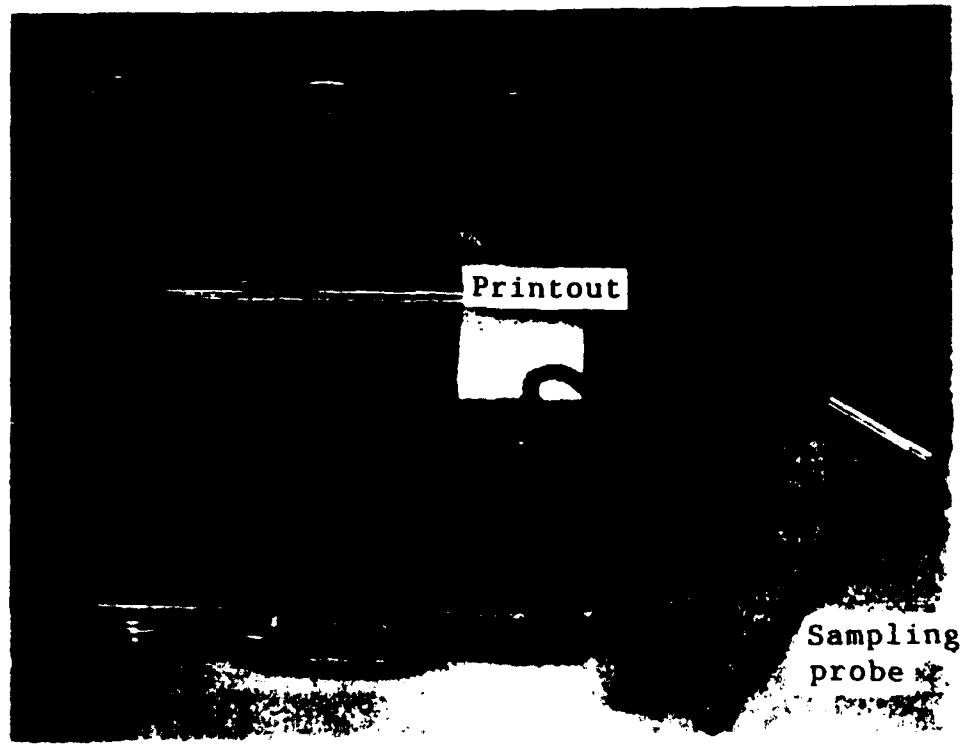


Figure 2.6 Schematic diagram of the computer-assisted data acquisition system.

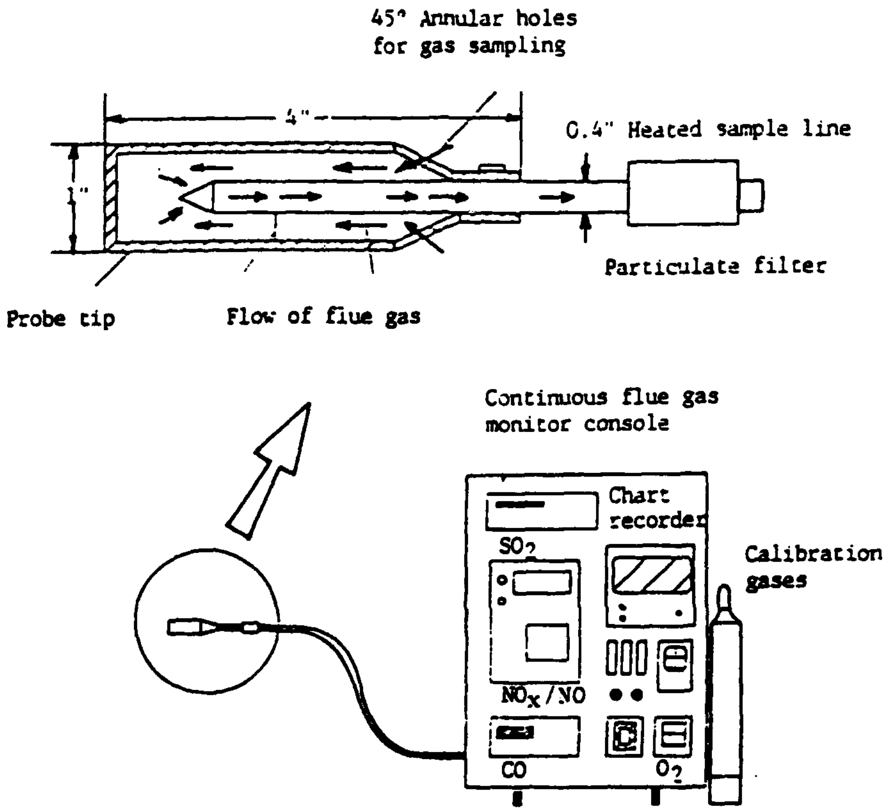


(a) Flue gas monitor console

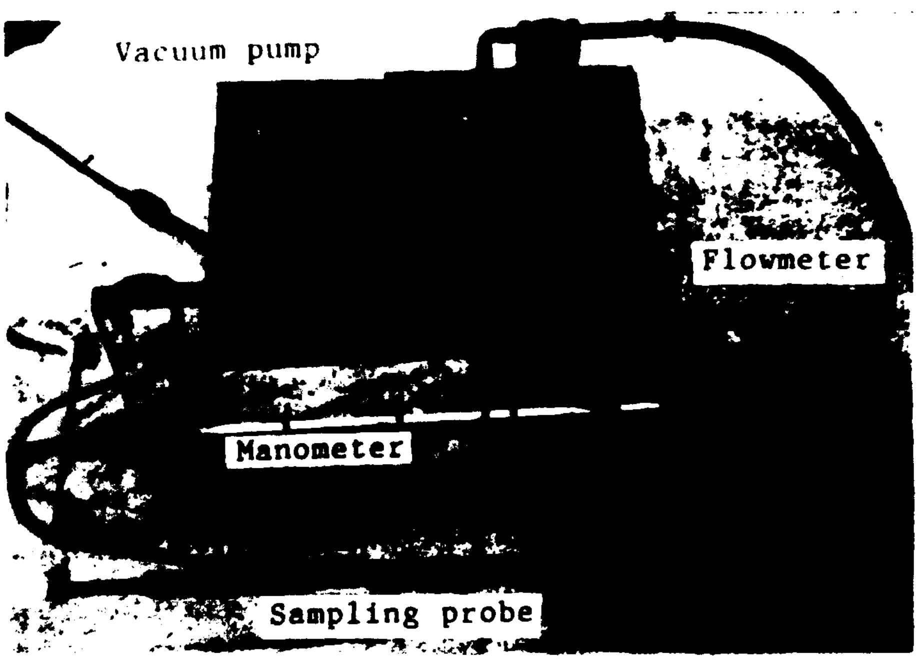


(b) ENERAC 2000 flue gas analyzer

Figure 2.7 Flue gas analysis systems.

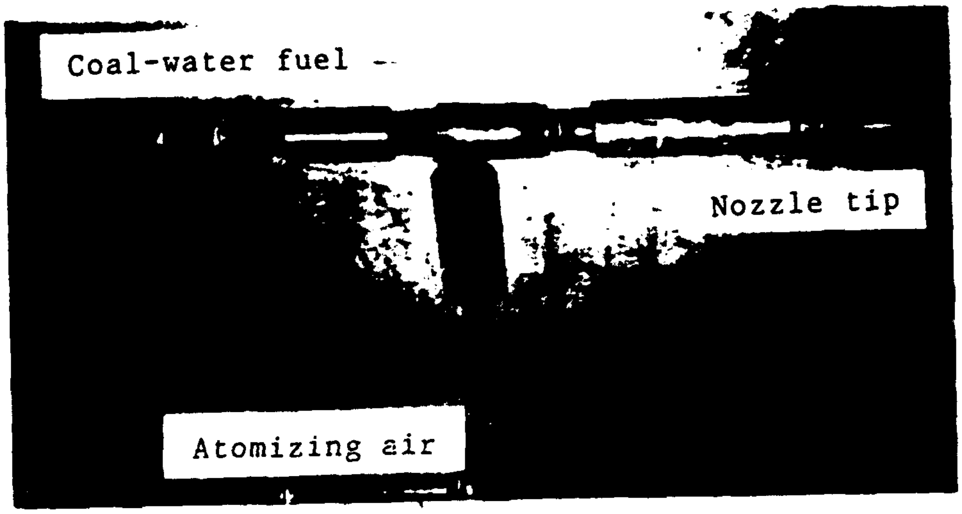


(a) Exhaust gas sampler.

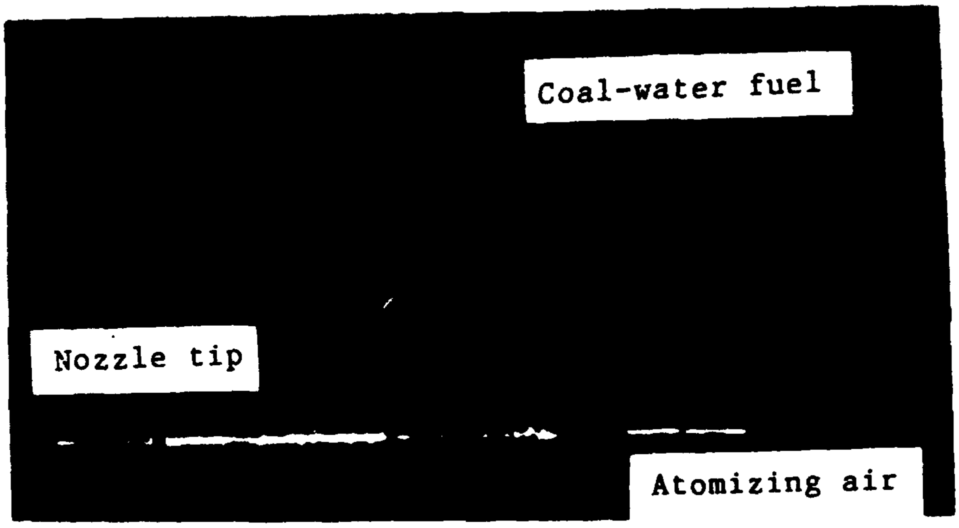


(b) Flyash sampler.

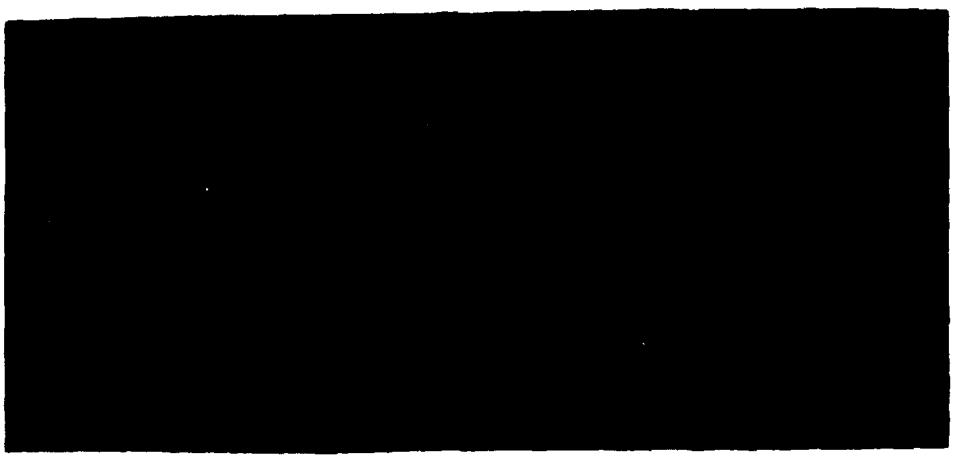
Figure 2.8 Exhaust gas/flyash sampling systems.



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



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



(c) CWF spray

Figure 2.9 CWF nozzles and spray.

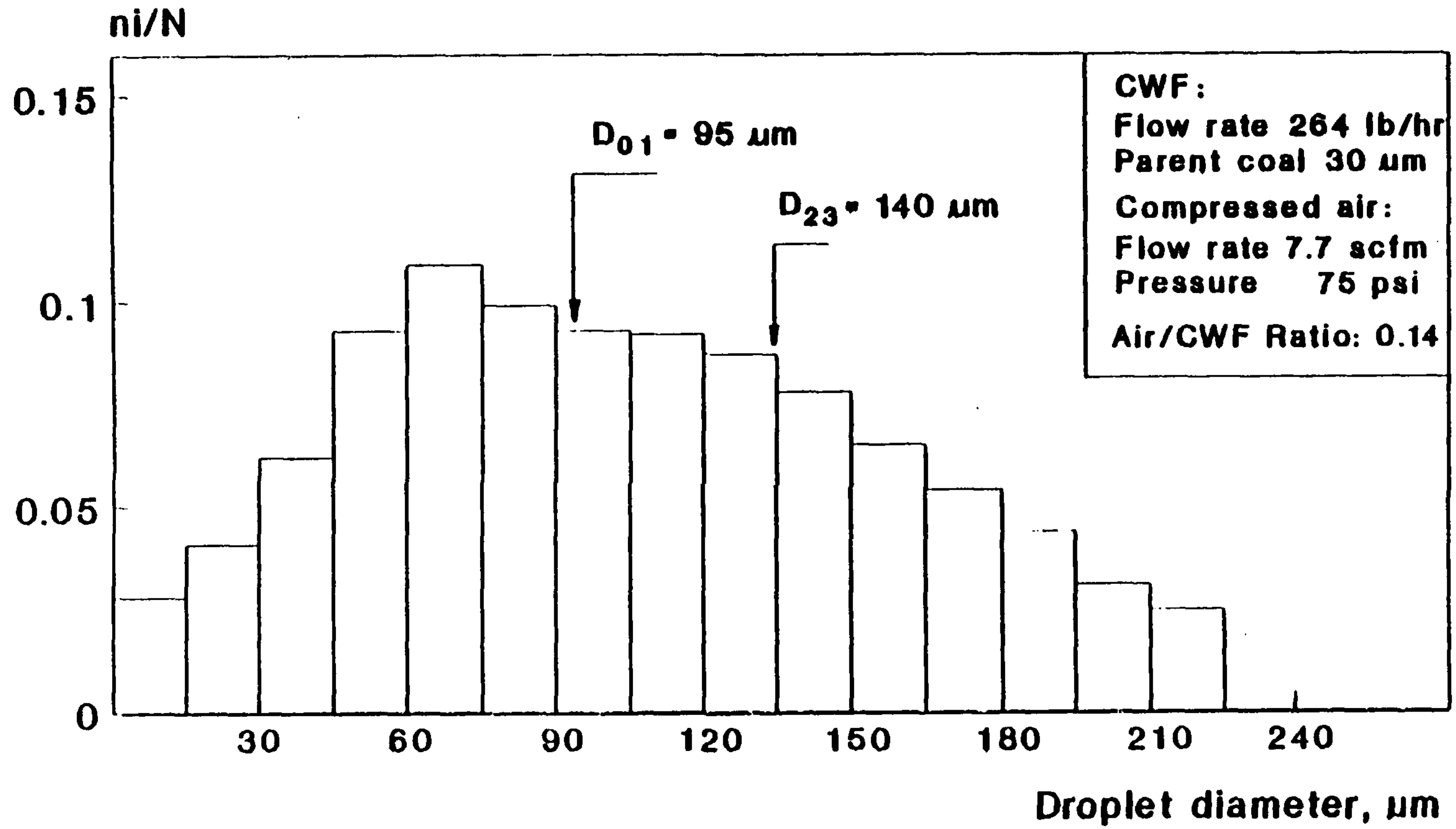


Figure 2.10 Typical droplet size distribution of a Type B CWF nozzle.

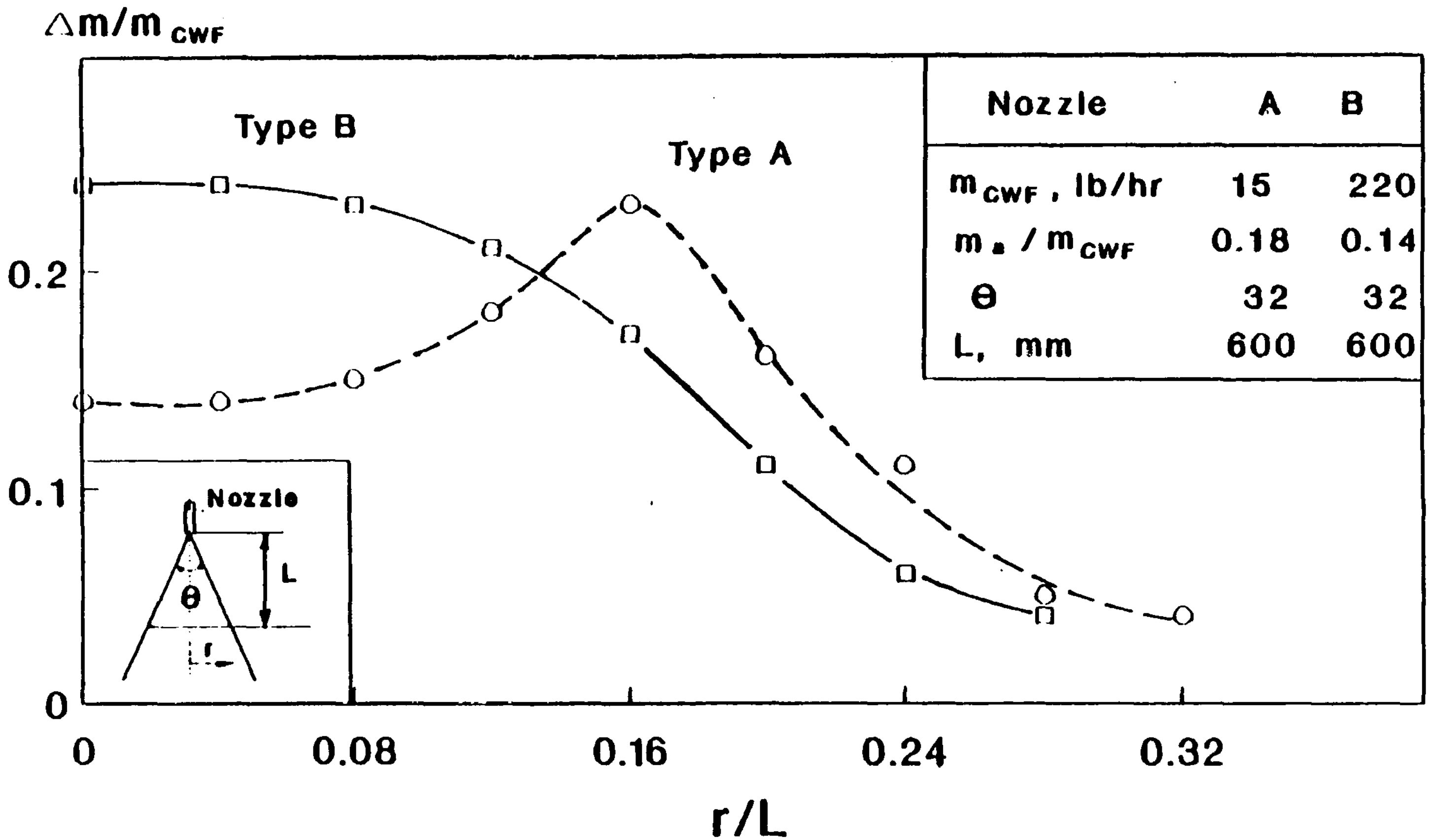


Figure 2.11 Spatial distributions of CWF sprays for Type A and Type B nozzles.

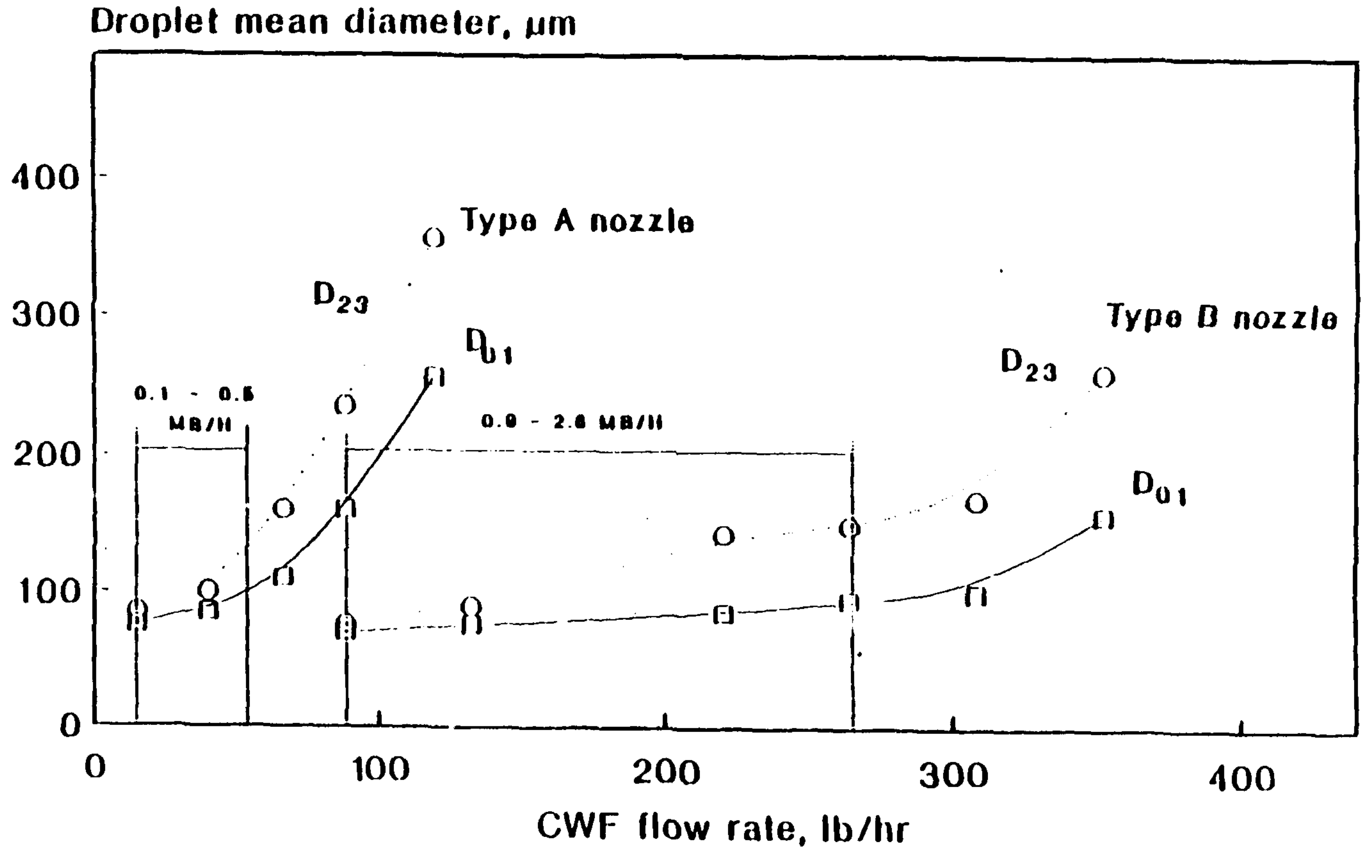


Figure 2.12 Effect of flow rate on atomization quality for Type A and Type B nozzles.

CHAPTER 3

AVC TEST MODELS

3.1 DESIGN CONSIDERATIONS

3.1.1 Design Guidelines

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

- Geometrically, an AVC 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 between the two tubes.

- 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.

- The vortex generator should produce a strong centrifugal flow field, whose swirl intensity and quality of air injection can be adjusted and controlled.

- The center tube should be designed to minimize fuel particle elutriation and to maintain the rigidity of the strong swirl for achieving the desired fuel residence time.

- Arrangement of air injection and heat removal surfaces should be made to maintain the desired low temperature with minimal temperature variations in the combustor for best NO_x and SO_x control. Heat removal surfaces may consist of fully or partially water-cooled walls.

- A proper combustor height-to-diameter ratio should be selected to facilitate the stage combustion and heat removal surface arrangements.

3.1.2 Design Calculations

The design calculations included basically mass and energy balances (Refs 24, 25, 26). The calculations began with the properties of the given fuel and the desired firing rate. The excess air in the design was set in the range of 10 to 30 percent. Based on these parameters, the fuel consumption, total combustion air requirement, amount of flue gases and ash to be generated, and overall combustor dimension were calculated first. Refinements were 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 an AVC were practically nonexistent and had to be developed from this work. Based on the features of strong swirl and low combustion temperature environment, the overall heat transfer coefficient in the AVC was assumed to be around 20 Btu/H-ft^2-°F in the preliminary design of PExp AVC model. With this, the needed area and location of the heat transfer surface was estimated. The average firing intensity (volumetric heat release rate), a parameter which affected the overall size of the combustor, arrangement of heat removal surfaces, and selection of combustor materials, was also not known. Based on experience with the vortexing fluidized bed combustor (Ref 6), an average firing intensity of 0.1 MB/H-ft^3 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 AVC. Judging from the assumed heat transfer coefficient and average firing intensity, all AVC test models provided more than adequate areas for the heat removal needs.

The design of the fuel nozzle (or atomizer) followed conventional engineering practice: the injecting velocity of fuel-air mixture was chosen to be 40 to 70 feet per second, with the primary air fraction being 5 to 30 percent. Being a part of the vortex generator, the fuel nozzles were designed to be adjustable in protrusion length, location on combustor wall, and injection angle. In the operation of AVC models, up to 95 percent of combustion air may be supplied by the secondary air nozzles. The design considerations for the air nozzles were:

- Adjustable air injection velocity of 100 to 180 feet per second.

- 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 degrees apart on combustor circumference.

- 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 the cyclone separator and experience with the vortexing fluidized bed combustor (Ref 6), the diameter ratio of the center tube and the combustor should be kept close to 0.5. The average velocity of the ascending hot gases in the annular space should be kept below 15 feet per second 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 feet per second.

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 AVC models (PExp and Exp) and two full-scale models

(PPOC and POC) were designed, built, and tested. Table 3.1 summarizes the major parameters of these four AVC models. The design features and test results are discussed in the following sections.

3.2 PExp AVC MODEL (0.15 MB/H)

The PExp AVC model was designed when the understanding of annular 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 AVC concept into practice. Based on the preliminary information generated from cold flow modeling studies (Ref 11) and complete energy and mass balance calculations (Ref 24), the PExp AVC model was designed and built (see Figure 3.1). It has the following design features:

- Sub-adiabatic configuration, including a refractory lower chamber (adiabatic) and a water-cooled metal upper chamber (non-adiabatic).

- A contraction between the upper and lower chambers to enhance recirculation and prolong the fuel residence time in the lower chamber.

- Low firing intensity and large height-to-diameter ratio.

- 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.

About 30 test runs totaling 150 hours of test time were 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 AVC 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/H ft^3	0.15	0.11
Combustion efficiency, %	98.9	99.4

The experience and lessons learned are summarized below:

- The AVC concept for coal firing was proven to be workable in terms of combustion performance and operational convenience.

- High combustion efficiencies (>98 percent), a large turndown ratio (>3:1), and acceptable operating temperatures (1,500 to 2,100°F) were achievable with DUC.

- The PExp AVC model and its auxiliary systems were found to be reliable and safe, and exhibited good control characteristics with regard to cold start, load variation, and hot restart.

- 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.

- 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.

- 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 Chapter 4, Figure 4.8b).

- The designed average firing intensity of 0.1 $MB/H\text{-}ft^3$ was low and can be increased by use of heat removal surfaces.

- The operational characteristics are depicted in Figure 3.2. 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 AVC MODEL (3 MB/H)

Based on the data and experience obtained from PExp AVC model tests and the successful development of CWF atomization nozzles, a 3-MB/H full-scale PPOC AVC 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 AVC are summarized in Table 3.1. Figure 3.3 is a pictorial view of this model and its auxiliary systems. The design features and major data are summarized below (Ref 29):

- The combustor outer wall is practically adiabatic, made of 5-inch castable refractory. A removable cooling coil made of 1-inch copper tubing is inserted at the bottom for temperature control.

- The center tube is water cooled on both sides of the wall. The height of the center tube is adjustable.

- 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.

- Adjustable fuel injection angle and deflecting air are provided.

- A removable contraction is located below the top two rows of secondary air nozzles.

A total of 27 test runs were 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	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/H-ft^3	0.16	0.15	0.11
Combustion efficiency, %	97.0	97.1	94.0

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

- Stable, on-time ignition, and self-sustained combustion of DUC was easily achieved at all firing rates up to 3 MB/H.

- 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 a 2-MB/H load.

- Deflecting air was effective in preventing CWF deposition on the combustor wall. A "spray shaper" was developed and was extremely useful for intensification of water evaporation and CWF ignition at full load. With this it was possible to ignite and burn up to 225 lb/H of CWF in the narrow annular space of the AVC without deposition buildup.

- DUC and CWF were successfully fired up to 3 MB/H with combustion efficiency up to 97 percent. This confirms the up-scaling potential of the AVC concept.

- The in-furnace cooling coil could effectively absorb heat and control the combustion temperature.

- Heat removal surfaces located either on the combustor wall or the center tube could remove heat without adversely affecting combustion.

- 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.

- The average firing intensity could be further increased by the increase of heat removal rate and vortex generator arrangement.

- Type B CWF nozzles performed very well both in atomization quality and in compatibility with the unique AVC configuration.

3.4 Exp AVC MODEL (0.3 MB/H)

Research efforts on PExp and PPOC AVC models point 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 the PPOC AVC model, the combustion tests on this model would require a large amount of fuel and excessive manpower. It was deemed not economical and feasible to conduct further tests on this model. An improved subscale exploratory hot model of 0.3 MB/H, the Exp AVC, was designed, built, and tested (see Figure 3.4). This model has the following features:

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

- Four runs of independently controlled water cooling coils were wound on the outer wall for studying the local heat transfer characteristics along its height.

- Two feed ports were provided at combustor bottom for both CWF and DUC. Deflecting air was used to prevent fuel deposition and clinker formation.

- 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.

- A 1/4-inch-thick Vycor glass plate was used as the combustor top to facilitate visual observations of the flame and particle behavior during tests.

- The overall design improved the average firing intensity to as high as 0.44 $MB/H\text{-}ft^3$.

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

Fuel Type Firing Rate, MB/H	DUC 0.22	DUC 0.31	PC 0.27	#2 Oil 0.20	Propane 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, $MB/H\text{-}ft^3$	0.31	0.44	0.38	0.29	0.42
Combustion efficiency, %	97.6	95.4	95.8	99.4	100

3.4.1 Improvement of Firing Intensity

The use of refractory liner to cover only some areas of the basically water-cooled combustor wall made the heat removal capability of Exp AVC much higher than prior models. The flow and turbulence was substantially improved via the arrangement of vortex generator. Consequently, a three-fold improvement on firing intensity over PExp and PPOC models was achieved. This paved the way for a successful design of our POC AVC.

3.4.2 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/H-ft^2-°F, depending on the swirling flow and combustion temperature.

3.4.3 Controllability of Temperature

The combustion temperature and its axial distribution was controllable by means of secondary air distribution as illustrated in Figure 3.5. If a large amount of secondary air is injected at the lowest level (90 percent at level a, 10 percent 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 percent at level a, 35 percent at level b, 15 percent at level c, and 10 percent 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.

3.4.4 Controllability of Particle Behavior

The flexibility of AVC in controlling fuel particle behavior, for example, elutriation and residence time, was demonstrated in our cold flow measurements (Ref 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.

3.4.5 Effect of Swirl

Figure 3.6 shows the effect of swirl on flame and combustion. Note the differences on flame shape and luminosity, burnout 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 AVCs. 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 an AVC to attain high combustion performance at low temperature. The AVC technology is truly state-of-the-art in coal combustion.

3.5 POC AVC MODEL (2 MB/H)

With the data and experience obtained from PExp, PPOC, and Exp AVC hot models, a 2-MB/H POC AVC 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 3.7. The design features are summarized below:

- A water jacket was used as the combustor wall. The lowest 1/4 of the wall was lined with castable refractory to ensure positive ignition, particularly for CWF firing. 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.

- The vortex generator consisted of a vertical array of six independent nozzles. The height, tip cross-sectional area and configuration, and injection angle are all adjustable.

- Two feed ports were provided for the fuels, both CWF and DUC/PC. The fuel nozzles were designed and built to fire multiple fuels. The primary air velocity was kept within 50 to 70 feet per second. To prevent CWF deposition on the chamber wall, the spray cone angle was kept at about 30 degrees.

- Two types of arrangements of heat removal surfaces were tested: 25 percent and 90 percent of water jacket areas were covered with refractory liner.

- The center tube is made of 9-inch O.D. steel pipe. For the convenience of installation and adjustment, it was cut into three sections. The configuration of the center tube inlet, size, and height are all easily adjustable.

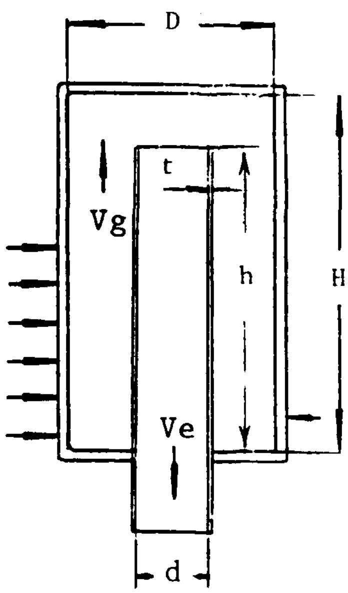
- Great efforts have been devoted to simplification of the design and operation. The simplicity of POC AVC enabled it to be fabricated and assembled by graduate students.

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

Table 3.1 Summary of Major Parameters of AVC Test Models

Parameter	PExp[a]	PPOC[b]	Exp[c]	POC[d]
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
t	1/8	1	1/8	3/8
Overall	16 x 50	48 x 60	10 x 24	23 x 40
Operation (@ design capacity)				
Average firing intensity, MB/H ft^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

[a]PExp = Preliminary exploratory.
[b]PPOC = Preliminary proof-of-concept.
[c]Exp = Exploratory.
[d]POC = Proof-of-concept.



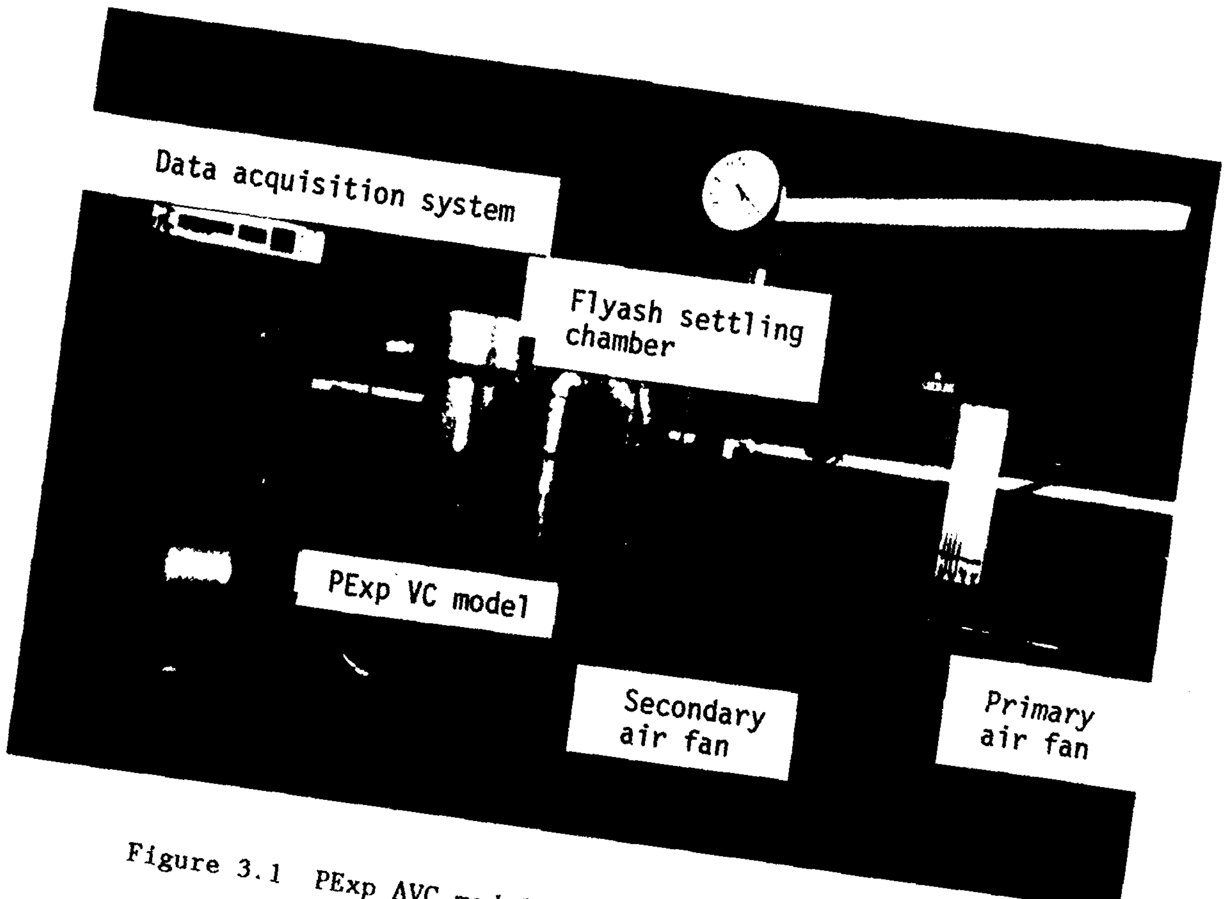


Figure 3.1 PExp AVC model and its auxiliary systems.

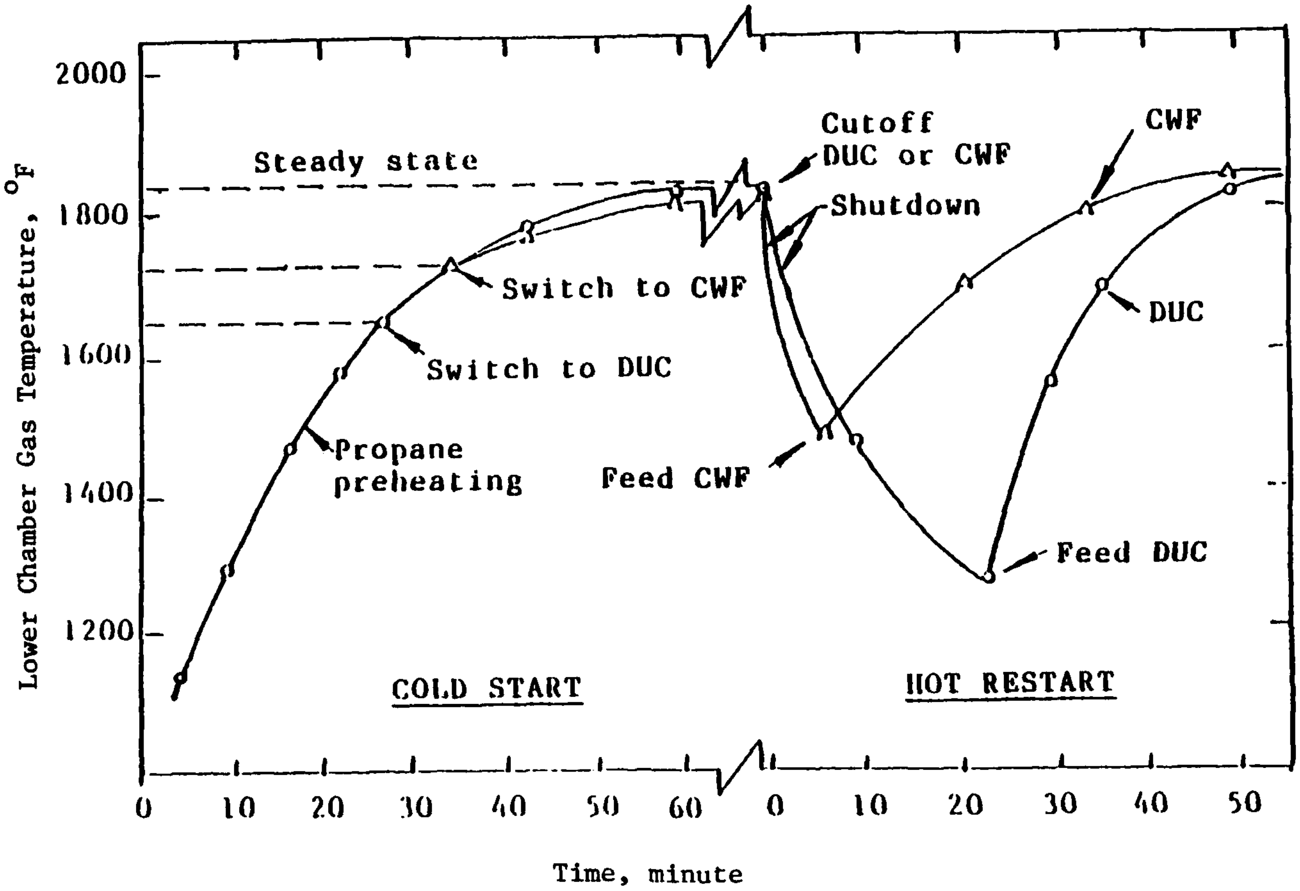


Figure 3.2 Operational characteristics of PExp AVC model firing DUC and CWF.

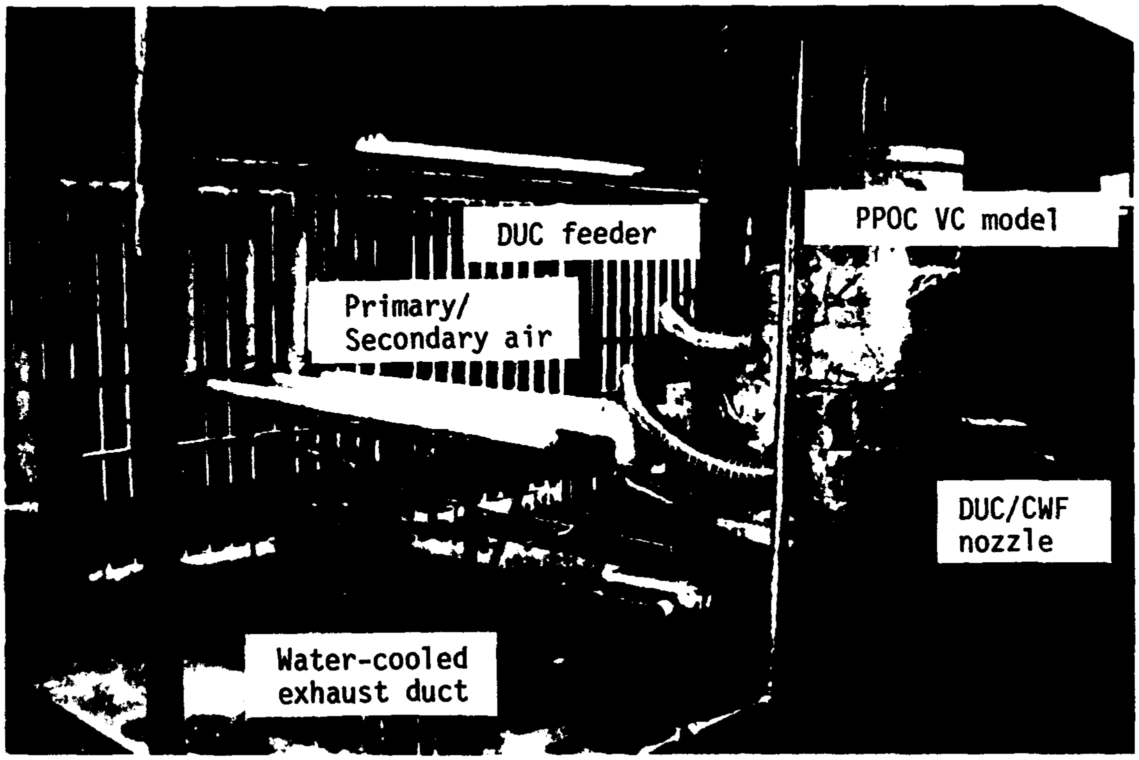


Figure 3.3 PPOC AVC model and its auxiliary systems.

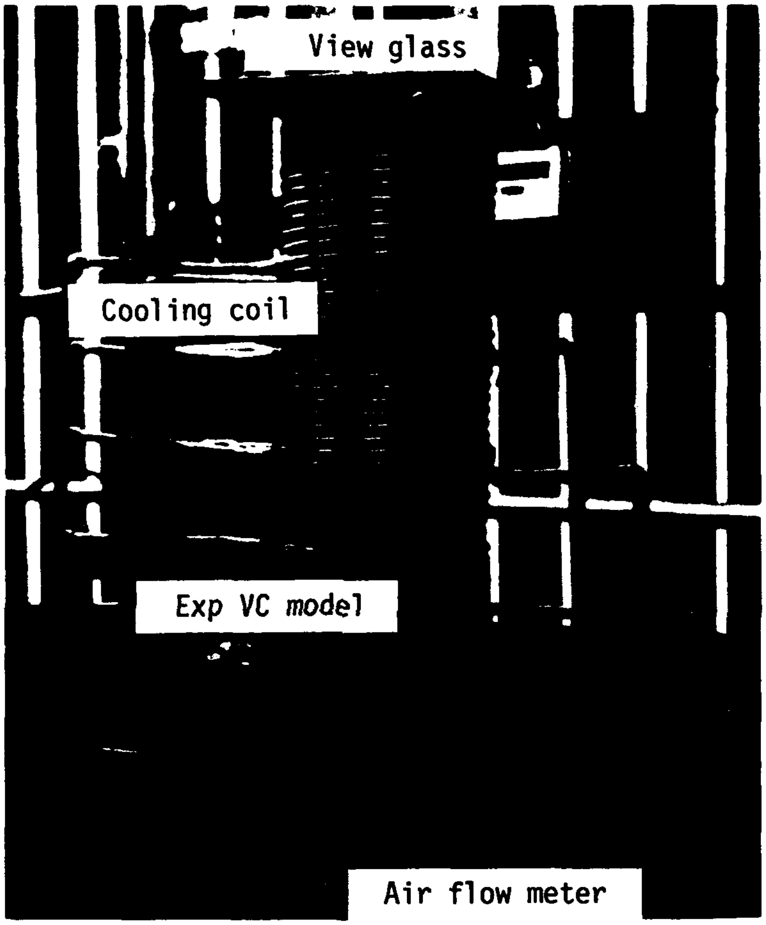


Figure 3.4 The Exp AVC model.

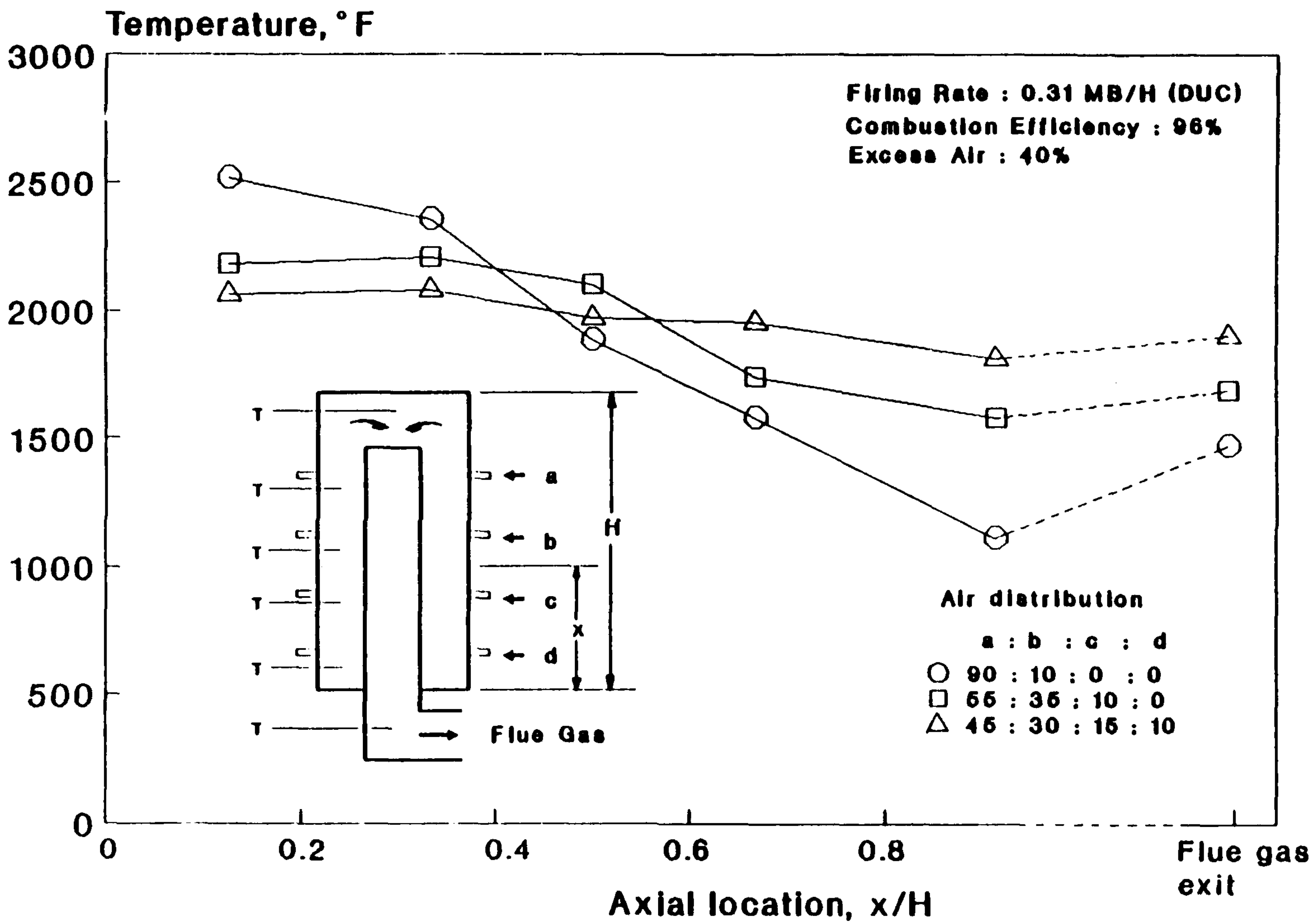
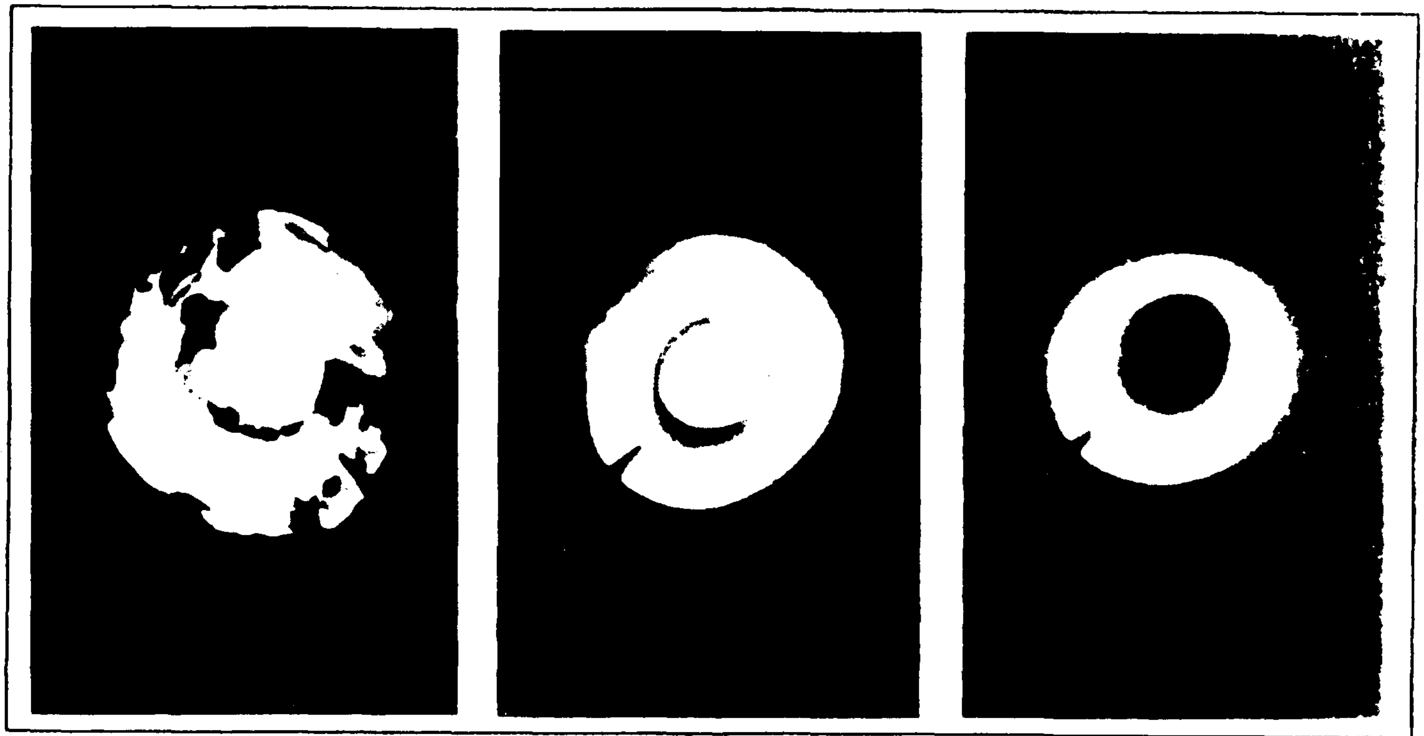


Figure 3.5 Controllability of combustion temperature by air distribution.



(a) (b) (c)

	(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^3	0.05	0.15	0.5

Figure 3.6 Effect of swirl on flame and combustion.

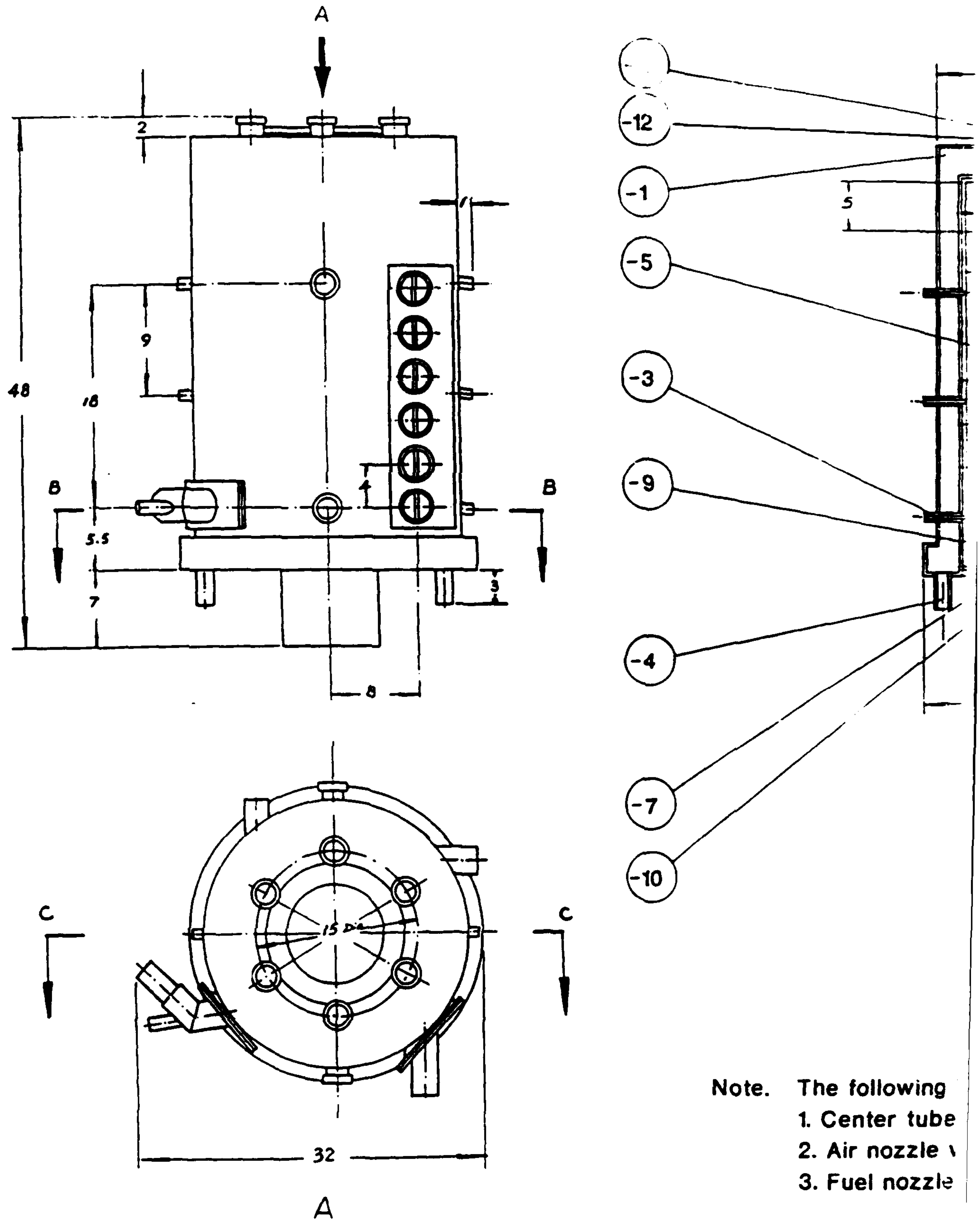
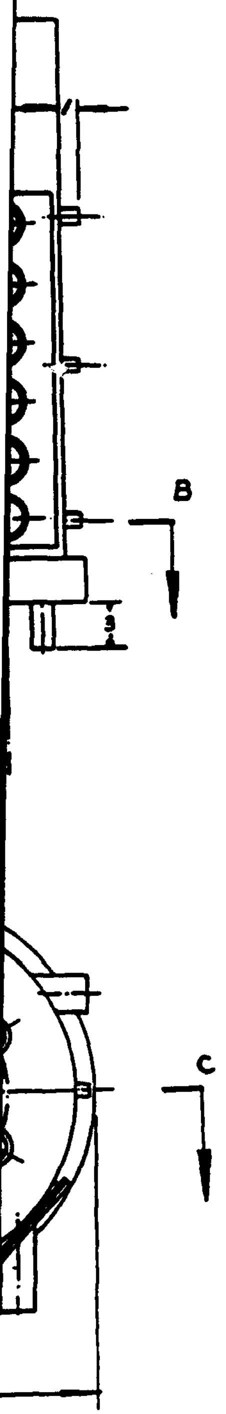
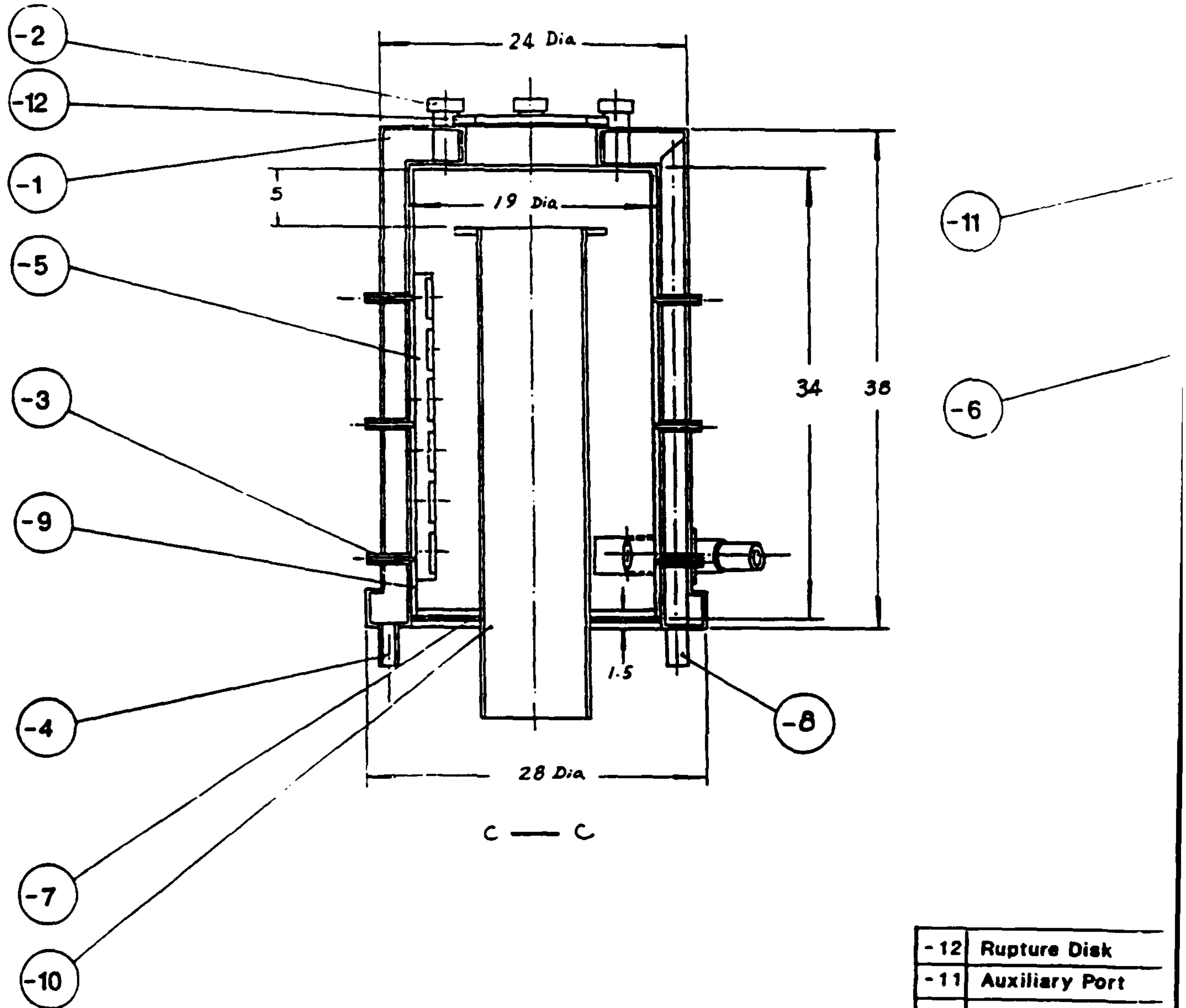


Figure 3.7 The POC AVC design.

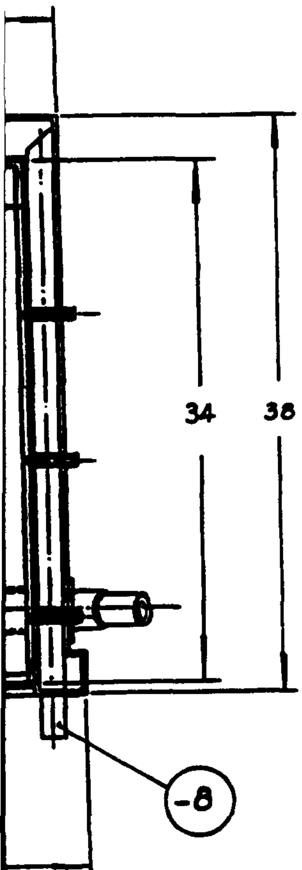


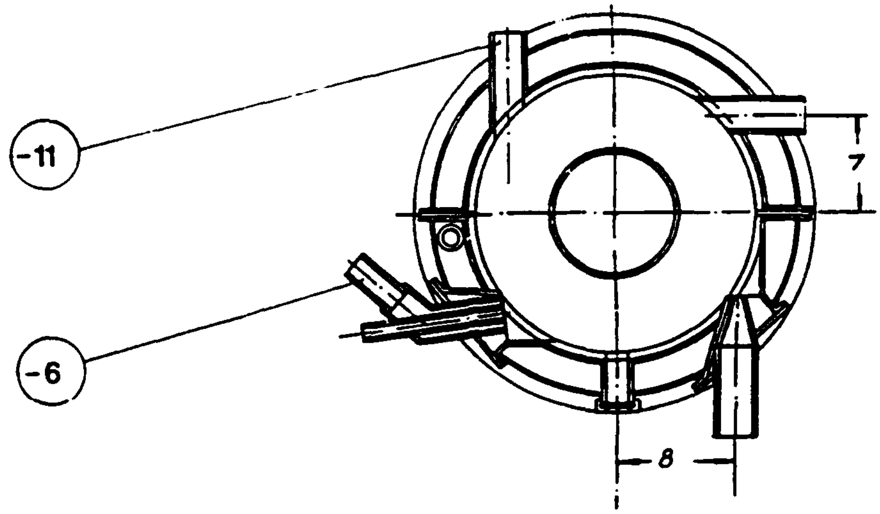


Note. The following items are adjustable:
1. Center tube vertical location.
2. Air nozzle vertical location and orientation.
3. Fuel nozzle orientation.

No.	Name
-12	Rupture Disk
-11	Auxiliary Port
-10	Center Tube
-9	Liner
-8	Hot Water Outlet
-7	Furnace Bottom
-6	Fuel Feed Port
-5	Vortex Generator A
-4	Feedwater Inlet
-3	Instrument Port
-2	View Port
-1	Water Jacket

POC AVC design.





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ble:

nd orientation.

No.	Name	Req'd	Material
-12	Rupture Disk	1	1/16" 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", 1" 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

POC AVC Assembly

DRAWN BVC Estimated total weight: 400 lbs

CHK'D Dimensions: inch

TRACED APP'D

DRAWING NUMBER CMFL - 89 - 10

3

CHAPTER 4

TEST RESULTS OF POC AVC MODEL

A total of 140 hours of combustion test time was accumulated on the POC AVC model firing CWF (5,000 pounds), DUC (4,000 pounds), and PC (1,500 pounds). The longest continuous running time was 6 hours. The performance characteristics of the POC AVC were 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 were explored. This chapter presents and discusses these results.

4.1 TEST ARRANGEMENT

4.1.1 Test Setup and Fuels

Figure 2.1 shows the test setup for systematic combustion tests of the POC AVC model. The details of the auxiliary systems and instrumentation are presented in Chapter 2. Three types of coals were used for the tests: CWF, DUC, and PC (see Table 2.1).

4.1.2 Test Plan and Procedure

Parametric studies on the effects of excess air (9 to 49 percent), firing rate (0.65 to 2 MB/H), secondary air arrangement, and ignition and burnout characteristics were conducted. A summary of these tests is given in Table 4.1.

The test procedure is briefly described below:

- Prepare, inspect, and adjust the combustor and its various auxiliary systems, including the instruments for various measurements. Load the fuels sufficient for 4 hours of testing. Test run all auxiliary systems.

- 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.

- Cofire propane and coal for about 10 to 15 minutes to stabilize the flame, cooling water temperature, and combustor performance at the preset test condition.

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

4.1.3 Data Collection and Analysis

Except for the flyash samples that 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 described in Chapter 2 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 more difficult to burn than dry powered coals. Since CWF is the design fuel of AVC, efforts were 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.

4.2.1 Intensification of Water Evaporation

The configuration of an AVC 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 build up, and eventually block the flow passage. The two types of CWF nozzles described in Chapter 2 were used (both with a spray angle close to 30 degrees). As illustrated 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 forms undesirable depositions (Refs 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:

$$t_{ev} = \frac{Q_{ev}}{\dot{Q}_{in}} \leq t_f = \frac{S}{V} \tag{4-1}$$

where: Q_{ev} = heat needed for water evaporation

$\dot{Q}_{in}$ = heating rate from the surroundings

S = droplet flight distance before impingement

V = flight speed of droplets

Equation 4-1 can be rewritten as:

$$\frac{d^2}{\Delta T \; Nu} \leq c \frac{S}{V} \tag{4-2}$$

where: d = mean droplet diameter

Nu = Nusselt number

ΔT = average temperature difference between surrounding hot gases and droplet

c = a constant

Based on Equation 4-2, the following measures were taken to resolve the deposition/accumulation problem:

- Improve the CWF nozzle performance to achieve a fine spray, or small d. This was accomplished and presented in Chapter 2.

- Increase the local temperature, or ΔT, and Nu in the ignition zone by partially lining the water-cooled surface with refractory.

- 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 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.

- Adopt a novel "sprav 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 were dried up almost as soon as they left the nozzle.

4.2.2 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 AVC in these aspects. Because of the strong swirl, unburned fuel particles are thrown toward the combustor wall by centrifugal force and form layers of suspended particles (the suspension layers) (Ref 11). They are trapped in these layers until completely burned out and become sufficiently small in size and mass to be entrained by the flue gas and leave 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 a center tube height h/H of about 0.8. A flat steel flange mounted at the lip of the center tube can prevent particles from rising along the outer wall of the center tube 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 CWF and dry powered coals to burn efficiently at high firing intensity and relatively low temperatures compared with most other combustors. With the measures mentioned above, >99 percent combustion efficiencies were consistently achievable in firing CWF.

4.2.3 Test Results

Systematic tests on firing CWF were conducted to accumulate performance data for AVC design and operations, and to demonstrate the superiority of this 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 in firing CWF. It should be noted that all CWF tests were carried out with combustion air at an ambient temperature of around 50°F. The CWF tested contained 33 to 35 percent water by weight and had a mean coal particle size of 30 μm.

4.2.3.1 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 percent. 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 percent, with more recent results all above 99 percent (see Table 4.2, Run Nos. 25, 28, 29, and 30). It appears that combustion efficiencies were above 99 percent around 25 percent excess air, which was also observed in DUC firing (see next Section). Figure 4.3 also shows that the combustion efficiency does not decrease with the decrease of excess air. This enables the AVC to be operated at low excess air and, hence, high thermal efficiency.

NO_x and CO levels ranged from 200 to 600 ppm, which were obtained with no special effort in emission reduction. Since AVC is effective in staging the air, the present results suggest a high potential for low NO_x combustion in AVC firing. The exiting flue gas temperature and the average gas temperature decreased generally with the increase of excess air. The difference in temperature became higher at higher excess air.

4.2.3.2 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 were all achieved. All combustion efficiencies were above 97 percent, and the best combustion performance (>99 percent) was at around 1.2 MB/H (or 0.2 MB/H-ft^3). NO_x and CO levels generally increased with increasing firing rate and fluctuated within 200 ppm. The average gas temperature was found to be about 200°F higher than the flue gas temperature. Both temperatures seemed to be relatively insensitive to the change of firing rates.

4.2.3.3 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 percent for the center tube at $h/H = 0.6$, 0.7, 0.8, and 0.9, respectively. Center tube height was found to have a significant effect on the combustor performance. The optimal height was around 0.8, where the combustion efficiencies usually exceeded 99 percent. When the center tube height increased, the levels of CO and NO_x tended to decrease. This trend was particulary clear for the CO level. A higher center tube generally gives somewhat higher average and flue gas temperatures (within 100°F).

4.2.3.4 Effect of Inlet Configuration of the 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 were conducted. Figure 4.6 shows the difference between a plain tube (original) and one with a flange at the lip (improved). A great improvement in combustion efficiency (~2 percent) was found with the flanged configuration. The effect of flange on NO_x level was not clear. It was, however, very effective in reducing the CO levels, suggesting a substantial improvement of gas-gas mixing in the burnout zone. At 25 percent excess air, a three-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 of the presence of the flange on the center tube.

4.2.3.5 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 percent. 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 percent when the refractory-lined area was enlarged from 25 to 90 percent. The average gas temperature increased by almost 200°F, as expected. NO_x emission was found to increase by about 100 ppm and CO emission decreased by about 250 ppm. This is caused primarily by the higher temperature which promotes complete combustion and thermal NO_x formation.

4.3 DUC TEST RESULTS

About 50 hours of combustion tests were 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.

4.3.1 Performance Comparison of DUC and CWF

The major differences between DUC and CWF are their ignition characteristics. DUC contains less than 2 percent of moisture, which does not cause delay or other problems (as it does for CWF in ignition). The average diameter of DUC (12 μm) is only 1/9 that of the average CWF droplet (106 μm). This means that the DUC and CWF particle masses or volumes may differ by three orders of magnitude. DUC can be ignited almost as soon as it enters the combustion chamber where it is 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 AVC design and operation. However, since the POC AVC model was designed for CWF firing, some difficulties in controlling the DUC combustion process under the same design configuration as for CWF were encountered. Higher temperatures can damage the combustor even in a few hours. Figure 4.8(a) shows a melted center tube made of 3/8-inch-thick low carbon steel after a 6-hour continuous test of DUC at 1.5 MB/H. *To contrast*, Figure 4.8(b) shows the burned-through hole in the center tube of the PExp model after 30 hours of tests.

Two measures were taken to alleviate 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, and (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.

4.3.2 Test Results

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

4.3.2.2 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 ranged from 97.4 to 99.1 percent. In the optimal firing range (1.3 to 1.5 MB/H), the combustion efficiencies were all above 99 percent. Results also show that the combustion efficiency and emission levels did not seem to be adversely affected by the firing rates in the three-to-one turndown range. NO_x and CO levels were all within 550 ppm. Different from what was concluded for CWF combustion, the average gas temperature in DUC combustion increased consistently with the firing rate, as expected.

4.3.2.3 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 percent, the combustion efficiencies were all above 97 percent. At 23 percent primary air, the combustion efficiency exceeded 99 percent. The available secondary air fraction of 77 percent for this case is considered adequate for combustion performance adjustments. The effects of primary air on CO and NO_x are not clear. The average temperature dropped about 400°F when primary air increased from 10 to 30 percent. It was also observed in the Exp AVC model tests that the secondary air injection in the POC AVC model had 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 to be largely controllable by secondary air injection. Combined with heat transfer surface adjustments, a large degree of flexibility in combustion control may be realized in AVC.

4.4 PC TEST RESULTS

Combustion tests with PC were conducted to further evaluate the fuel flexibility of the POC AVC model. Since PC and DUC are made from the same parent coal, they differ only by the 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). These tests will enable study of the effects of particle size on the performance of AVC. Table 4.4 summarizes the major results.

4.4.1 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 percent was achieved for PC, being almost the same as DUC. The results further demonstrate the superior performance of the AVC concept in fuel flexibility. Compared with DUC, the only differences found in PC combustion tests were that it is easier to clinker and it is 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 to prevent clinker formation. More air was injected into the lower portion of the combustor. This created a more turbulent and oxygen-rich atmosphere in the ignition zone. As a result, the process of devolatilization and combustion of volatiles was accelerated and formation of viscous soot was reduced. In this way, clinker was successfully prevented, and the operations were satisfactory.

4.4.2 Test Results

The effects of excess air on PC combustion were systematically tested for a total of 20 hours (see Figure 4.12 and Table 4.4). For excess air ranging from 10 to 50 percent, the combustion efficiencies were higher than 97 percent. The optimal range of excess air was 25 to 30 percent, the same as for DUC and CWF firing. The highest combustion efficiency was 98.7 percent, slightly lower than DUC and CWF firing. NO_x and CO levels ranged from 500 to 650 ppm and 350 to 600 ppm, respectively. As excess air increased, both levels reduced slightly. The average gas and flue gas temperatures decreased with the increase of excess air. The temperature dropped about 200°F when excess air changed from 10 to 50 percent. The average gas temperature was about 2,000°F in the optimal excess air range of 25 to 30 percent.

4.5 DISCUSSION

The combustion of coal fuels occurs 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 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, combustion efficiency, and boiler rating. The test results presented in this chapter, strengthened by the cold model results (Ref 11), conclusively demonstrate the superiority of the AVC 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 AVC model 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 percent) were 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 serious agglomeration. The POC AVC model can ignite and effectively burn these fuel particles to completion. This performance of fuel flexibility demonstrates the inherent superiority of the AVC 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 AVC 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 also seen that the particle residence time is always longer than the needed burnout time in an AVC, 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 combustor which can be effectively controlled by means of secondary air injection. This feature of the AVC helps achieve high combustion efficiency, burn lower grade fuels, suppress particle elutriation, and reduce pollutant emissions.

Table 4.1 Combustion Tests Conducted on the POC AVC Model

Parameter	Fuel		
	CWF	PC	DUC
Excess air:	5 runs	5 runs	5 runs
<20%	M[a]	M	M
20 - 40%	M	M	M
>40%	M	M	M
Firing rate:	5 runs	1 runs	6 runs
<1 MB/H	M	O[b]	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: h/H = 0.6 - 0.9	-	-	4 runs
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

[a]M = Measurement.
[b]O = Observation.

Table 4.2 Major Results of POC AVC Firing CWF

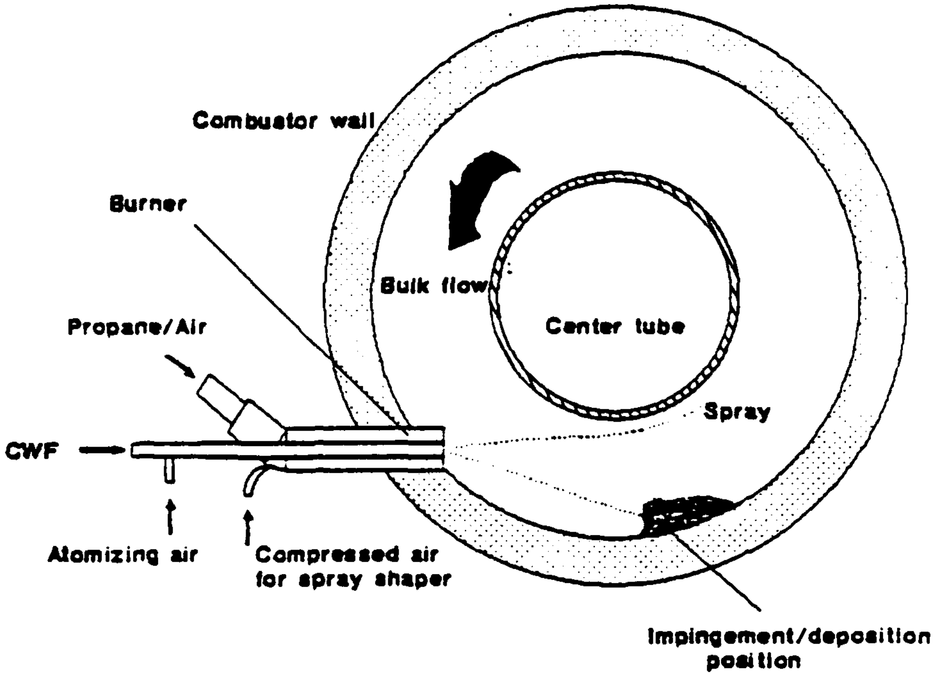
Parameter	Run No.					
	24	25	26	28	29	30
Firing rate, MB/H	1.04	1.13	1.03	1.22	1.54	1.81
Center tube height, h/H	0.8	0.8	0.8	0.8	0.8	0.8
Excess air, %	40	27	48	13	26	34
Total air distribution, %						
Primary	8	15	13	12	9	6
Secondary	92	85	87	88	91	94
Secondary air distribution, %						
Nozzle L	40	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/H ft^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

Table 4.3 Major Results of POC AVC Firing DUC

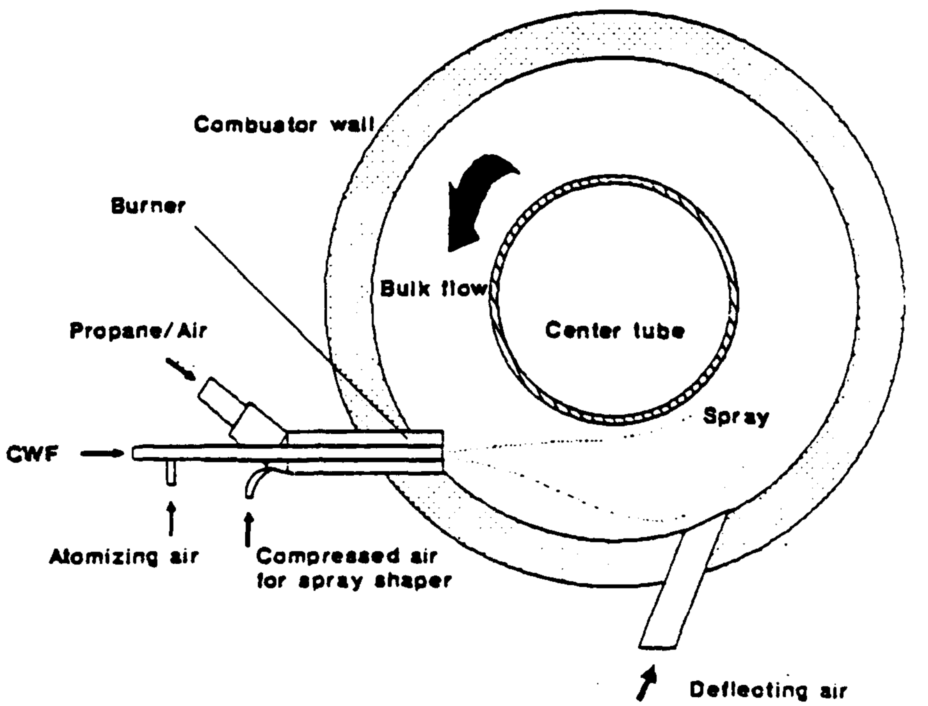
Parameter	Run No.					
	1	6	7	8	22	23
Firing rate, MB/H	1.36	2.02	0.65	1.52	1.13	0.81
Center tube height, h/H	0.9	0.9	0.9	0.9	0.8	0.8
Excess air, %	47	27	40	9	26	37
Total air distribution, %						
Primary	30	12	29	12	23	23
Secondary	70	88	71	88	77	77
Secondary air distribution, %						
Nozzle L	25	25	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/H ft^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

Table 4.4 Major Results of POC AVC 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



(a) Deposition of CWF spray

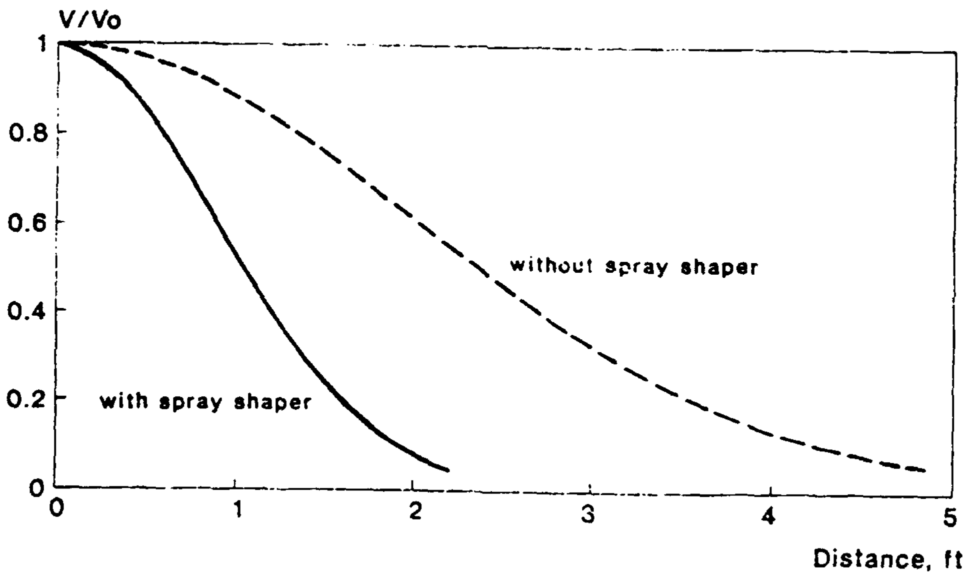


(b) Deposition elimination by deflecting air

Figure 4.1 Control of CWF deposition in AVC.

(a) Without spray shaper

(b) With spray shaper



(c) Spray velocity attenuation

Figure 4.2 Effect of spray shaper.

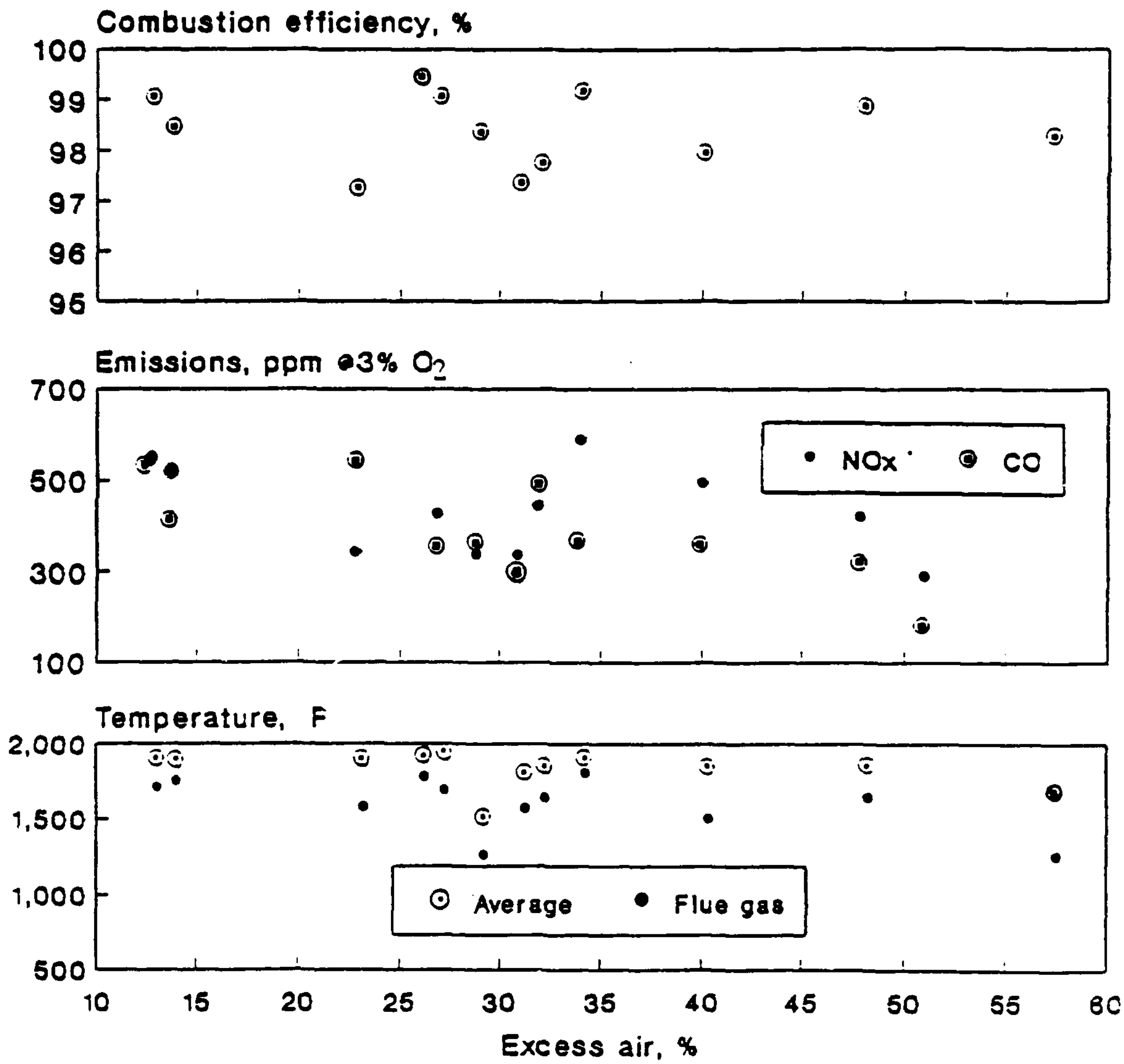


Figure 4.3 Effect of excess air on POC AVC performance firing CWF.

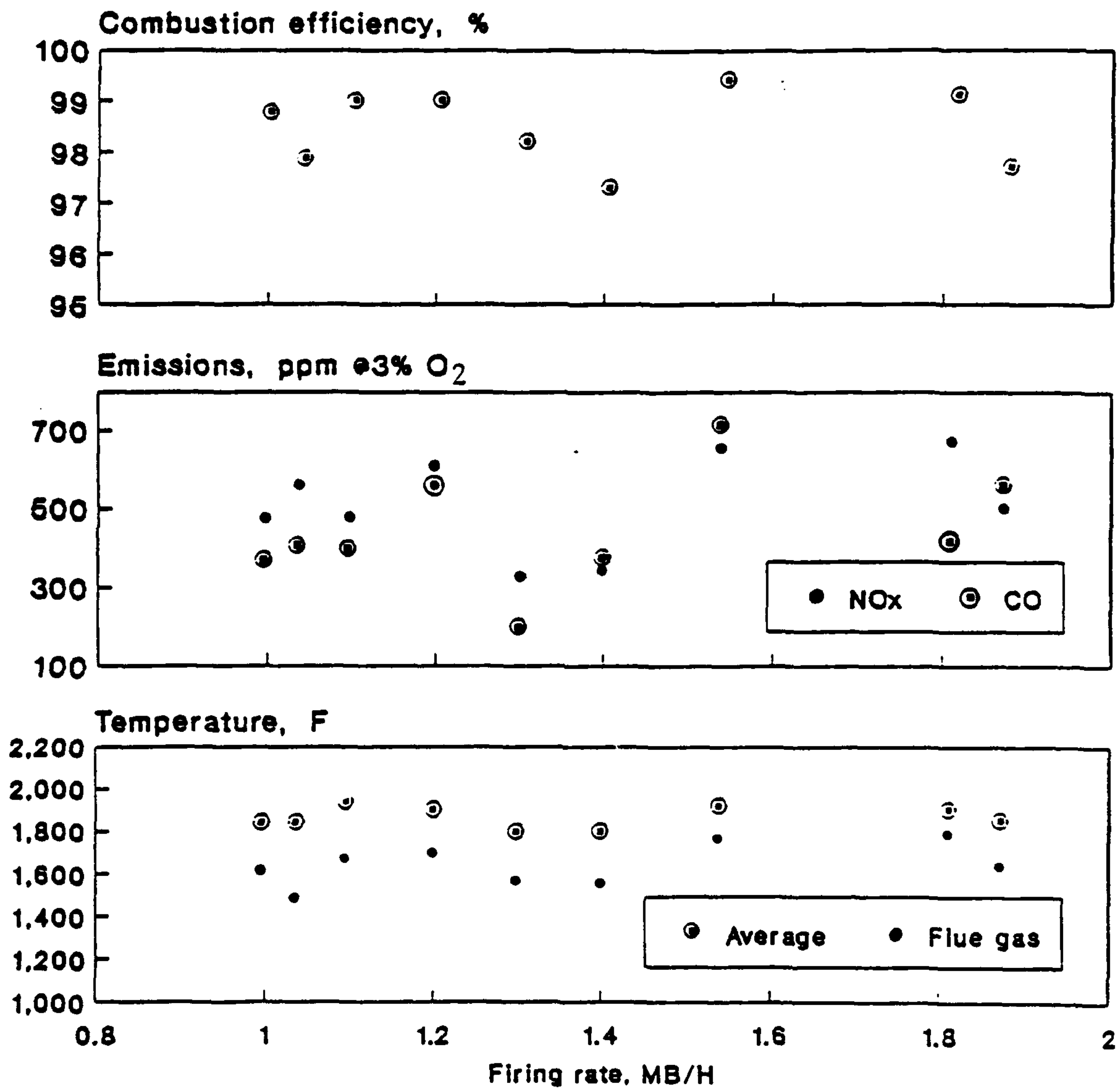


Figure 4.4 Effect of firing rate on POC AVC performance firing CWF.

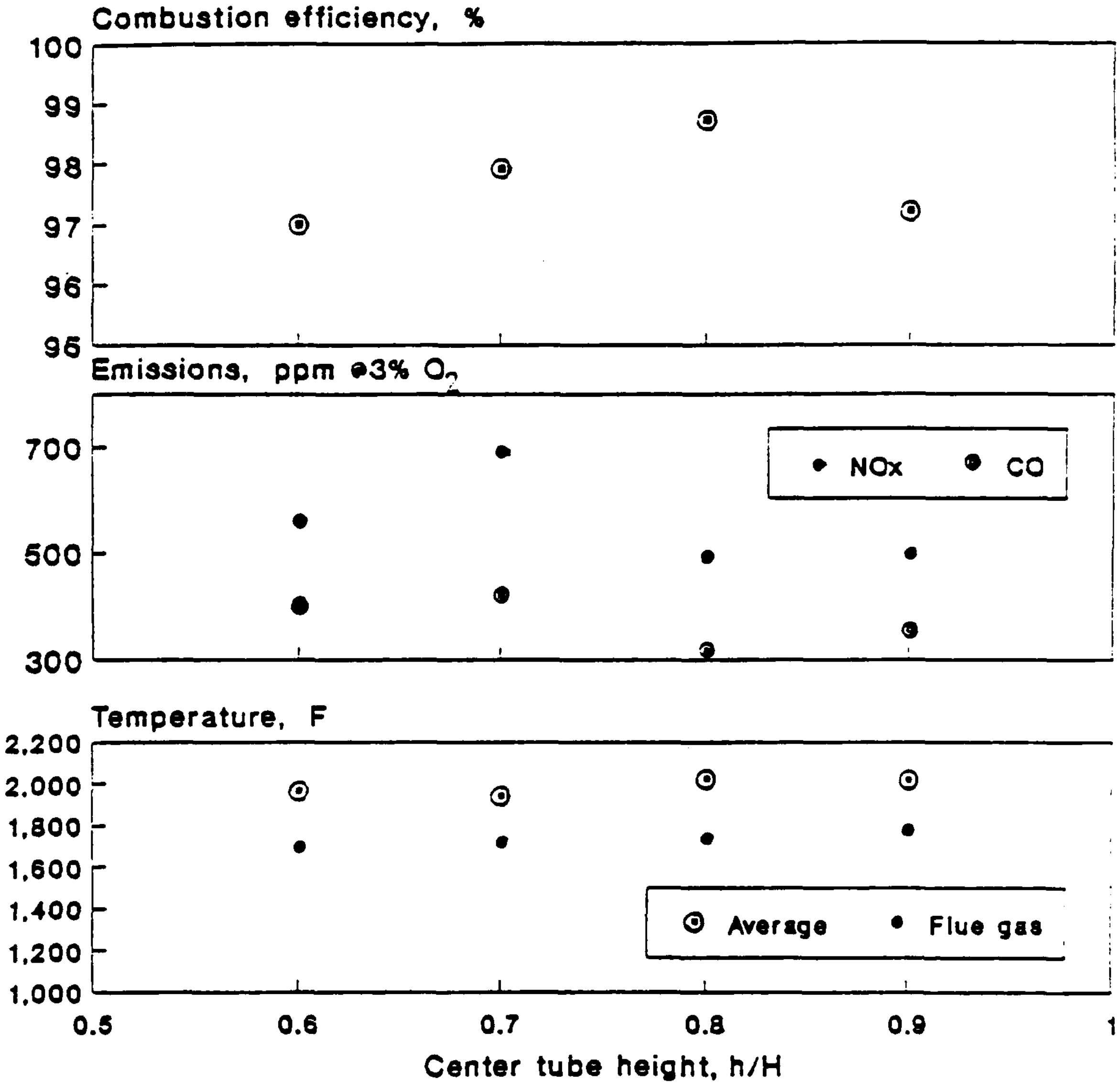


Figure 4.5 Effect of center tube height on POC AVC performance firing CWF.

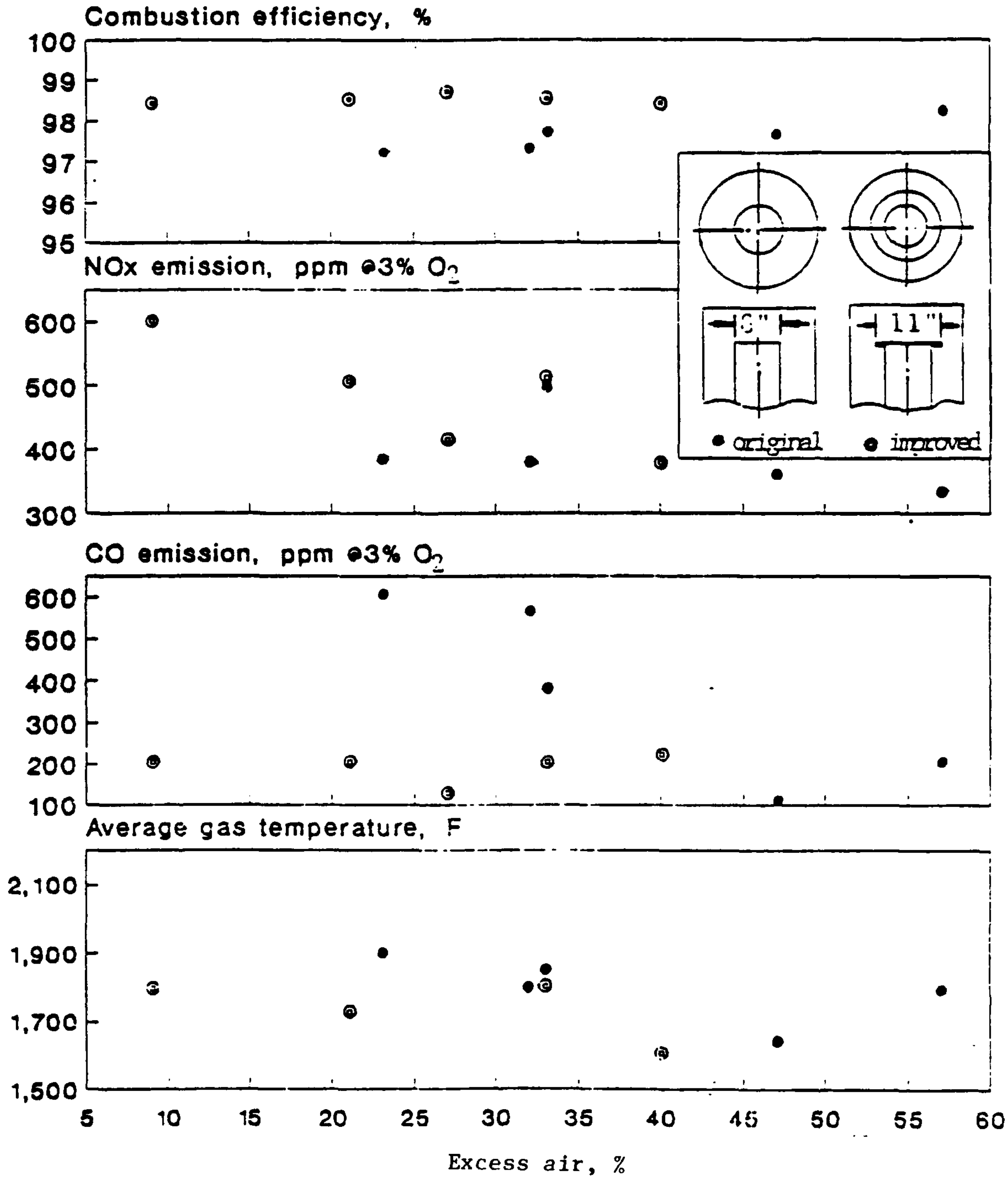


Figure 4.6 Effect of center tube inlet configuration on POC AVC performance firing CWF.

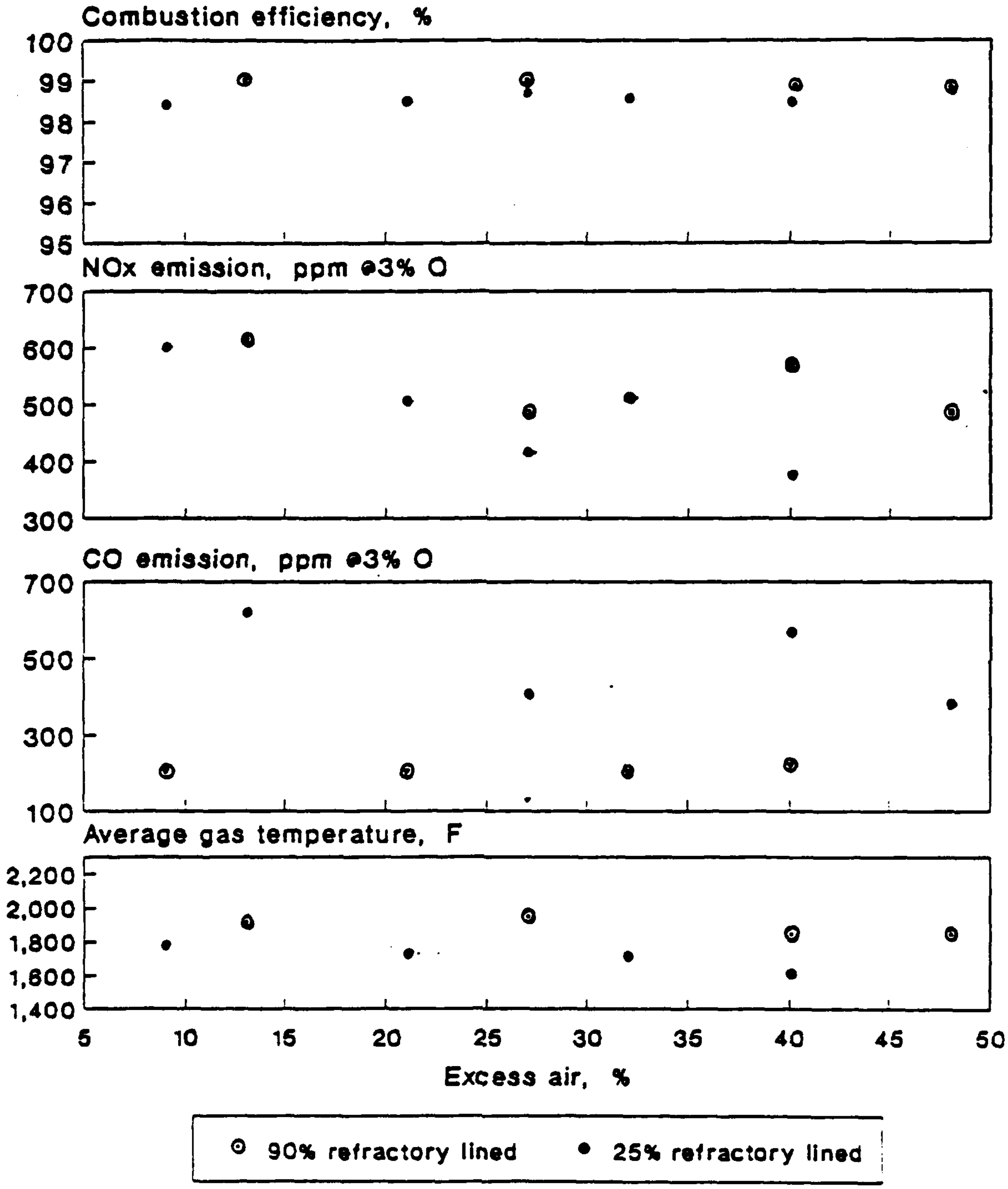
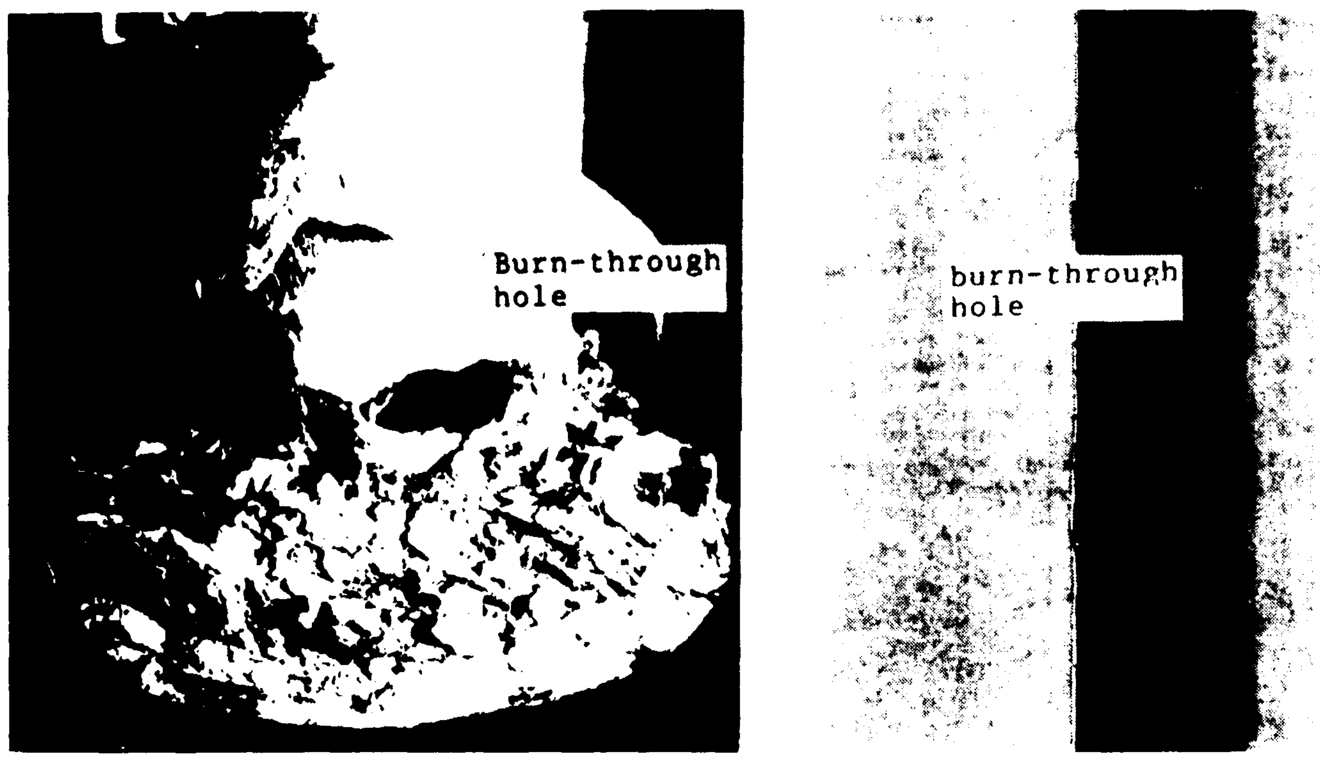


Figure 4.7 Effect of refractory liner on POC AVC performance firing CWF.



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

(b) After 30 hours of tests (PExp AVC model)

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

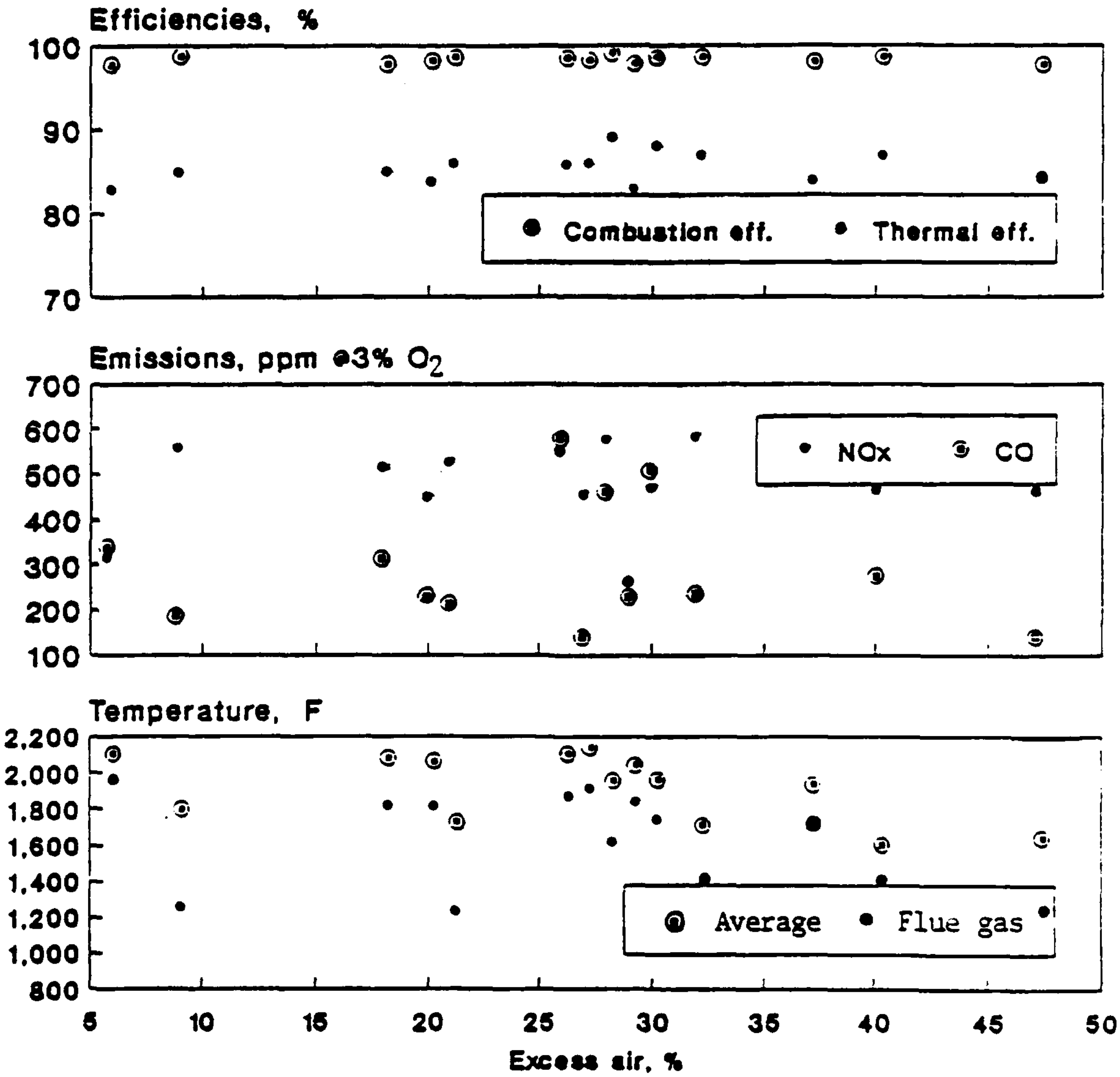


Figure 4.9 Effect of excess air on performance of POC AVC firing DUC.

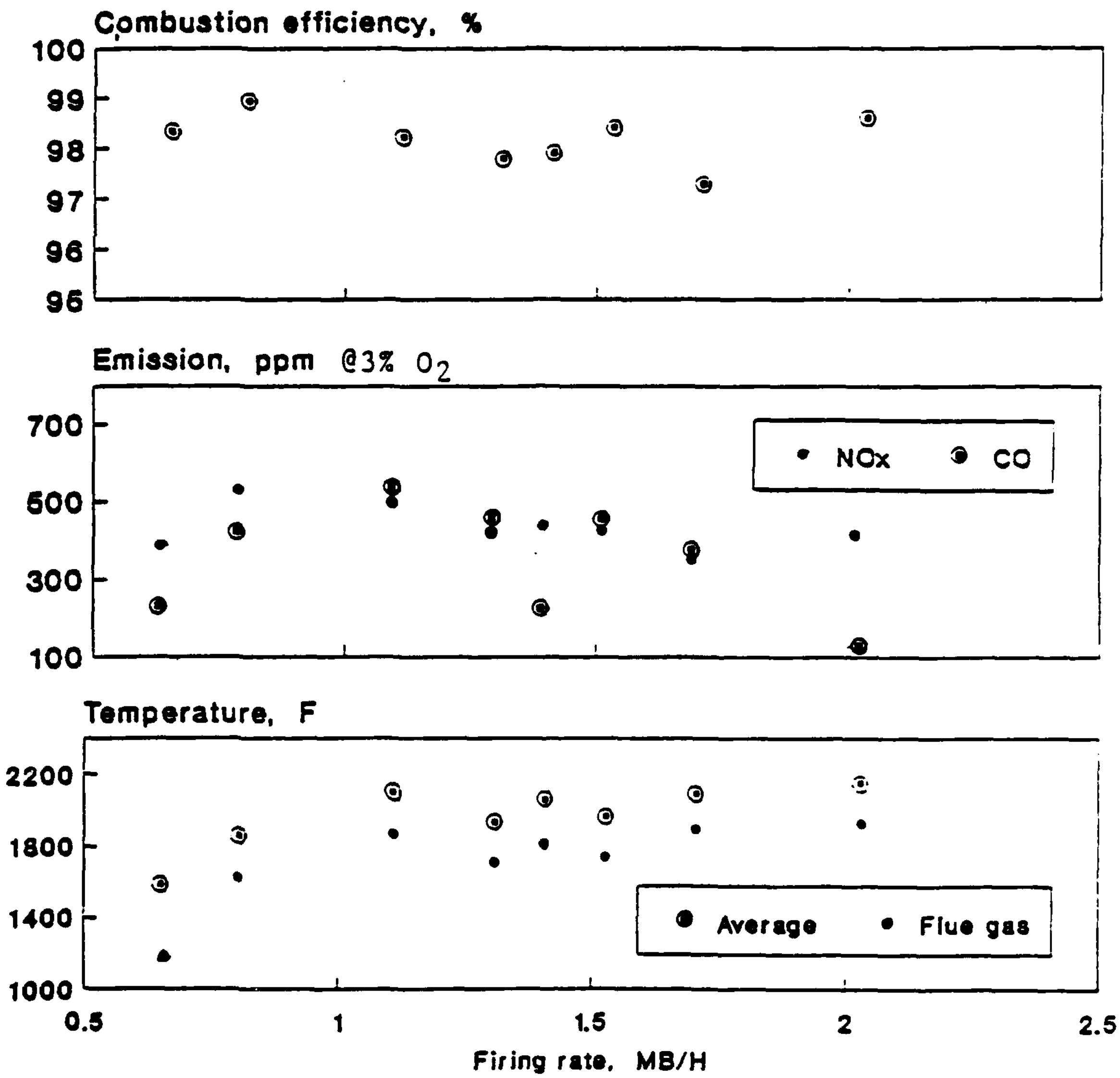


Figure 4.10 Effect of firing rate on POC AVC performance firing DUC.

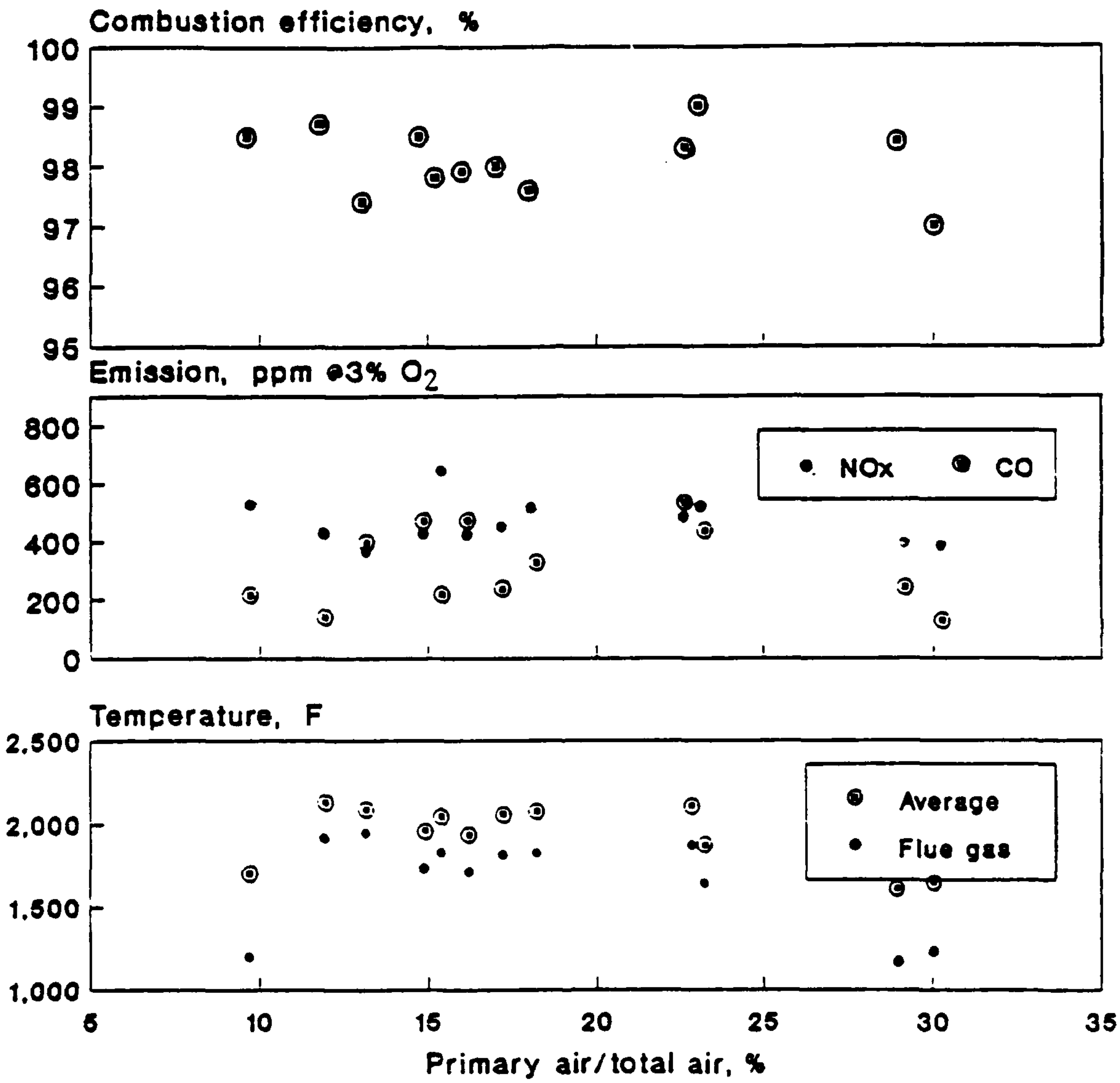


Figure 4.11 Effect of primary air on performance of POC AVC firing DUC.

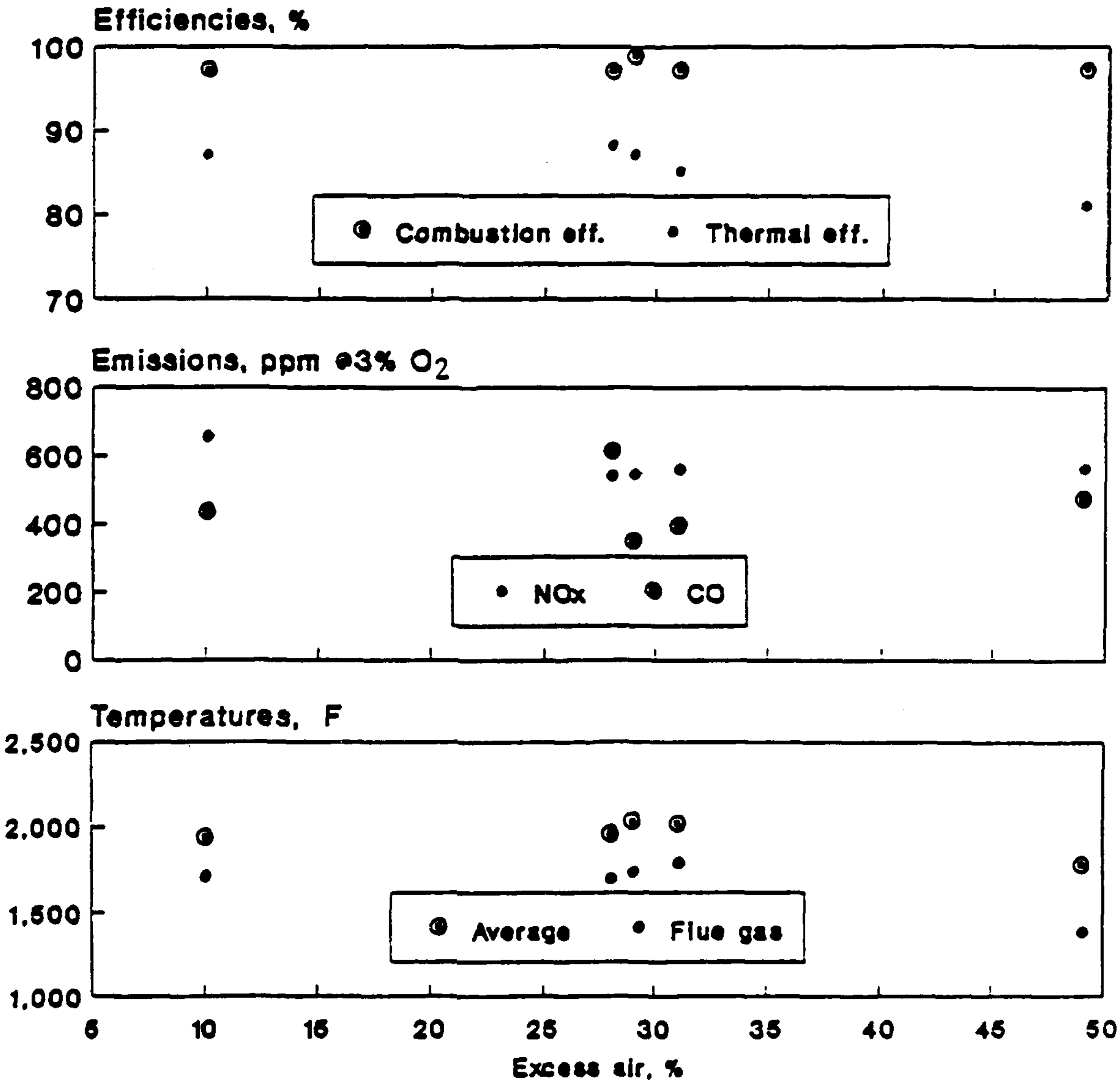


Figure 4.12 Effect of excess air on performance of POC AVC firing PC.

	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

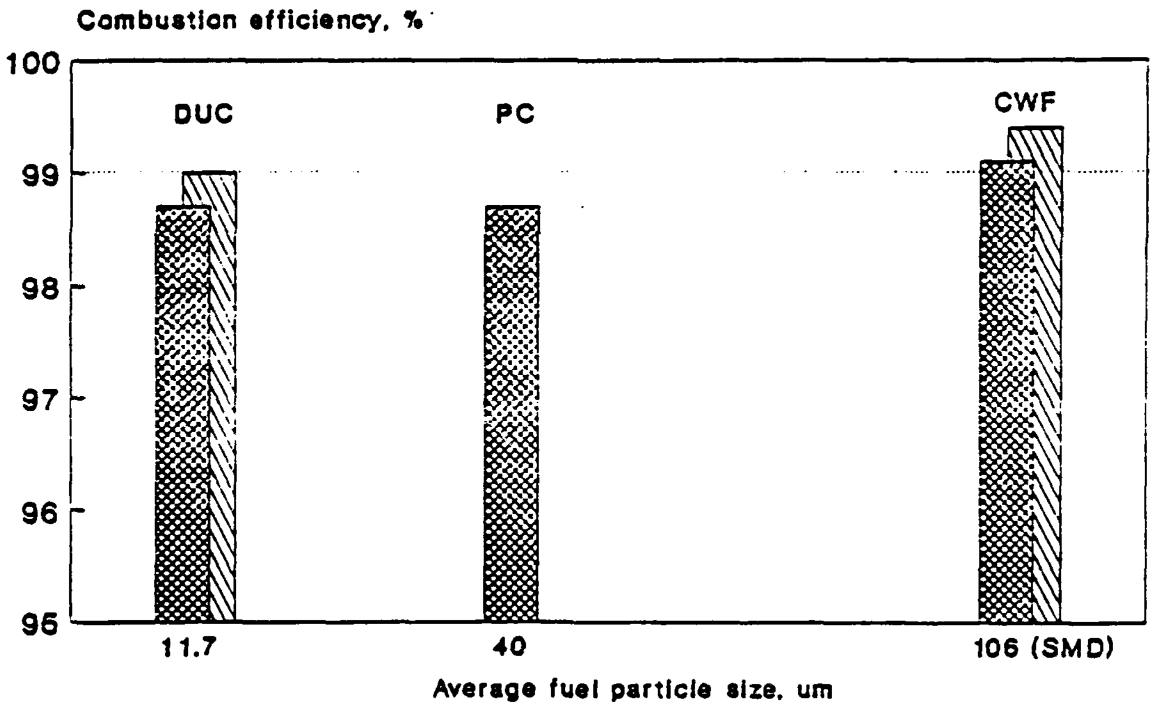


Figure 4.13 Fuel flexibility of POC AVC model.

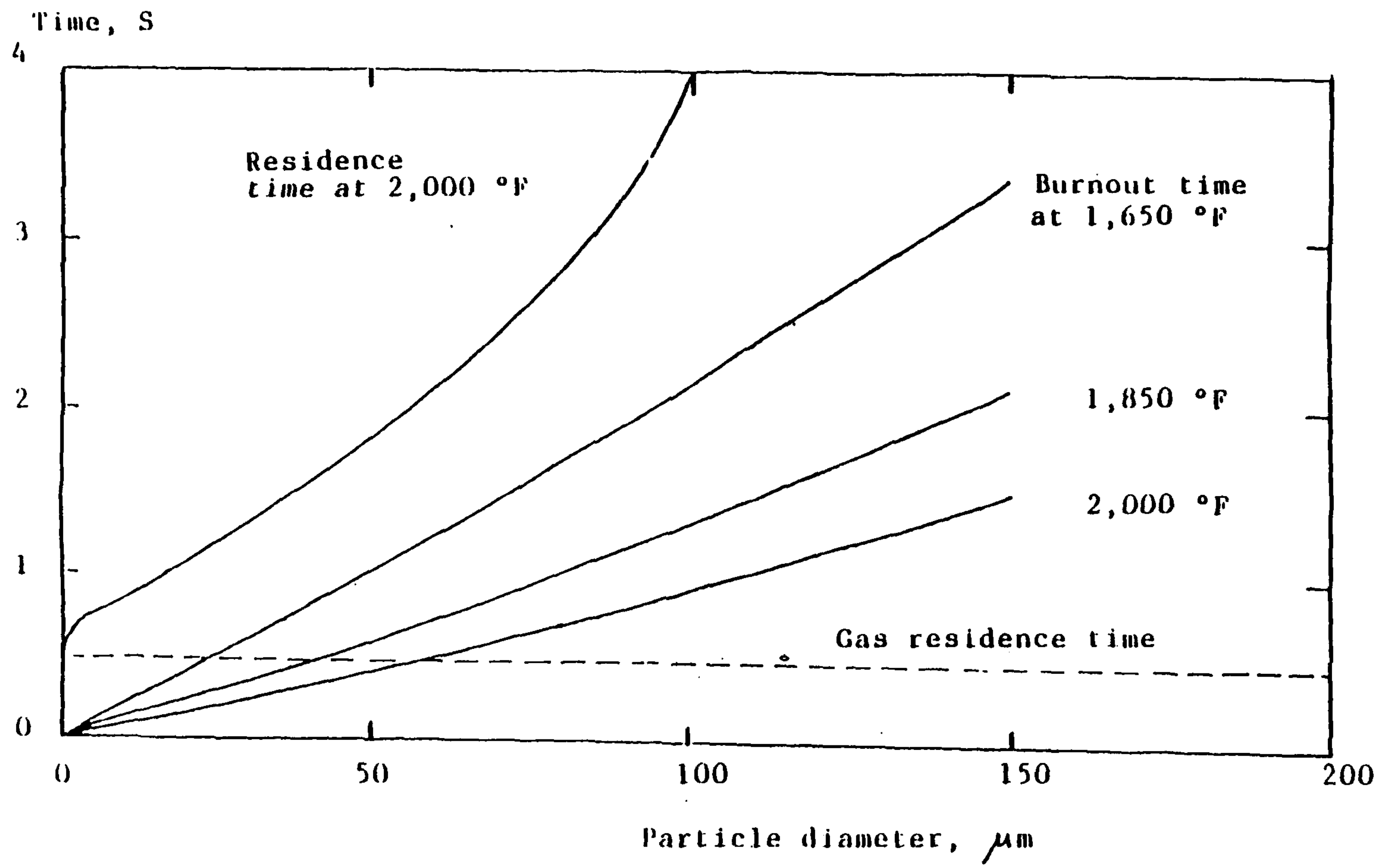


Figure 4.14 Particle residence time in AVC.

METRIC CONVERSION FACTORS

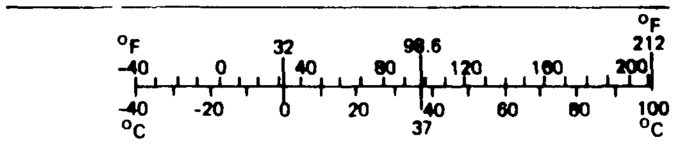
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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 practices using dedicated O&M crews 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 AVC systems unattended using automatic controls. A centralized O&M concept serving a group of AVCs 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 approximately 30 people will serve about 100 AVC systems. The operations between the center and satellite AVC systems will be monitored and controlled via an Energy Management Control System (EMCS). In this fashion, dedicated operators are eliminated and O&M costs are greatly reduced.

The AVC and the required various auxiliary systems can be easily packaged into a turnkey steam or hot water generating system made up of individual functional modules such as: the combustor itself, a steam/hot water generator, a baghouse/ash collector, fuel/air supplies, flue gas exhaust, controls, etc. These will be completely shop-assembled, packaged, and tested. The complete AVC system will fit into the envelope of a standard 8- by 8- by 20-foot shipping container for easy shipment and fast installation. The system will be automatically controlled and operated. 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, retrofitting 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 boilers discussed here.

The economic analysis, therefore, is based only on a new, prepackaged turnkey unit of an AVG space/water heating system firing CWF. It includes capital investment, operating cost estimates, and related sensitivity analysis. The firing rate of the AVC heating system considered here is 4 MB/H (producing 2,900 lb/H saturated steam at a 120 psig or equivalent amount of hot water) at a system thermal efficiency of 85 percent. The annual capacity factor is assumed to be 80 percent, which is typical for heating applications in hospitals or other commercial buildings in mid-Atlantic states. Major assumptions and data used in the economic analysis are given in Table 5.1.

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 tradeoff. The capital investment and operating costs of a 4-MB/H AVC heating plant firing CWF are considered below.

5.3.1 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 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 (Refs 31, 32).

Table 5.2 summarizes the costs of major equipment of a shop-assembled, packaged AVC heating system. The cost of individual equipment is given on an FOB basis. These costs were obtained either directly from quotations of equipment vendors, or by using conventional engineering practice, or based on our experience accumulated from this research. All cost data are converted to January 1990 dollars based on the Marshall and Swift all-industry index (Ref 33). It is estimated that the costs of instrumentation and control devices are 30 percent of other equipment costs.

5.3.2 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 AVC heating system is shown in Table 5.2 (Refs 31, 32, 34). Brief explanations are given below:

- Freight and Taxes - The sales taxes, freight, and insurance charges of purchased equipment are estimated to be 10 percent of item 5 of Table 5.2 (Ref 31).

- Installation Costs - These costs include costs for equipment installation and integration with other tie-ins at the operation site, and 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 cost factors for each item in Table 5.2 are estimated differently (Refs 31, 32). The average factor is about 17 percent of item 5 in Table 5.2.

- Other Direct Costs - Other costs, such as electrical facilities, buildings, and site improvements are estimated to be 18 percent of item 5 (Refs 31, 32).

- Engineering and Construction - The costs for construction design, engineering drafting, technical document preparation, project management, and startup cannot be directly charged to equipment, materials, or labor in capital investment. It is normally considered an indirect cost and is estimated to be 5 percent of item 5 (Refs 31, 32).

- Contractor's Fee - The contractor's profit is estimated to be 6 percent of item 5 (Ref 31).

- Contingencies - The contingency factor is to compensate for overlooked or unanticipated elements and unpredictable expenses. It is estimated to be 10 percent of the total system cost (Refs 31, 32).

5.3.3 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 AVC heating systems of other capacities (Ref 32). That is:

$$C_n = r^{0.5}C$$

where C_n is the cost of an AVC system of capacity other than 4 MB/H, C is the known cost of a 4-MB/H AVC system, and r is the ratio of AVC capacities.

Figure 5.2(a) shows the estimated capital investment versus design capacities of AVC heating systems. It increases almost linearly with the capacity. For a 4-MB/H AVC 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).

5.3.4 Operating Costs

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

- Fuel Cost - The CWF price is estimated to be at $4.1/MB delivered (Ref 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).

- Operating Labor Cost - Based on the centralized servicing concept, only a small group of O&M personnel will be required to service many AVC plants at the same time. On an average, one dedicated man-hour per day and two additional man-hours per week for operating one AVC system are expected. Assuming an hourly rate of $40 (Ref 32), the needed annual labor cost per AVC system is 376 man-hours or $15,040. This is only a small fraction of the operating labor cost for conventional coal fired systems which often require at least one dedicated full-time operator.

- Utility Cost - The price of electricity is assumed to be $0.065 per kWh.

- Maintenance - The maintenance expenses include costs for labor and materials (assumed to be 3 percent of total direct cost (Ref 31)).

- Overhead and Supervision - This cost covers the general expenses for supporting offices, overhead, security and fire protection, and laboratory fees. It is assumed to be 70 percent of the operating labor cost (Ref 31).

- Annual Capital Charge - To recover initial investment, the total fixed-capital investment is amortized over the lifetime of the equipment at 8 percent interest.

5.3.5 Steam Production Cost

Total production cost of steam or hot water is usually calculated on an 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 AVC space/water heating system. For a 25-year payback at 8 percent interest and $4.1/MB CWF, the operating costs of a 4-MB/H AVC system require the steam to be sold at $7.15/MB, in which the fuel cost is 67.6 percent, capital investment is 9.2 percent, and others 23.2 percent. The cost breakdowns are also plotted in Figure 5.2(b).

5.3.6 Effects of Payback Period and Interest Rate

Figure 5.3 shows the effects of payback period and interest rate on the steam/hot water production costs of a 4-MB/H AVC heating system. It is seen that the unit production cost not only decreases with the decrease of interest rate but also with the increase of the payback period. At the assumed CWF price of $4.1/MB and 8 percent interest, steam cost is $8.25/MB for a 5-year 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 the CWF price, the production cost drops only from \$7.91/MB (at 20 percent interest) to \$7.04/MB (at 6 percent interest). The effects of payback period 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 percent) in steam production cost.

5.4 NUMERICAL SIMULATION OF POC AVC FIRING DUC

The recently developed mathematical model and computer code (Refs 7, 11, 36, 37) were used to simulate the conditions in the POC AVC 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 tube, the tangential velocities in the annular space are consistently high and relatively uniform, which is beneficial for combustion and pollution 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 the 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 AVC 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) 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. 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 AVC. The slip velocity near the fuel feed port is large, which is favorable for coal particles to interact 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 AVC. The char reaction zone in the annular space is close to the center tube. This is believed to be due to the 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 AVC. 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 AVC 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 link among the different variables in the AVC combustion processes.

The above detailed results of combustor performance illustrate the unique gas-particle flow and combustion features of the AVC: 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 (Ref 11) and the combustion tests reported here and earlier (Refs 27, 28, 38, 39).

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:	Hourly	Annually
CWF	411 lb	1439 ton
Air	39,060 N ft^3	274 MN ft^3
Limestone	(optional)	
Makeup water	280 lb	981 ton
Electricity	21 kW	147,000 kWh
Chemicals	(optional)	--
Waste Generation:		
Flue gas	51,840 N ft^3	363 MN ft^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

Table 5.2 Cost Estimates for a 4-MB/H Packaged, CWF-Fired AVC 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	900	
		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	
		42,580	43.1
3. Flue gas/ash system:			
Baghouse	800 ft^2 filter area, 4-in. water	8,640	
Flyash remover x 2	Intake electrical valve	2,000	
Induced draft fan	1,200 scfm, 15 hp	3,360	
		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%[a]		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

[a]Percentages of items 6-12 are based on item 5.

Table 5.3 Production Cost of Steam or Hot Water

Parameter	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

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 Removel 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

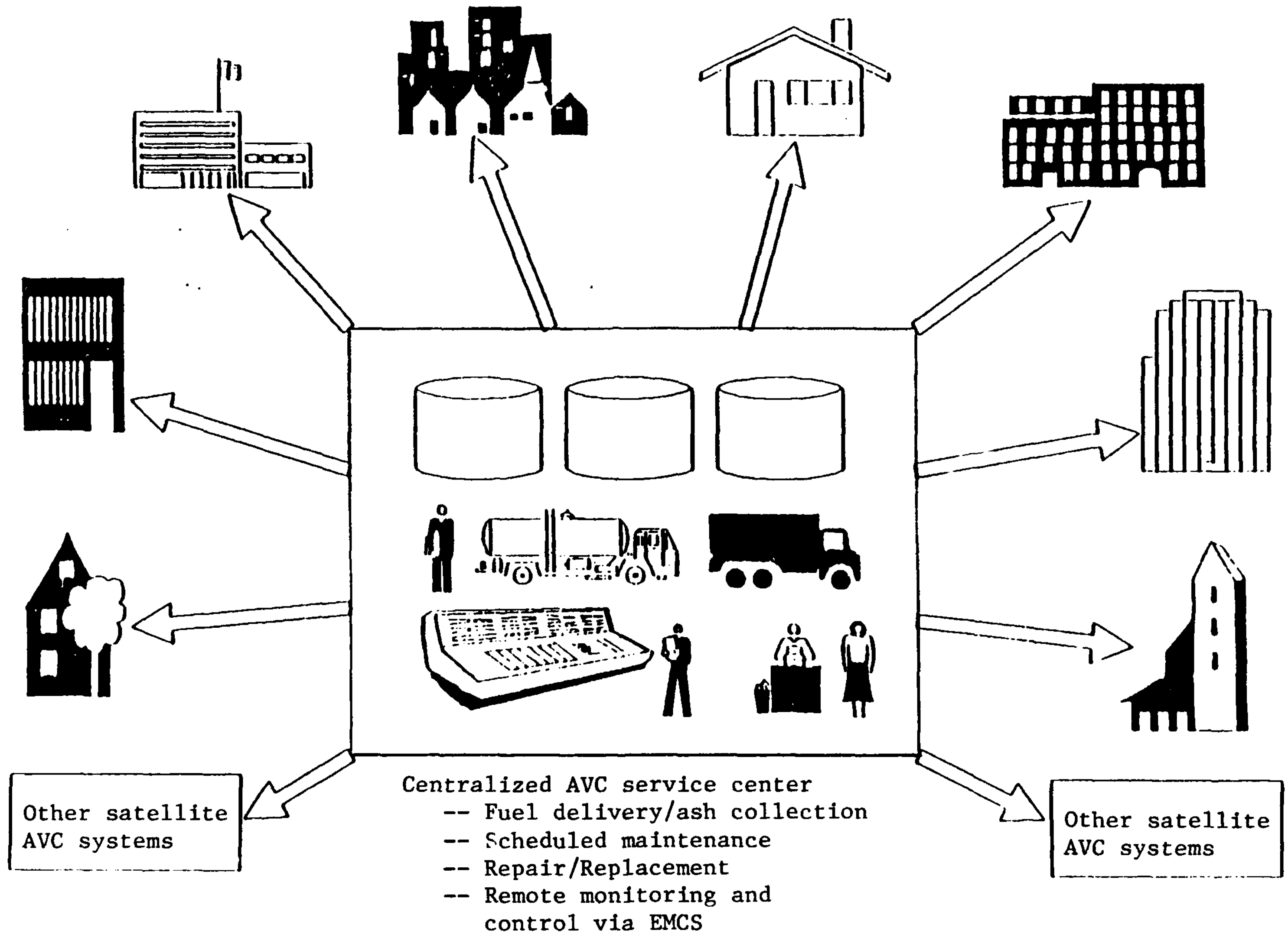
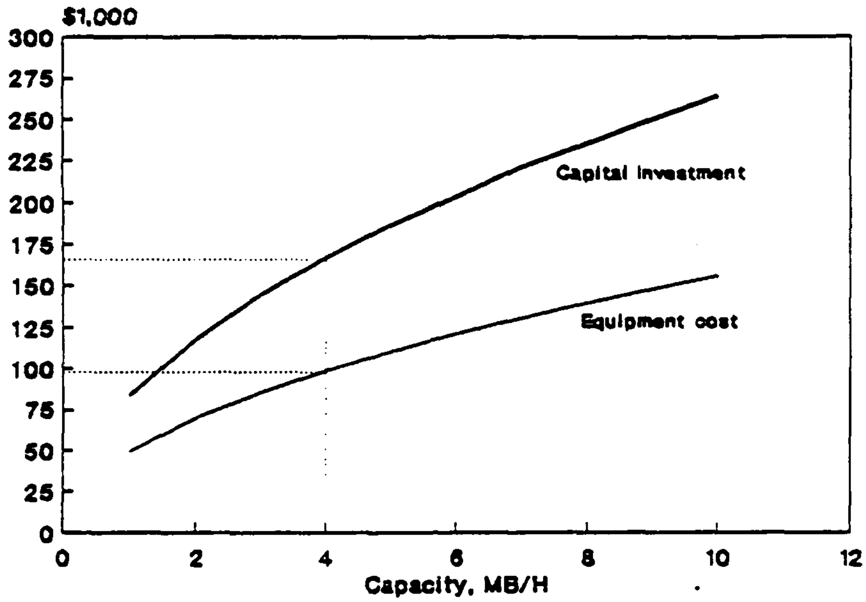
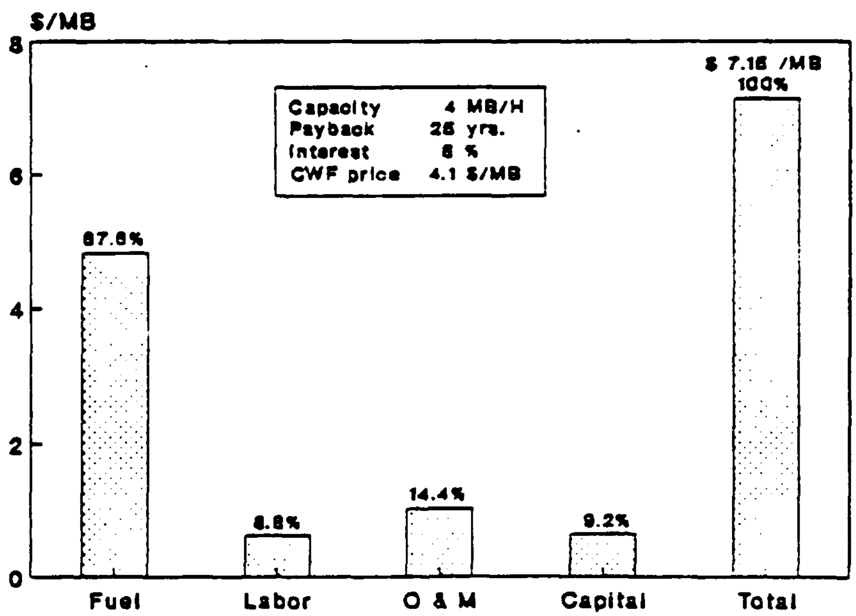


Figure 5.1 Centralized O&M concept to serve a group of satellite AVCs.

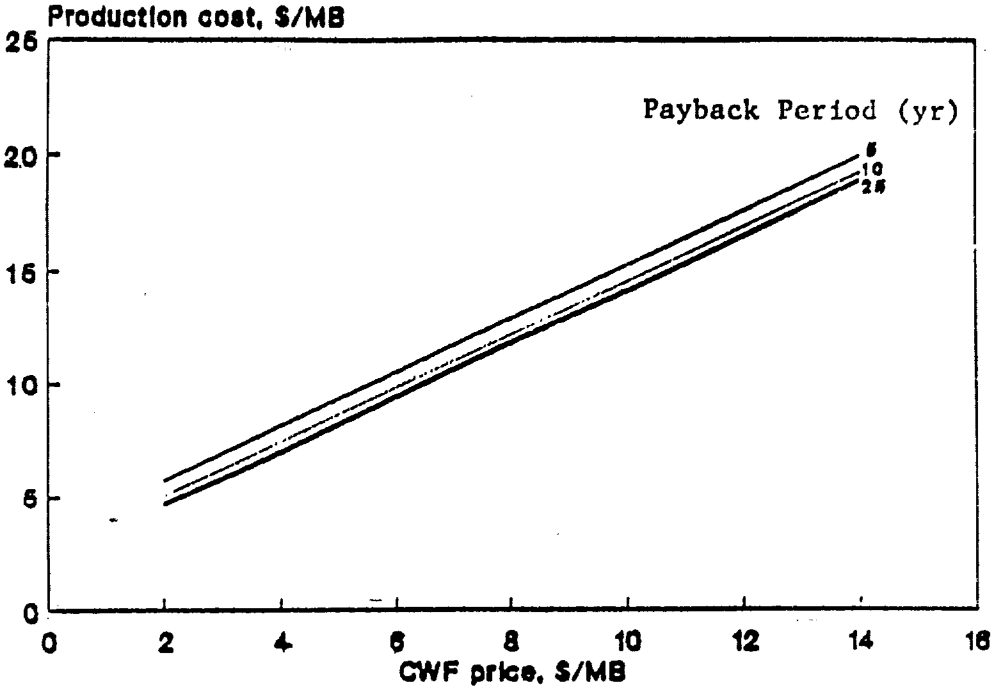


(a) Capital investment of AVC systems

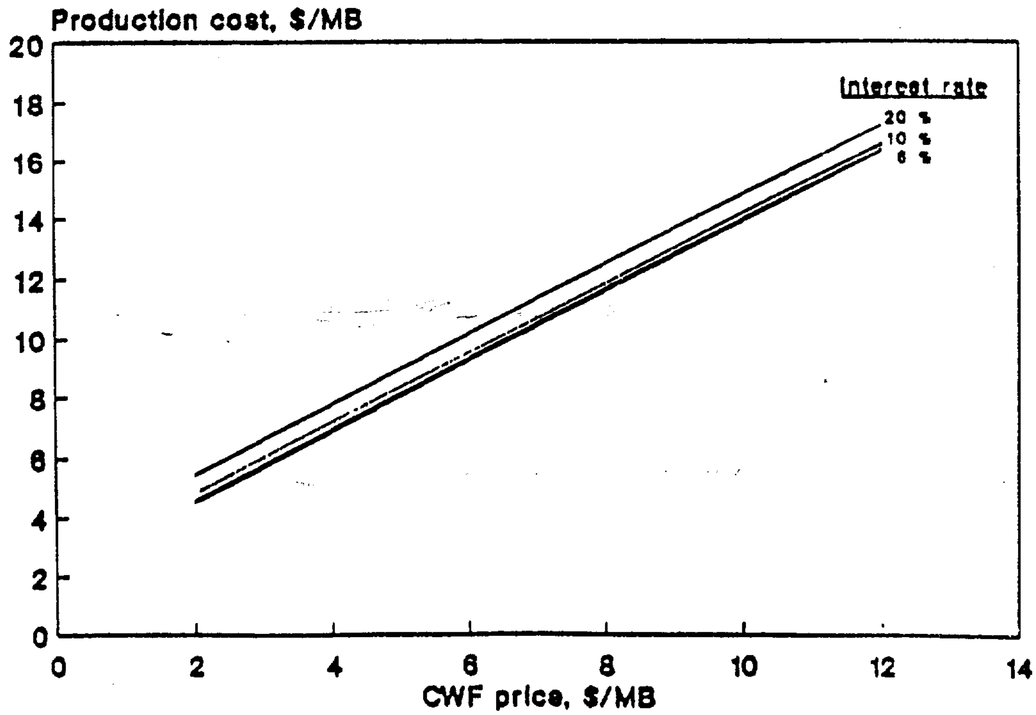


(b) Steam/hot water cost breakdown

Figure 5.2 Economics of CWF-fired AVC heating plants.



(a) Effect of payback period (8% interest)



(b) Effect of interest rate (25-year payback)

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

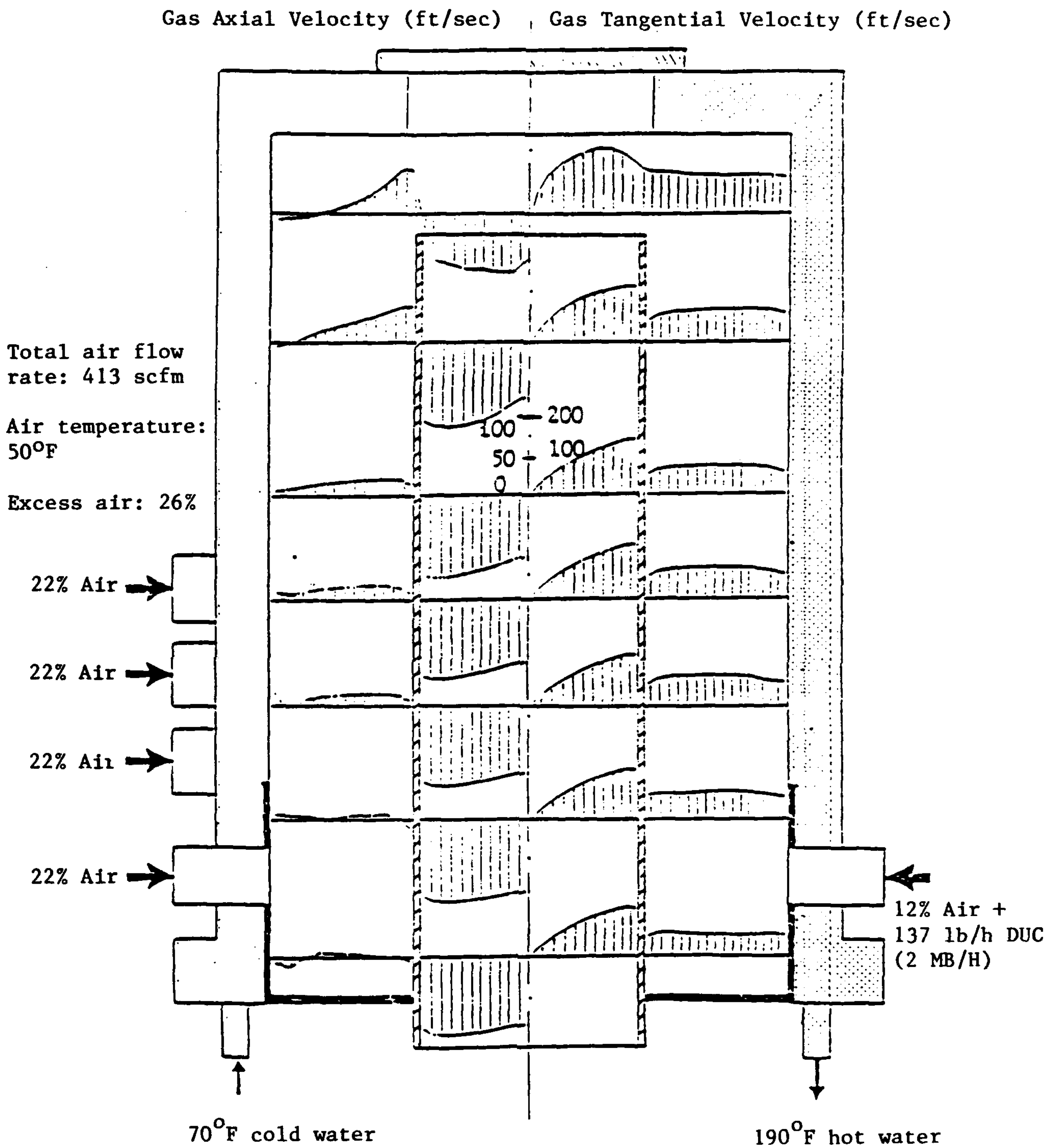


Figure 5.4 Calculated gas velocity distributions.

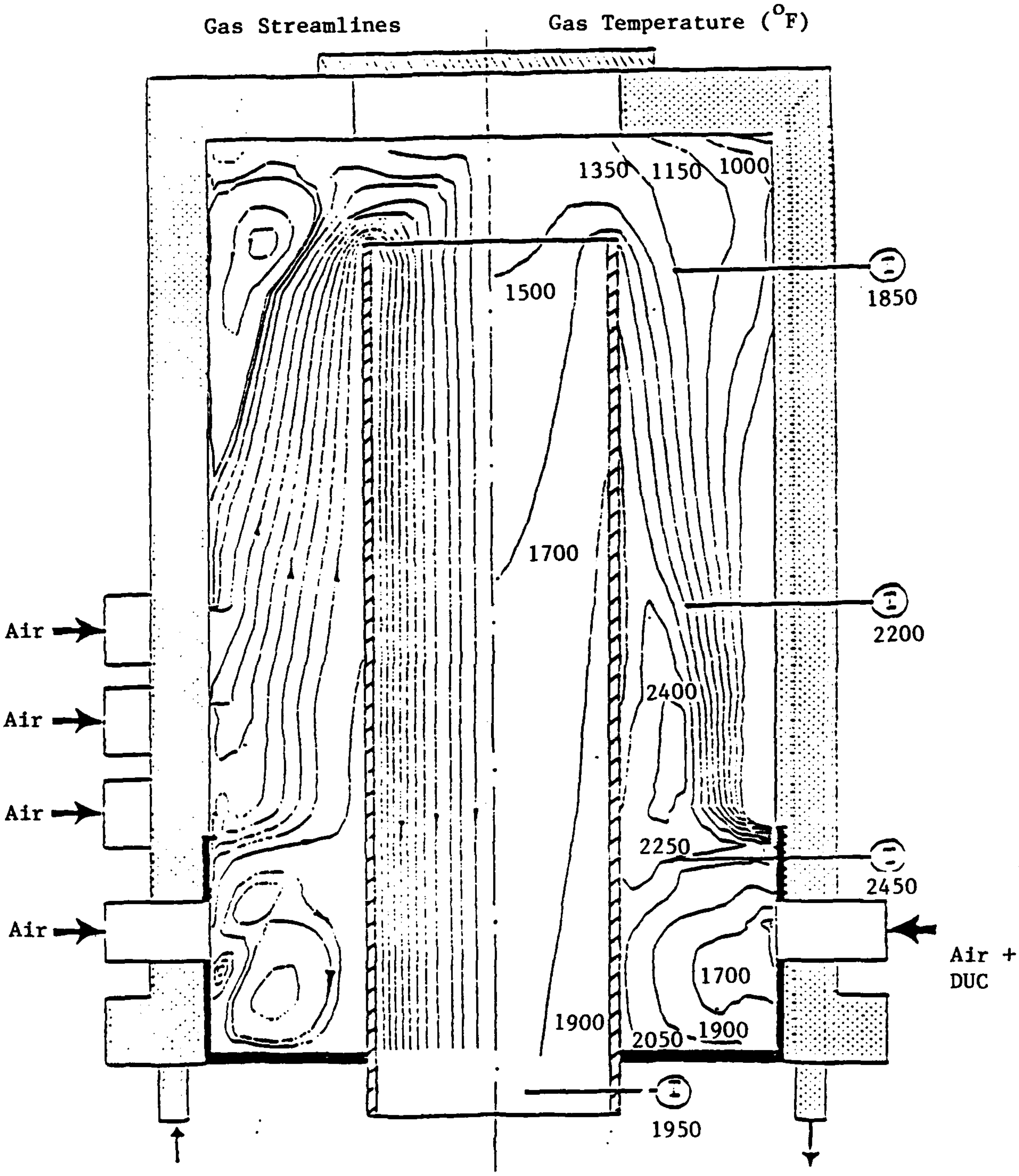


Figure 5.5 Calculated gas streamlines and temperatures.

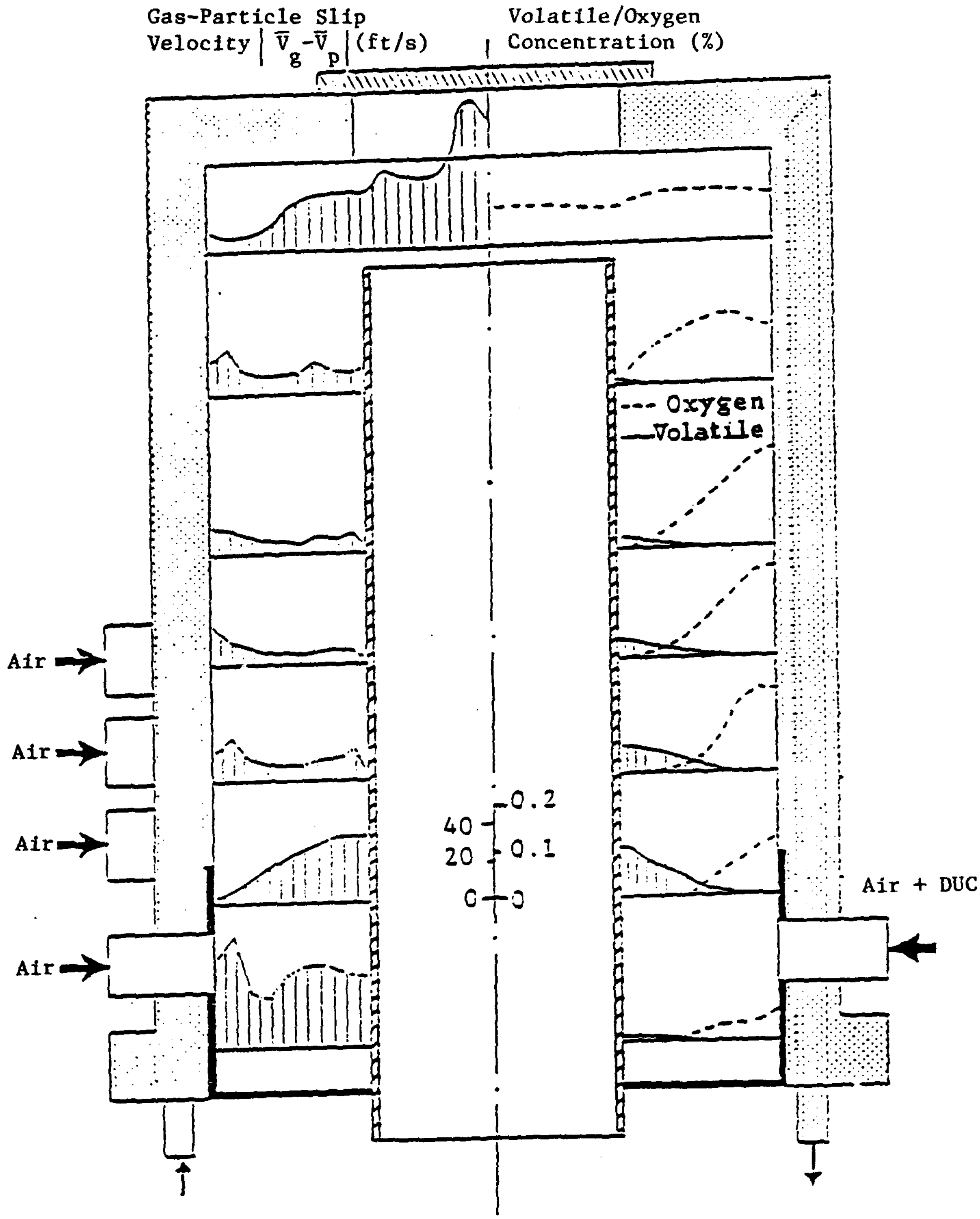


Figure 5.6 Calculated gas-particle slip velocity and oxygen/volatile concentrations.

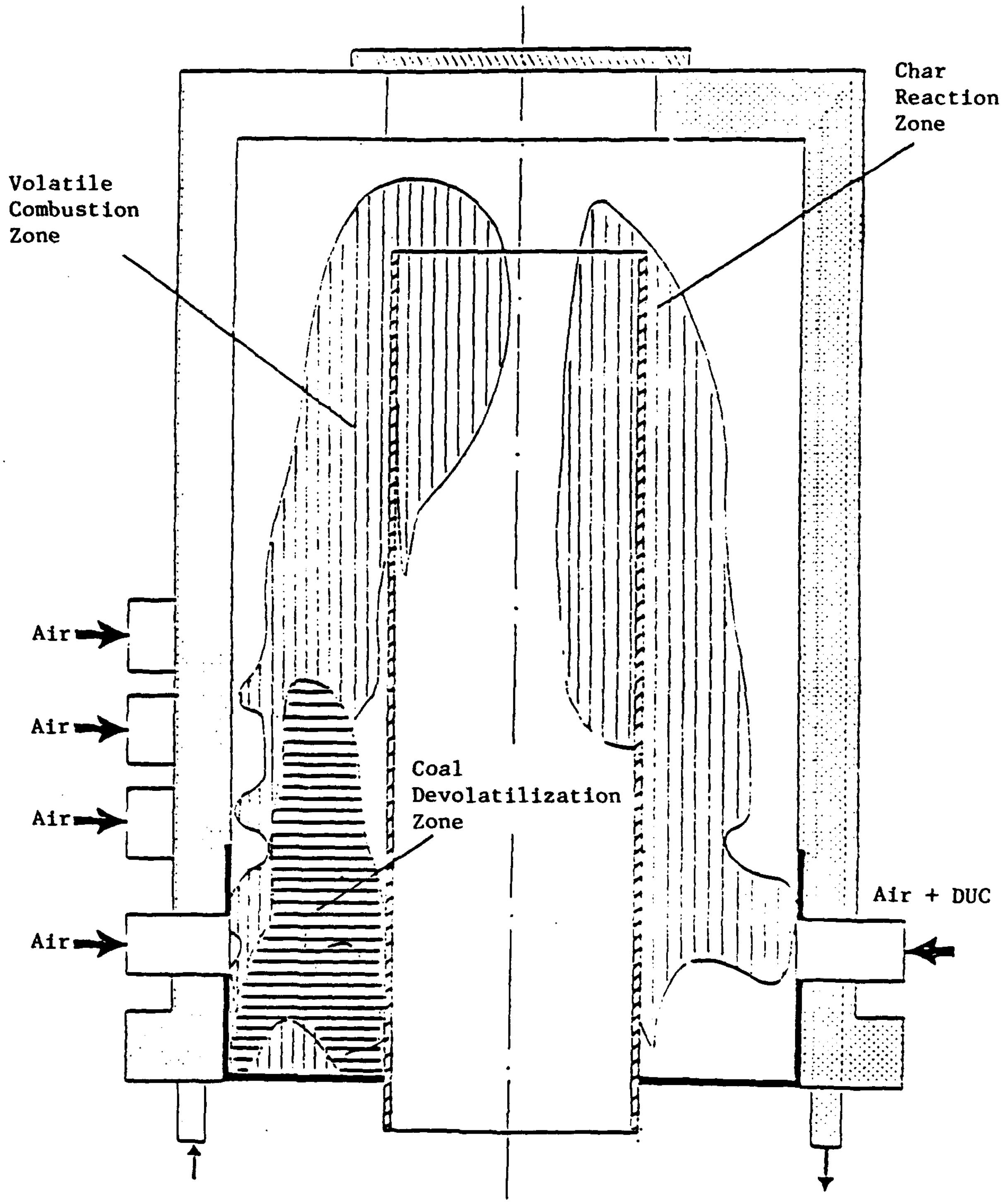


Figure 5.7 Active zones of coal devolatilization, volatile combustion, and char reaction.

CHAPTER 6

ONE-DIMENSIONAL COMPUTATIONAL MODEL

The combustion process in the environment of an Annular Vortex Combustor (AVC) is by no means simple (see examples in Chapter 5). Calculations, however, are an indispensable step in design and performance predictions. In order to serve this purpose with the limited resources available, a one-dimensional computational model was developed. This model is simple and fast and can be programmed to run on personal computers. It is intended for preliminary design and performance calculations.

6.1 GENERAL DISCUSSION

An AVC is a fuel burning device that is characterized by its strong swirl and low temperature combustion environment. As shown in Figure 1.1, this device is basically made up of two vertical, concentric tubes with combustion taking place in the combustion chamber (the annular space in between). Fuel and primary air are blown tangentially into the chamber at the bottom. Additional air is supplied at higher elevations for controlling the combustion processes, swirling flow, and temperature. In order to maintain the mixture in the combustion chamber at the desired temperature with minimal temperature variations, certain amounts of heat must be removed as it is being generated. This is achieved by the use of a combination of distribution of air supply, water cooling, and refractory lining. Due to the large slip velocities between fuel particles and the surrounding gases, heat and mass transfer in the combustion chamber of an AVC is much more effective than conventional devices. As a result, AVC can achieve high firing intensity at relatively low temperatures.

In this model, all governing parameters, as shown in Figure 6.1, are treated as changing only along the average path (the x-direction) of the gas bulk flow. Mass and energy balance calculations are conducted for an elemental volume defined by Δx, initiating at $x = 0$ and marching along x until the flue gas (combustion products) exits the combustor.

For a given elemental volume,

- Heat of combustion Q is released within
- Heat is carried through by flue gas entering and leaving the volume
- Heat is removed through solid boundaries by cooling water and exiting flue gas in the center tube

The following relationships are used for calculations:

$$\dot{Q} = \dot{m}_f (\Delta H)_f$$

$$= \dot{Q}_g + \dot{Q}_w$$

$$\dot{Q}_g = \dot{m}_g H_g$$

$$\dot{m}_g = \dot{m}_f + \dot{m}_a$$

$$\dot{Q}_w = \dot{m}_w c (T_{out} - T_{in})$$

$$= h_w (T_2 - T_w) 2\pi (R+t) \Delta x$$

$$= h_g (T_g - T_1) 2\pi R \Delta x$$

$$V_g = \frac{\dot{m}_g v_g}{\pi (R^2 - r^2)}$$

where: c = specific heat of water

h_g = gas side overall heat transfer coefficient

h_w = water side heat transfer coefficient

H_g = enthalpy of flue gas at T_g

$(\Delta H)_f$ = heat of combustion of fuel

$\dot{m}_a$ = mass flow rate of air

$\dot{m}_f$ = mass consumption rate of fuel

$\dot{m}_g$ = mass flow rate of flue gas

$\dot{m}_w$ = mass flow rate of cooling water

t = thickness of the refractory lining

T_g = flue gas temperature in combustion chamber

T_1 = gas side refractory lining temperature

T_2 = water side refractory lining temperature

T_e = flue gas temperature in center tube

T_w = cooling water temperature = $(T_{in} + T_{out})/2$

v_g = specific volume of gas at T_g

V_e = gas bulk flow velocity in center tube

V_g = gas bulk flow velocity in combustion chamber

Except for the dimensions and material properties, the variables above are all functions of x. Engineering units are used throughout.

In the above equations, h_g is an extremely complex quantity. It is the combined result of contributions from radiative, convective, and conductive heat transfer of the combustion products (hot gases, glowing coal (the fuel) particles, and ash particles). In the lower portion of the combustor (small values of x) where vigorous burning of the coal takes place, glowing coal particles are constantly bombarding the refractory lining. Heat transfer to the lining by conduction is therefore most effective and dominating in this region. Radiative and convective modes of heat transfer become increasingly more important with the increase of x (i.e., in the upper portion of the combustor). The heat removal capability of this type of system is usually limited by the heat transfer coefficient h_g on the gas side. Unfortunately, due to the inadequate amount of data available, h_g can only be estimated. Its value is large near the combustor bottom where intense combustion takes place and decreases with the increase of x.

The value of h_w is obtained from the correlation of forced convection inside the tubes as follows:

$$h_w = 0.023 \; Pr \; Re^{0.8}$$

Other than the flow velocity V and tube diameter d, all quantities in this correlation are properties of water that vary only slightly in the operating temperature range (50 to 250°F). Based on this correlation, it can be shown that:

$$h_w \propto \left(\frac{\dot{m}_w}{d}\right)^{0.8}$$

Thus, in practice, we first select a suitably small tube diameter, d, for the cooling coil. Having d fixed, water flow rate then becomes the only parameter that controls the value of h_w and hence T_g. T_g can also be controlled more directly by properly distributing the combustion air supply, thereby controlling the heat release profile along x.

In operations, the gas temperature inside the combustion chamber is controlled by a combination of water flow rate and air distribution. For the computational model described here, the major effort is to conduct heat and mass balances using a combination of heat removal by cooling water and controlled heat release by combustion air supply distributions so that a reasonably uniform T_g can be achieved in the combustor. A preliminary interactive PC software was developed for these calculations. In order to arrive at an optimal design, the designer must participate in the calculation process and be aware of the results at critical intermediate steps so that proper actions can be taken when needed.

6.2 ASSUMPTIONS

To reduce the complexity of the problem, the following assumptions and some first cut default values are used:

- Heat release is proportional to the air locally available.
- For optimal SO_2 removal, T_g = 1600 to 1700°F.
- For stable combustion: T_1 = 600 to 700°F.
- Geometric proportions: $L_{ct} = 0.8L$, $L = 3R$, $r = .5R$.
- Heat release intensity: 0.3 MB/hr-cu ft.
- No heat transfer in the x-direction, across the center tube, and to the surroundings.
- Excess air: 20 percent.

6.3 FLOW DIAGRAM

The overall computing scheme is shown in Figure 6.1. This scheme is consistent with the discussions and assumptions described above and is self-explanatory. A summary of the operating ranges of the AVC models tested so far is tabulated in Table 6.1 for reference purposes.

Table 6.1 Summary of Operating Experience of AVC Models

Description	PExp	PPOC	Exp	POC
Firing rate, MB/H	.12-.16	2.15-3.0	.22-.31	.65-2
Excess air, %	38-60	19-22	20-45	9-49
Primary air/total air, %	70-75	5-24	18-39	6-30
Firing intensity, $MB/H\text{-}ft^3$	.11-.15	.11-.16	.31-.44	.10-.27
Average gas temperature, $^{\circ}F$	1600-1660	1910-2050	1700-1900	1610-2140
Gas bulk velocity, ft/sec				
V_g (in combustion chamber)	3-4	5-7.4	5-8	2.4-6
V_e (in center tube)	15-21	16-23	27-42	11-27
Heat removed by water, %	-	-	31-60	40-56
Local heat transfer coefficient, $Btu/ft^2\text{-}hr\text{-}F$			10-55	

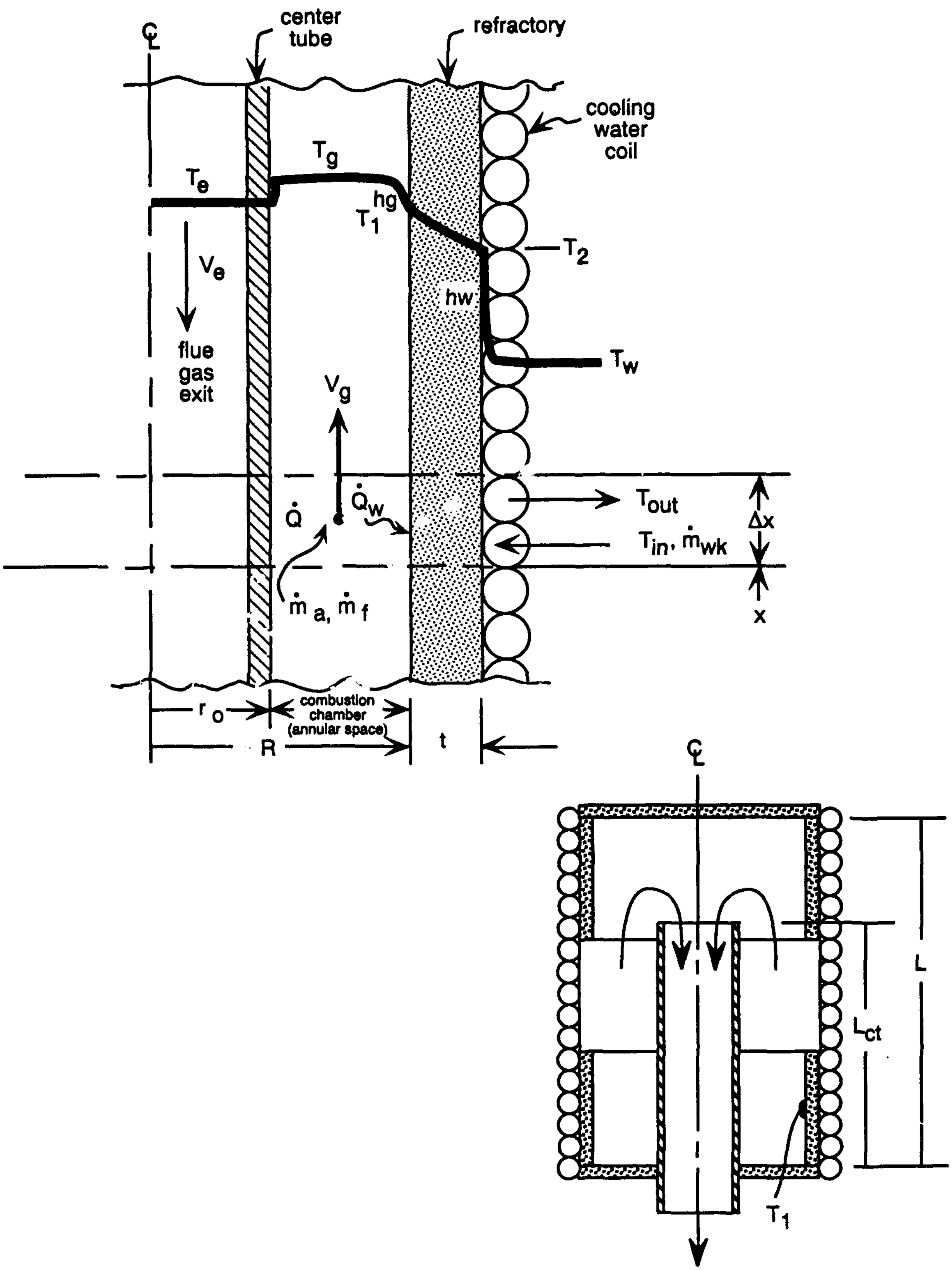


Figure 6.1 Schematic of governing parameters.

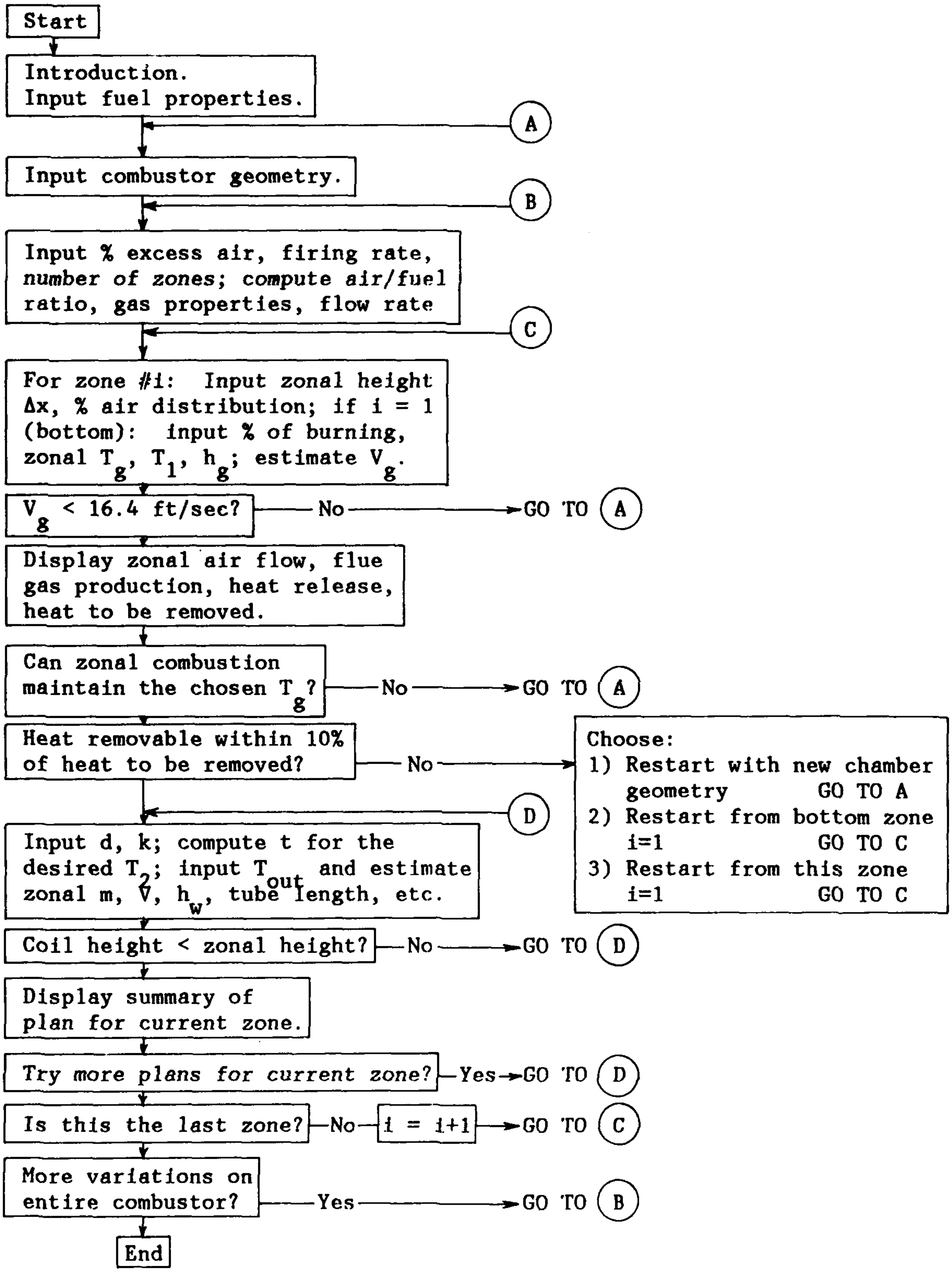


Figure 6.2 AVC computation flow diagram.

CHAPTER 7

ACCOMPLISHMENTS AND RECOMMENDATIONS

7.1 ACCOMPLISHMENTS

This research has successfully demonstrated that Annular Vortex Combustion is a feasible and highly promising concept for small-scale burning of coal in an environmentally acceptable manner. The following is a summary of the major accomplishments:

1. The AVC concept was refined and used to guide the design of two exploratory subscale models (0.15-MB/H PExp and 0.3-MB/H Exp AVCs) and one preliminary full-scale model (3-MB/H PPOC AVC). The auxiliary systems and measuring devices for testing these AVC models were successfully developed.

2. A total of 250 hours of combustion tests of CWF, DUC, PC, No. 2 heating oil, and propane gas were conducted on the above three AVC models. Systematic evaluations of these models were also 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 AVC was established.

3. Two types of CWF nozzles and a special atomizing technique compatible with the AVC configuration and applications were designed, fabricated, and successfully demonstrated.

4. A 2-MB/H proof-of-concept (POC) AVC model capable of firing CWF, PC, and DUC was successfully demonstrated to PETC and Navy sponsors and guests. A total of 140 hours of systematic combustion tests were conducted.

5. The AVC concept was demonstrated to be a superior multiple fuel combustion device that is especially ideal for small boilers. Unlike some coal combustors that rely on a combination of precombustion, post combustion, and preheating combustion air and fuel, the burning of fuel in an AVC is totally completed in the combustor itself without the requirement of preheating either the air or the fuel.

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

- Working Concept and Scaling - The AVC concept was brought into reality for a wide range of sizes (0.1 to 3 MB/H). No adverse impacts on technical performance were noted. Potential for up-scaling still exists.

- High Combustion Efficiency - Consistently greater than 99 percent for firing both DUC and CWF can be achieved. The thermal efficiencies were also high, ranging from 82 to 89 percent.

- High Average Firing Intensity - 0.1 to 0.45 MB/H ft^3 (an order of magnitude higher than typical pulverized coal-fired utility boilers) can be achieved. This makes the AVC package very compact.

- Large Turndown Capability - Greater than 3:1.

- Fast Start - It takes less than 15 minutes from cold to full load operation.

- Broad fuel flexibility:

  Fuel type - dry powdered coals, coal slurries, heating oil, and gaseous fuel

  Particle size - DUC (12 μm), PC (40 μm), and CWF (120 μm)

- Controllable Particle Behavior - Fuel particle residence time can be controlled to ensure complete burnout of the fuel.

- Controllable Combustion Temperature - The temperature level is controllable and can be maintained low (1,600 to 2,200°F) to facilitate pollution abatement and nonslagging/dry ash removal.

- No Preheating - No air/fuel preheating is needed for all fuels to achieve high combustion performance.

- NO_x and SO_x levels are, respectively, around 400 ppm and 300 ppm (at 3 percent O_2), 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.

- Simple Construction and Stable Performance - High level of safety and reliability.

7.2 RECOMMENDATIONS

Although sufficient data were obtained to demonstrate the AVC concept, data for optimizations and commercialization are generally lacking. Therefore, the following are recommended in order to further this technology.

- Conduct systematic tests to obtain technical and operational data necessary for emission controls, optimizations of combustor design, and the entire system.

- Develop guidelines for scaling.

- Develop specifications for materials, fabrication, and retrofit.

- Develop a plan for logistic support.

- Develop a plan for in-service test and evaluation.

- Develop a plan for AVC implementations.

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