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Task 2 Pilot Scale Combustion Tests

FINAL REPORT

Performance of a High Efficiency Advanced Coal Combustor

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DEVELOPMENT OF AN ADVANCED HIGH EFFICIENCY
COAL COMBUSTOR FOR BOILER RETROFIT

TASK 2: PILOT SCALE COMBUSTION TESTS
FINAL REPORT

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Preface

Work described in this report forms part of a project which was initiated in October 1986. The report provides detailed analysis and discussion of the pilot scale testing conducted at the MIT Combustion Research Facility during the period of 10/1/87-12/22/87.

Under a subcontract from Combustion Engineering, Inc. work was carried out at MIT for DOE-PETC under a Contract No. DE-AC 22-86PC90275; this work covered evaluating a new high efficiency advanced coal combustor (HEACC) using No. 2 fuel oil and coal water fuels. The overall program has been under the management of Mr. Michael J. Rini of the Kriesinger Development Laboratory at Combustion Engineering, Inc.

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EXECUTIVE SUMMARY

In the mid 1970's the OPEC situation provided strong economic motivation for using coal-based fuels as replacements for expensive fuel oils in oil-designed utility and industrial boilers. After some investigation of the potential of Coal-Oil Mixtures (for which there was an existing source of experience gained mainly in the metallurgical industries), combustion engineers turned to Coal-Water Fuel (CWF) as a promising alternative. There was, however, much less experience with CWF and the technical problems seemed to be more difficult. On the other hand, the potential reward was also more significant; i.e., complete substitution of oil by coal.

Under contract from DOE-PETC, Combustion Engineering, Inc. undertook the lead-role in a multi-task R&D program aimed at development of a new burner system for coal-based fuels; the goal was that this burner system should be capable of being retro-fitted in oil- or gas-fired industrial boilers, or usable in new units. In the first phase of this program a high efficiency advanced coal combustor (HEACC) was designed jointly by CE and MIT. Its burner is of the multiannular design with a fixed shrouded swirler in the center immediately surrounding the atomizer gun to provide the "primary air", and three further annuli for the supply of the "secondary air". The degree of rotation (swirl) in the secondary air is variable. The split of the combustion air into primary and secondary air flows serves the purpose of flame stabilization and combustion staging, the latter to reduce NO_x formation.

MIT's role as a subcontractor in this program included the following:

- (1) Fabrication of a 5×10^6 Btu/hr pilot- scale version of this

HEACC burner, and installation of the burner into the flame tunnel of the MIT Combustion Research Facility (CRF)

- (2) "fine tuning" of the burner with the combustion of No. 2 fuel oil
- (3) detailed experimental investigations into its combustion behavior using two types of coal-water-fuels (CWF). The coal in the CWFs was a high volatile bituminous coal ground to two levels of fineness, 9.1 μm and 21.2 μm mean particle sizes, which are characterized as "ultrafine" and "fine-grind", respectively.

Prior research studies have shown that the problems to be resolved before coal-water fuel technology can be readily applied in industrial boilers fall into the following categories:

- o On substitution of fuel oil by coal, the input rate of inorganic matter increases by about two orders of magnitude. This can be the potential cause of a number of operational problems: furnace wall slagging, tube bank fouling, and erosion.
- o The 30% water in the CWF has the effect of retarding ignition and making flame stabilization more difficult, especially at part load.
- o Achieving the complete burn-out of the coal char in the restricted combustion space of an oil-designed boiler is a technical challenge.
- o It is necessary to adopt NO_x -reducing combustion process modifications, to counteract the higher fuel-N content of the coal which is a potential additional source of NO_x .
- o Special attention must be paid to maintain acceptably low emission of SO_x when burning CWFs made from a high sulfur coal.

All of these issues were addressed in the MIT experiments using the CWFs in the pilot-scale HEACC burner.

RESULTS AND CONCLUSIONS

1) Burner Tuning Tests

Preliminary studies (burning a No. 2 fuel oil) showed that by varying the burner geometry it is possible to sensitively influence the position of the flame front, combustion length of the flame and the NO_x emission; the burner geometry changes are effected by adjustment of the axial positions of the atomizing nozzle, the primary swirler and the secondary air annuli. An unexpected finding from these preliminary studies was the very low NO_x emission (NO_x : 125 ppm) obtainable with the HEACC when burning No. 2 oil.

2) CWF Combustion Tests

The CWF combustion tests that followed the burner optimization study proved that:

(a) The burner is capable of stable operation, with high carbon conversion efficiency ($\eta_c > 99\%$) and moderate NO_x emission. Without overfire air the measured NO_x was in the range 600-700 ppm; With overfire air the NO_x emission was ~ 350 ppm.

(b) As in previous CWF combustion studies, atomization quality was shown to be of critical importance. Fuel pre-heating to improve the spray quality by achieving disruptive atomization proved to be beneficial, both for better flame stability and for more rapid carbon burnout.

- When the "ultrafine" CWF was heated to 116°C upstream of the atomizer nozzle, a very fine fly ash particle size distribution (p.s.d), close to that of the individual mineral inclusions, was obtained. This fly ash was virtually carbon-free. The same heat treatment for the "fine-grind" CWF also led to excellent flame conditions, but

the presence of traces of unburned carbon in the fly ash contributed to a slighter coarser fly ash p.s.d.

- Although good flame behavior was observed when no fuel preheat was used, the measured fly ash p.s.d. was significantly coarser, close to the p.s.d. calculated on the assumption that all the mineral inclusions within each agglomerated coal char particle (formed from an individual CWF spray droplet) coagulated into a single ash particle. This behavior could be induced by the presence of high sodium concentration (measured as 12.5% in the ash) introduced into the CWF with the additive.

- (c) A significant potential in the use of water dispersible sulfur sorbents was observed; the sulfur capture efficiency with calcium acetate addition to the CWF was high (71% sulfur capture at $\text{Ca/S} = 1.8$) and sulfur capture with Ca(OH)_2 addition was satisfactory (50% at $\text{Ca/S} = 2.1$). It appears that having the sorbent in close proximity to the coal particles while these are undergoing pyrolysis in a fuel-rich flame zone enhances the sulfur capture efficiency.

In summary, these experimental studies showed that the HEACC design has potential for becoming a high efficiency, clean combustion device.

Section 1

1.0 Background, an Overview of CWF Combustion

Coal-Water Fuel (CWF) application in steam raising plants represents a relatively new and developing technology. While there had been some previous experiments carried out by the International Flame Research Foundation (IFRF) in Holland (1962) and by the VGB in Germany (1963) it was much more recently that this new fuel attracted interest, primarily because of its potential as a replacement fuel in oil-designed utility and industrial boilers.

Interest on the part of utility companies began to climb in 1981/2, and remained high until the recent steep fall in the price of oil. CWF still provides a convenient way of burning coal in many applications, and represents a feasible fuel for the conversion to coal of industrial boilers currently fired by natural gas or oil to burn coal based fuels. In addition to industrial boilers, CWF combustion could be applied to cement kilns, mineral processing equipment and some chemical process heaters.

Overall interest in this new technology has been demonstrated by the magnitude of U.S. research and development effort and by the research activities and demonstrations in other countries such as Canada, Italy, Japan and Sweden.

The present research is aimed at supporting the development of an advanced coal combustion system called the High Efficiency Advanced Coal Combustor (HEACC) at Combustion Engineering Inc's Kreisinger Research Laboratory under a contract to CE from DOE PETC. The HEACC has been jointly designed by CE and MIT to fire microfine coal water fuel with alkali sorbent for SO₂ reduction and to operate at high combustion efficiency and reduced NO_x emissions. It has been designed also to be fully scaleable for boiler

plant ranging in output from 12,000 to 250,000 lb/hr steam. The present report contains results of experimental studies carried out with a pilot scale HEACC (5×10^6 Btu/hr) in the flame tunnel of the MIT Combustion Research Facility.

1.1 Use of CWF in Oil Designed Units

One of the major problems in retrofitting oil-designed boilers for coal-water fuel combustion arises from the risk of erosion of the convective tube bank by fly ash. The design practices for oil-fired units take advantage of the low ash content of the fuel and permit high gas velocities in the convective tube banks. This, in turn, increases the convective heat transfer coefficients between the gas and heat exchange (superheater, economizer, air preheater) surfaces, with the result of reduced cost of the boiler. In pulverized coal-fired designs the gas velocities are lower because of the risk of erosion from the particle-laden gas flow. The coal is often beneficiated in coal water fuels and has reduced ash content. However, even with an ash content of 5% in the coal, the particle concentration in the combustion products will be about two orders of magnitude higher than the solids concentration for oil combustion, and protection of the convective heat exchangers would require reduction of gas velocities, causing a corresponding derating of the boiler performance (see Table 1.1).

The probability of a particle impacting on a heat exchanger tube surface depends on a number of factors, but especially on the ratio of drag to inertia forces acting on the particle. This force ratio determines whether the particle can follow the gas flow streamlines around the surface, or will separate from the streamline and impact on the surface. Calculations (1) show that the gas velocity and the diameters of heat

Table 1.1

Typical Boiler Design Differences

Fuel	Ash Content Typical		Heat Input (1000 Btu/hr-ft ²)		Maximum Convection Pass Velocity (fps)	Clear Tube Spacing Side to Side (in)	
	Weight Percent	lbs/10 ⁶ Btu	Per Plan Area	Per Effective Projected Radiant Surface		Radiant Surface	Convective Surface
Natural gas (or distillate oil)	0	0	3000	200	100	2	2
Residual oil	0.15	0.08	2400	175	75	5	2
Bituminous coal	15	12	1700	100	50	8-14	4-6

exchanger tubes will primarily determine the minimum particle size of an ash particle that will impact on a cylindrical surface. Particles larger in diameter than 30 μm will be collected by impaction at gas velocities as low as 25 ft/s. At gas velocities in oil-designed boilers of about 150 ft/s, and for a heat exchanger tube of 2 inches in diameter, particles larger than 15 μm will impact on the surface. From the point of view of erosion, however, larger particles can be expected to do more damage because of the significantly larger momentum with which they will impact on the metal surface. Smaller fly ash particles may deposit by mechanisms of Brownian motion, turbulent diffusion, particle diffusion and thermophoresis, processes which occur at relatively low velocities and do not incur erosion. It is the large particles in the 50 to 250 μm size range which should preferably be eliminated from the fly ash as these are expected to be the main cause of erosion of heat exchanger tube surfaces. Clearly there is strong incentive for reducing fly ash particle size and in obtaining information on combustion variables most likely to affect fly ash particle size distribution.

Demonstration studies carried out with coal-oil mixtures (COM) have shown that the amount and nature of coal ash is perhaps the most important factor to be considered for retrofit of an oil-designed plant; slagging and fouling were seen as important operational difficulties even when only about 35% of the heat input was provided by coal using a 50/50 wt% coal-oil mixture. When the total heat input is to be carried by coal it is clear that the mineral matter content of the coal has to be significantly reduced.

Coal beneficiation to the level required by retrofit of oil-designed boilers requires fine grinding of the coal, and the mixing of the pulverized coal with water provides an attractive means for transporting, storing, and

feeding the fuel (in the form of atomized spray) into the combustion chamber. Studies have indicated that it is feasible to produce CWF for boiler applications with about 30% water content. The coal is generally ground to the usual specifications for pulverized coal, i.e. 70- 80% < 74 μm , although fuels have been prepared in which the coal particle size is reduced even further (~99% < 44 μm). In addition, "micronized" coal (99% < 20 μm), has been tested for possible application in gas turbines. About 1% by weight of the mixture consists of chemical additives which act as dispersants, make the coal hydrophilic, control the viscosity of the mixture and serve as an algicide to permit long term storage without deterioration.

The presence of water in the fuel sets it apart from other liquid and slurry (COM) fuels. Maintenance of flame stability at part-load is especially difficult. Before combustion can be initiated, the water contained in the fuel issuing from the spray nozzle must be vaporized and the individual coal particles must be brought up to ignition temperature. This must be achieved within milli-seconds in order for a stable flame to be obtained.

1.2 Mechanism of CWF Droplet Combustion

Scanning electron micrographs of particles sampled in various CWF flames suggest that the life history of a CWF droplet can be considered to be divided into five stages - evaporation of the liquid film, evaporation of the "interstitial" moisture, particle heat up, coal devolatilization and char oxidation. On entering the combustion chamber, the droplet temperature rises until the wet-bulb temperature is reached. Evaporation rates during this unsteady state period are small and controlled by mass transfer. Following this, the droplet temperature remains constant, the evaporation rates are high, and are controlled by the rate of heat transfer.

During this process, the liquid film surrounding the coal particle is removed, with the consequence that the coal particles at the surface of the droplet are exposed to the hot gas. The interstitial water is then vaporized at a radially shrinking spherical interface. Temperature in the spherical annulus, between this interface and the outer radius, starts to rise, and the coal particles within the shell soften and devolatilize. A schematic of the combustion history of a droplet according to this scenario is depicted in Figure 1.1.

The volatiles trapped within the coal agglomerate break through the surface and when they reach a macropore they form a jet. The number of these macropores is relatively small so that their cumulative orientation is statistically non uniform and hence they impart a non zero tangential component to the particle. This sets the particle into rotation. The drag on the rotating particle is reduced by the high rate of mass transfer (volatile evolution) which favors high rotational speeds.

It should be pointed out that the major fraction of the nitrogen containing species present in the coal are released with the volatile matter. If the conditions surrounding the individual coal agglomerates are fuel-lean, the organic nitrogen will be primarily oxidized to NO, however, if the coal agglomerates release the organic nitrogen into a fuel-rich environment, the latter will be converted to N₂. In contrast to the volatile nitrogen, the char bound nitrogen is either oxidized or reduced heterogeneously depending on the availability of oxygen at the char particle surface.

As the volatile matter evolves, it leaves a cenospheric char particle with one or more large blow-holes through which part of the gas escaped. The walls of the cenospheres have bubbles in them which makes the

Figure 1.1 Transformations of a bituminous coal-water fuel droplet during its combustion history.

carbonaceous material vary widely in thickness. The wall burns through in positions where it has minimum thickness and the mineral inclusion in the burned region forms a slag droplet which comes to the coal surface to which it lightly adheres. Slag does not wet the char surface and the droplets on the outer surface of the particle may be separated by the strong centrifugal forces. If the slag droplets do not separate from the char particle they may move on the surface and coagulate with others to form larger droplets.

While the "primary" slag droplets will have the chemical composition of the ash inclusion from which they were formed, the chemical composition of the coagulates will be closer to that of the average of the coal ash in the particle.

On the inside of the char cenosphere the slag droplets are trapped. Depending upon the temperature and the ash fusion/viscosity characteristics they either form clusters by sintering or melt into a large single droplet.

As the char particles burn they weaken structurally and break into fragments still relatively large. The crescent formed from char fragmentation upon their burn-out may lead to the formation of single slag droplets of corresponding size. These particles, while smaller than the cenospheres, have strong drag forces acting upon them and are carried over unburned if combustion conditions (O_2 , temperature) at the point of their breakup are not favorable.

The penetration of oxygen into the reacting particle depends on whether the mass transfer of oxygen to the char surface, or the rate of the surface reaction is the rate limiting step. Upon penetration of oxygen, the char particle's porosity increases until a critical value is reached after which a layer of the particle separates in the form of very fine char fragments. This process which is termed as "percolative fragmentation" continues with

thin layers separating from the char unless the particle burns in the chemical kinetically controlled regime, it is fully penetrated by oxygen and disintegrates at a critical porosity of about 0.7 - 0.8. It is thought that the size of these fragments are commensurable with those of the macropores in the range of 0.1 to 1.0 μm .

Although high temperatures and high oxygen concentrations are needed to complete the combustion of a single CWF droplet, such conditions cannot be sustained at all times in a practical system. Hence, optimum flame conditions are required not only to CWF sprays but also to maintain low pollutants emissions.

1.3 Coal-Water Fuel Combustion Problem Areas

The problem areas associated with CWF combustion which were identified for detailed investigation included:

- o ignition, flame stability and carbon burnout,
- o ash formation and deposition, and
- o pollutants emission, with particular reference to NO_x and SO_x

1.3.1. Ignition, Flame Stability and Carbon Burnout

Although its presence represents a heat loss amounting to only a small fraction (~3%) of the total heat input, the water in the coal-water fuel entails operational difficulties, in particular in achieving ignition and good flame stability over practical ranges of turn-down ratio. Achievement of ignition is hampered partly by the requirement for evaporation of the water close to the spray nozzle, and also by the lack of a fine particle size fraction of the fuel spray that is available for rapid ignition close to the nozzle. The heat necessary for the evaporation of water has to come from energy feedback from the flame in the form of recirculated hot combustion products. The fine end of the coal particle size range is

missing because most of the fine coal particles will be in droplets which are much larger and contain several larger coal particles, while many of the finest droplets in the spray will not contain any coal particles.

These effects of the water content were investigated in previous programs and experimental studies were carried out to elucidate methods of achieving successful combustion in spite of the difficulties. However, in this discussion of problem areas it is helpful at this point to focus briefly on one problem area which was unexpected; it arose from one of the earliest and most significant findings of the initial experimental work with CWF flames in the CRF, a finding obtained from in-flame sampling of particulates in the region fairly close to the burner. From these measurements it was established that the particle size distribution (p.s.d.) of the solid particles in the combustion zone correlated much more closely with the p.s.d. of the droplets in the fuel spray than with the p.s.d. of the original coal used in the manufacture of the slurry. It was clear that this effect resulted from the formation of coal agglomerates upon the drying of droplets and heating of the coal due to the plastic behavior of bituminous coal particles in the temperature range of 600°-800°K. Coal agglomerates devolatilize more slowly than individual coal particles and the resultant cenospheric (hollow sphere) char particles also take longer to burn out.

There are various methods which may help to overcome the above difficulties. Agglomeration can be reduced by the choice of non-swelling coal types and the quality of atomization can be improved by "secondary atomization", a process in which droplets are disrupted by sudden expansion due to evolving gas or steam, or from micro-explosions caused by a chemical compound (additive) that becomes unstable upon injection into the flame.

1.3.2. Ash Formation and Deposition

The occurrence of mineral matter deposits on heat exchange surfaces of utility and industrial boilers can create serious adverse effects upon their performance and operation. Such deposits can substantially lower heat transfer rates, cause corrosion and eventual destruction of boiler tubes, and obstruct the gases flowing past heat exchanger surfaces.

Studies at NIT and elsewhere on coal water fuel combustion have shown that ash deposition is one of the most difficult problems encountered in utilization of these fuels in utility boilers designed for oil firing.

Little information exists that ties the behavior and fate of fuel mineral matter in coal water fuel combustion to both its initial composition in the fuel and the combustion processes taking place in the flame. Research in this area is considered to be potentially of great value. An understanding of how the combustion process influences the transformation of mineral matter in CWF flames can eventually lead to the development of strategies for lessening the severity of slagging problems that accompany the use of this fuel.

1.3.3 Pollutants Emission

- NO_x Emission

Nitrogen oxides produced in combustion processes originate from the molecular nitrogen in the combustion air and from hetero-cyclic nitrogenous compounds when these are present in the fuel. In the case of coal water fuel combustion, NO_x formed from both sources can lead to a serious emission problem. The key to controlling N₂-derived or 'thermal' NO lies in maintaining peak combustion temperatures at a level which is below approximately 1800°K (2800°F). At temperatures below this value the rate of formation of NO from N₂ is insignificant.

Under fuel-rich conditions and sufficiently high temperatures a major proportion of the fuel nitrogen can be converted to N_2 rather than NO. Hence by slowing or delaying the completion of the mixing of the fuel with the combustion air, either aerodynamically or physically, and by closely controlling heat extraction along the flame, a major fraction of the nitrogen in the fuel can be converted to N_2 without a subsequent oxidation of N_2 to NO taking place.

The flame stability problem characteristic of coal water fuel combustion is expected to present additional complications as far as abatement of NO_x emissions is concerned. Flame stability is generally favored by high rates of entrainment and fast fuel-air mixing. These conditions, however, tend to increase both thermal and fuel NO_x formation. Requirements for good flame stability and low NO_x emissions are somewhat conflicting and it requires therefore careful selection of flame input conditions to satisfy both these requirements.

- SO_x emission

Unlike NO_x , SO_x emissions are harder to control using flame staging techniques. The formation rates of SO_2 under fuel-rich and fuel-lean conditions are faster than SO_2 destruction rates, thus SO_2 emissions are insensitive to combustion process modifications which are favorable to the reduction of NO_x emission.

Consequently, scientists and engineers have resorted to the reduction of SO_x emissions by introducing additive sorbents into the flame or into the post combustion region of the furnace. Since the results obtained to date show a large variance in the efficiency of sulfur removal from the flue gas it is felt that studies pertinent to the fundamental understanding of the mechanisms of sulfur capture could be instrumental to the determination of

design criteria for maximum reduction of SO_x emissions and would help in explaining the observed differences in the performance of the additive sorbents.

1.4 Input and Operating Variables Affecting CWF Combustion Characteristics

As will be demonstrated in this report, the design and operating variables of the burner and atomizer are key variables in the process of overcoming the problems of CWF combustion. Some of the input variables considered to be of greatest significance with respect to these technical problem areas are discussed in the following sub-sections.

1.4.1 Flame Aerodynamics -- The linear and angular momentum of the burner jet flow.

The burner air exit velocity and swirl degree are two input variables that control the mixing of the fuel, air and hot burned gases in a turbulent diffusion jet flame, and can be effectively used to enhance the convective heat transfer from the flame to the cold fuel exiting the atomizer. Increasing the exit velocity of the air jet leaving the burner has the effect of increasing the rate of entrainment of gases across the jet boundary. When the burner air and fuel penetrate a combustion chamber filled with hot combustion products, the hot gas is recirculated towards the burner and is entrained into the jet issuing from the burner.

If the burner air flow has a strong rotational velocity component this produces a reverse flow on the jet axis. As a result of this ignition improves, the mixing of burner fluids and hot burned gas becomes more intensive, and the flame length shortens.

The combination of high burner air exit velocity (high linear momentum) and high degree of swirl (high angular momentum) results in enhanced degree of turbulence. The combustion process is intensified due to the rapid mixing of the reactants and consequently rates of fuel burnout are also

enhanced. However, there are penalties to be paid in terms of higher NO_x levels and increased slagging in and around the burner at these high intensity combustion conditions, and also in terms of pressure drop through the burner.

1.4.2 Atomization

The fineness of atomization determines the effective surface area of the coal water fuel per unit volume in the jet that is available for heat and mass transfer. Consequently, it has a direct bearing upon the vaporization rate of the water in the fuel and on the rate of heat absorption via both radiation and convection. Hence there is strong incentive to achieve as fine a fuel spray as possible from the ignition and stability viewpoint. The same reasoning holds for fuel burnout and carbon combustion efficiency. Emission of combustibles can be expected to increase significantly as the quality of atomization decreases and large agglomerations of coal particles are formed.

Ash deposition and slagging are likely to increase with decreasing atomization quality. The mineral matter present in large agglomerations of coal particles undergoing combustion will tend to coalesce into relatively large molten or semi-molten masses which will not follow the flow streamlines of the combustion gases and which will tend to deposit on various surfaces in the boiler combustion chamber and flow passages. In addition, the presence of unburnt fuel, i.e., carbon, will result in depressed softening and melting point temperatures of the ash, which will even further aggravate the slagging problem. Thus, good atomization is highly desirable not only from the viewpoints of ignition and stability, but also from carbon combustion efficiency and ash deposition.

1.4.3 Combustion Air Staging

It has been demonstrated in heavy fuel oil combustion tests that rich-lean combustion, as accomplished by staging of the combustion air, leads to reduced emissions of NO_x in the case where high nitrogen-bearing liquid fuels are burned. The same is expected to be true for rich-lean combustion of coal-water fuel, although longer fuel-rich zone residence times may be required to ensure that a major proportion of the fuel-nitrogen is released for subsequent conversion to N_2 before the combustion mixture enters the fuel-lean stage.

In the case of CWF, combustion staging could offer an additional advantage from the viewpoint of ignition and flame stability. Staged air introduction effectively reduces the mass of air that must initially be heated along with the fuel spray entering the furnace chamber. Provided that upstream radiative and convective heat transfer levels in the fuel-rich zone are maintained relatively high, the ignition time for the fuel can be effectively reduced in this manner.

It is noteworthy that flame staging can be accomplished by principally different systems of air/fuel mixing for producing the requisite fuel-rich and -lean flame zones. In the first of these, both the fuel-rich and -lean flame zones are formed aerodynamically, usually by a single burner. This system is termed internally staged. Examples of internal staging are given in Fig. 1.2. Fuel-rich and -lean zones necessary for NO_x reduction are produced by the appropriate mixing of burner fluid flows; burners designed to accomplish this mixing are the so-called "low- NO_x burners." These burners will yield improvements when used by themselves in new or retrofitted boilers, but they can also be used in combination with external staging (spatially separated rich and lean flame zones).

Figure 1.2(a). Schematic of internally staged low NO_x burner flame.

Figure 1.2(b). Multi-annular swirl burner for liquid fuels.

While the application of low- NO_x burners is convenient, the rate at which fuel and oxidant and combustion products are mixed, and the residence times in the fuel-rich and -lean zones, are less well controlled than in systems with spatially separated fuel-rich and -lean combustion zones. This causes uncertainty in the application and scale-up of low- NO_x burners. The suppression of radial mixing near the burner by a positive radial density gradient and radial distribution of the combustion air swirl is intended to produce better defined mixing zones in burner flames. A further cause of uncertainty in the behavior of low- NO_x burners using coal water fuels arises from the fact that fuel droplets will transform into char cenospheres within the fuel-rich region of the flame, necessitating careful attention to the combustion conditions to insure subsequent burnout of all carbonaceous particulates.

In the second system, external staging air or fuel staging can be achieved by spatially separated combustion zones (see Figure 1.3). The furnace zone near the burner may be operated fuel-rich, and secondary (or "overfire") air may then be injected at some distance downstream in the combustion chamber to create a lean furnace zone for completion of combustion. Similarly, fuel can be injected into fuel-lean burned gas to turn it into locally fuel-rich for NO_x reduction, followed by more air injection necessary to complete combustion.

Since it is expected that both techniques would result in similar levels of reduced- NO_x emissions, the option of using internal flame staging to achieve such reductions is preferable because of the lower cost of implementation in retrofit applications.

Staging is expected to result in increased slagging and ash deposition, especially in the fuel-rich zone where reducing conditions prevail. It is

Figure 1.3 External staging strategies for NO reduction.

well-known from pulverized coal combustion that reducing conditions can significantly depress the softening and melting temperatures of coal ash.

The fuel burnout and carbon combustion efficiency obtained under staged conditions, based on results from previous studies, are expected to be highly dependent upon the mode and rate of secondary air admixing. The mixing of the secondary air must be sufficiently rapid to achieve acceptable fuel burnout without causing excessive temperature rise that might result in the formation of thermal NO.

1.4.4. Sorbent injection

The type of sulfur capturing agents, their mode of injection and the Ca/S ratio can affect significantly the level of sulfur removal from the flue gas. For coal water fuels, the sorbent can either be premixed with the fuel before introducing it into the combustion chamber, or it can be injected as a pulverized solid mixture and/or as a spray into the flame or into the low temperature zones of the combustion chamber. The sulfur capture efficiency will highly depend on the local conditions the agent encounters as it flows towards the exit of the furnace. Another important feature that might affect the level of SO_x removal is the sorbent type. Solids particles in the form of calcium hydroxide and water soluble calcium compounds such as calcium acetate are expected to have different sulfur removal efficiencies.

Another important parameter which affects the level of sulfur is the Ca/S feed ratio. It is expected that for a particular sorbent an optimum value of Ca/S could be determined for a coal containing a specific amount of sulfur.

1.5 Research Objectives

Following a careful review of CWF combustion problem areas and their possible solutions an experimental burner was designed jointly by CE and MIT. According to the tasks of CE's contract with DOE-PETC a scaleable high efficiency advanced coal combustor (HEACC) had to be developed for CWF combustion. Supporting research with detailed experimental characterization of this newly designed burner was to be carried out at MIT while the scaled up version was planned to be tested later by Combustion Engineering, Inc. in their own laboratory.

The specific aims of the MIT study were to characterize the burner over wide ranges of combustion conditions, with special emphasis on the topics of:

- Carbon conversion efficiency
- NO_x and SO_x emission
- Fly ash composition and particle size distribution

1.6 The Research Program

The research had both experimental and theoretical parts. The experiments can be divided into two groups:

- Combustion tests in the Combustion Research Facility (CRF).
- Measurements in a Spray Test Facility (STF) designed to determine spray atomization quality.

(Descriptions of the CRF and STF together with methods of the experimental measurements are given in the Appendix).

1.6.1 Flame Studies at the CRF

The main input variables of the combustion experiments were as follows:

- o Fuel Type

- No. 2 fuel oil (preliminary experiments)

"ultra fine" coal water fuel with MMD ~ 9 μm

"fine" CWF with MMD ~ 21 μm

- o Burner Parameters

- swirl degree of secondary air

- primary/secondary air ratio

- secondary air annuli configuration

- spray gun position in burner throat

- o Atomizer Type and Mode of Operation

- OR-KVB nozzle (Fig. 1.4a)

- CE swirl jet nozzle (Fig 1.4b)

- atomizing air/fuel ratio

- o CWF fuel temperature

- o combustion air staging level

- o Sulfur sorbent type

- calcium acetate

- calcium hydroxide

The CRF experiments were of two types: parametric and detailed in-flame studies, respectively, and these involved differing levels of measurements.

In the parametric studies, properties of gaseous combustion products and the size distribution and chemical composition of the particulates carried by the gas stream were determined at the exit of the combustion chamber.

For the detailed flame studies, in-flame measurements were made of

- velocity and temperature

- gas composition (CO_2 , O_2 , CO , NO_x and SO_2) and

(a) OR-KVB nozzle

(b) CE-swirl jet nozzle

Figure 1.4 Schematic of two internally mixed CWF atomizers used in the study

- sampling of solids species along the flame for analysis of combustible matter and particle size distribution

1.6.2 Atomization Study

In the atomization study the drop-size distributions of CWF sprays were determined by laser diffraction measurements for the effects of:

- CWF dilution with water (variation of CWF effective viscosity)
- Atomizing air to fuel mass flow ratio
- Fuel temperature
- Coal particle size

All spray tests were carried out with a "solid cone" (CE swirl jet) atomizer.

1.6.3 Theoretical Modeling

Based on the information obtained from flame probing, a mechanistic model of char combustion was developed. The model is capable of predicting the progress of combustion along the flame of the various size ranges of polysize char particles. The calculated burnout times and particle size distributions were compared with those determined experimentally.

Section 2

2.0 Experimental Plan

In order to evaluate the performance of the high efficiency advanced coal combustor, the work performed in this research program was divided into three phases. These included optimization tests with No. 2 fuel oil, CWF combustion tests, as well as, CWF spray characterization experiments.

In order that the performance-related advantages of the burner's variable geometry can be appreciated, a description of the burner is provided first followed by a detailed description of the experiments carried out under the individual phases.

2.1 Burner Description

A new multi-annular burner was developed by Combustion Engineering, Inc., and Massachusetts Institute of Technology under the sponsorship of the Pittsburgh Energy Technology Center (PETC-DOE). The burner is equipped with a CWF gun surrounded by primary and secondary air supplies. The primary air is introduced through a fixed vane swirler, while the secondary air passes first through a variable swirler and then is introduced through three concentric air annuli (rings A, B and C) before entering the combustion chamber. These annuli can be moved independently from each other, allowing the aerodynamic variation of the size and shape of fuel-rich and -lean flame zones necessary for NO_x reduction. A schematic of two modes of operation using this burner is shown in Figure 2.1.

In the experiments, the new burner was attached to the front end of the combustion tunnel of the Combustion Research Facility (CRF) shown in Figure 2.2. The 1.2 m x 1.2 m x 4.5 m test section is designed to permit detailed investigation of industrial type turbulent diffusion flames by in-flame probing and optical measurements.

Figure 2.1 Cross Section of Pilot-Scale HEACC

Figure 2.2 Schematic of the Combustion Research Facility.

2.2 Workscope

Task 1. Burner Optimization Study

In the initial tests, combustion experiments with No. 2 fuel oil were carried out to define the optimum burner configuration for a stable oil flame which has low NO_x emission levels. The variables considered in these tests included:

- (1) position of fuel nozzle relative to primary air swirler
- (2) primary/secondary combustion air flowrate ratio
- (3) position of rings, A, B and C relative to primary air swirler
- (4) swirl degree of the secondary combustion air

To simulate the combustion conditions which exist in practical CWF flames, the thermal input in these experiments was maintained at 1.5 MW, and the fuel spray introduced into the combustion chamber was issued using the CWF 20° solid cone internally mixed OR-KVB nozzle.

During the experiments, still photographs of the flame front were taken. In addition, measurements of CO, CO₂, O₂ and NO_x concentrations were made at the exit of the combustion tunnel.

Task 2. Coal Water Fuel Combustion Tests

Task 2.1 Parametric CWF Combustion Tests

After the completion of the optimization tests using No. 2 fuel oil, it was evident that the optimum combustion conditions for No. 2 fuel oil were different from those expected for coal water fuels. Consequently, an optimization study of the burner relative to coal water fuel combustion had to be carried out before the detailed CWF flame characterization experiments. For this purpose two coal water fuels, prepared by OXCE Fuel Co. Inc., were used in these combustion tests; one fuel had a mean coal particle size (MMD) of ~ 21 μm while the other had an MMD of ~ 9 μm.

The coal used to prepare the CWFs was an Upper Elkhorn high volatile bituminous coal. It was washed by the coal supplier to obtain a lower mineral matter content. Coal and ash analyses were performed by Wyoming Analytical Laboratories Inc. (WAL) and are given in Table 2.1.

The WAL analysis of ash composition showed a very high sodium content (12.35%). This high sodium content is attributed to a sodium-containing additive used in the fuel preparation.

The burner parameters varied in these tests included:

- primary/secondary air ratio
- primary air swirl degree
- fuel atomizer position relative to primary air swirler
- position of rings A, B and C relative to primary air swirler
- secondary air swirl degree
- CWF atomizer type

Ignition and flame stability were monitored by visual observations. Carbon burnout, CO, CO₂, O₂, NO_x and SO_x emissions were measured at the combustion tunnel exit.

Task 2.2 CWF Flame Characterization Experiments

After the conclusion of the parametric combustion study an optimum burner configuration was chosen for flame characterization experiments. The ultra-fine CWF which proved to have better combustion characteristics than the fine grind CWF was used. The thermal input in these experiments was maintained at 1.5 MW. The fuel atomizer used was the internally mixed twin fluid spray nozzle supplied by C.E., Inc. (the CE-swirl jet nozzle in Figure 1.4b). Fuel temperature was varied from 20°C to 115°C and flame characterization studies were carried out to determine if disruptive atomization could influence carbon burnout and NO_x emissions. In-flame and

Table 2.1

Analysis of Parent Coal

	Moisture Free	Mineral Ash Analysis (wt%, Ignited Basis)	
Proximate	-		
Moisture	-	SiO ₂	40.98
Ash	3.24	Al ₂ O ₃	24.18
Volatile matter	36.65	Fe ₂ O ₃	9.60
Fixed carbon	60.11	CaO	1.58
Total	100.00	MgO	0.68
		Na ₂ O	12.35
Ultimate		K ₂ O	1.80
Hydrogen	5.91	TiO ₂	1.62
Carbon	86.39	MnO ₂	0.04
Nitrogen	1.01	P ₂ O ₅	0.11
Sulfur	0.87	SrO	0.26
Oxygen	2.58	BaO	0.29
Ash	3.24	SO ₃	5.20
Total	100.00	Sum	98.69
Heating value	15222		
Btu/lb			

Ash Fusion Analysis

Reducing Atmosphere:

Initial Deformation	2110 F
Softening	2160 F
Hemispherical	2220 F
Fluid	2340 F

Oxidizing Atmosphere

Initial Deformation	2280 F
Softening	2360 F
Hemispherical	2430 F
Fluid	2540 F

flue gas measurements were made to obtain information on the chemical and physical structure of the two coal water fuel flames as well as on the combustion products leaving the test chamber. Gas and solids sampling was used to determine the chemical species concentration distributions in the flames. Gas temperatures were measured using a suction pyrometer, and gas velocities were measured by a two-hole impact probe especially suited for particle-laden flows.

Task 2.3 Sulfur Capture

Six batches of the OXCE ultrafine CWF premixed with three known quantities of calcium hydroxide and calcium acetate, respectively, were burned in the CRF in an investigation on sulfur capture. The fuels so generated were introduced via the HEACC burner into the combustion chamber and measurements of gas composition including SO₂ concentration and fly ash loading, composition and size distribution were made at the exit of the combustion tunnel. To compare the combustion characteristics of these fuels with the base fuel, in-flame sampling was made for a calcium hydroxide-doped CWF in which the Ca/S ratio was 1.26.

Task 2.4 NO_x reduction

Two principally different systems of air/fuel mixing for producing the fuel-rich and -lean flame zones were tested; the internally staged flame technique vs. the externally staged system.

In the first of these both the fuel-rich and -lean flame zones were formed aerodynamically, by adjusting the secondary air supply.

In the second system (termed external flame staging), staging of air was achieved by spatially separated combustion zones. The furnace zone near the burner was operated fuel-rich, and secondary (or "overfire") air was

then injected at some distance downstream in the combustion chamber to create a lean furnace zone for completion of combustion.

As the level of external staging was varied, gas composition and carbon burnout (from fly ash samples) were measured at the combustion tunnel exit. To compare the combustion characteristics of the CWF which contained a sorbent with the base fuel, a fly ash sample was collected from the exit of the externally staged flame using the doped fuel and was analyzed for carbon burnout and particle size distribution.

Task 3. Fuel Spray Characterization

To establish the effect of fuel properties upon the combustion characteristics of the particular OXCE CWFs, atomization tests were carried out in the spray rig facility. The fuels which were used in this investigation included the ultrafine and fine grind CWFs as well as a calcium hydroxide-containing ultrafine coal water fuel. The parameters which were varied during these experiments were fuel temperature and atomizing air/fuel ratio.

Section 3

3.0 Optimization of Burner using No. 2 Fuel Oil

3.1 Introduction

In the first phase of experiments, No. 2 fuel oil was burned and the composition of flue gas, in particular NO_x , was monitored as the burner parameters were varied. The purpose of the oil burning experiments was to permit the exploration of the mixing in the near-field flame region as affected by the burner adjustments. It was not expected that these experiments would yield data that defined the optimum burner configuration when burning CWF, and therefore, the optimization studies were continued with CWF.

3.2 Experimental Conditions

Since the objective of this task was to determine the optimum burner configuration for staging the flame internally, the parameters varied were those that affected the aerodynamic mixing pattern of the fuel and the combustion air near the burner throat. The combustion conditions which were maintained constant are listed in Table 3.1. The burner parameters which were varied included:

- (1) position of fuel nozzle within burner
- (2) primary/secondary combustion air ratio
- (3) mode of secondary air injection
- (4) swirl degree of secondary air

It is noteworthy that by varying the secondary air distribution ring configuration, the mixing rates of the combustion air with the fuel and the aerodynamic mixing patterns change accordingly.

3.3 Experimental Results and Discussion

Since the combination of the above mentioned variables leads to a large number of burner configurations, several burner geometries thought to result in low NO_x emission were chosen and the concentration of NO_x in the flue gas was measured as the burner parameters were varied.

During these initial experiments it was observed that the swirl degree of the secondary air did not influence NO_x emissions, therefore, in all of the experiments reported no swirl was imparted to the secondary combustion air.

Although the total quantity of the secondary air could be varied, the distribution of the air among the three annuli could not be sufficiently controlled. The adjustment of one annulus while keeping the other two fixed resulted in redistribution of the combustion air among the three secondary air nozzle distribution rings and had an effect upon NO_x emissions. The experimental results shown in Figure 3.1 illustrates this effect. Extending annulus C into the burner while keeping annuli A & B at a fixed location resulted in higher emissions of NO_x ; i.e., NO_x emissions rose from 125 ppm to 140 ppm when ring C was extended into the burner.

In this particular configuration, the major fraction of the secondary air passes through the passage between ring C and the outer wall of the burner as well as between rings A & B. It can be seen from Figure 3.1 that the air passing between rings A and B has to flow around the extension of ring C and in turn it is redirected towards the furnace axis as it enters the combustion chamber. This aerodynamic pattern enhances the mixing process between the fuel and the secondary air and therefore results in fuel lean conditions.

It should be pointed out that an important component of the burner is the primary air swirler. It was evident from the experiments that the forced vortex swirler served the purpose of providing the internal recirculation zone needed to stabilize the No. 2 oil flame. However, as the fraction of the total air going through this swirler increased from 0.066 to 0.14, NO_x emissions rose from 125 ppm to 180 ppm. The adjustments of the secondary air distribution rings, the fuel gun and the primary air supply were needed to drop the NO_x emissions from 180 ppm to 135 ppm. The experimental results indicated that at low primary/secondary air ratios the location of the swirler and the fuel gun relative to the rest of the burner did not have any effect upon NO_x emissions (cases 2 and 3 of Figure 3.1). However, at higher primary/secondary air ratios, the adjustment of the positions of the swirler and the fuel gun caused a major change in NO_x emission levels. When the fuel gun and the primary swirler were fully retracted relative to ring A (Figure 3.2), the NO_x concentration measured in the flue gas was 135 ppm. As the two were moved forward, the NO_x concentration increased to 180 ppm and then dropped to 160 ppm. When a large fraction of the secondary air passed between rings A, B and C, as in Case (6), the fuel spray was shielded from the air, resulting in a highly fuel-rich core at the root of the flame and in low NO_x emissions.

Even at higher primary/secondary air ratios (Case 7, Table 3.1), NO_x emission levels rose by only fifteen ppm (to ~ 150 ppm). This result might not be of significance to No. 2 fuel oil flames, but it would be important to coal water fuel combustion. It is anticipated that high primary/secondary air ratios (~ 0.25) are required to stabilize CWF flames close to the burner. Therefore, at high primary/secondary air ratios, an appropriate burner configuration could be found to facilitate both flame

CASE (1)
P/S AIR RATIO = 0.07

NO_x CONC. = 140 PPM

CASE (2)
P/S AIR RATIO = 0.07

NO_x CONC. = 125 PPM

CASE (3)
P/S AIR RATIO = 0.07

NO_x CONC. = 125 PPM

Figure 3.1 Effect of burner configuration upon NO_x emissions for a low primary/secondary combustion air ratio in No. 2 oil flames.

CASE (4)
P/S AIR RATIO = 0.14

CASE (5)
P/S AIR RATIO = 0.14

CASE (6)
P/S AIR RATIO = 0.14

Figure 3.2 Effect of burner configuration on NO_x emissions from No. 2 oil flames for a moderately high primary/secondary combustion air ratio

Table 3.1

Combustion Conditions for No. 2 Fuel Oil Optimization Flame Experiments

<u>Case No. 1</u>	<u>Thermal Input</u> <u>(MWt)</u>	<u>Excess Air</u> <u>Level %</u>	<u>Primary Combustion</u> <u>Air Temperature °C)</u>	<u>Secondary Combustion</u> <u>Air Temperature (°C)</u>	<u>Primary/Secondary</u>	<u>NO_x Emission</u> <u>(ppm)</u>
1	1.5	14	213	259	0.07	140
2	1.5	14	214	263	0.07	125
3	1.5	14	214	263	0.07	125
4	1.5	14	214	263	0.14	180
5	1.5	14	233	260	0.14	160
6	1.5	14	236	261	0.14	135
7	1.5	14	237	261	0.18	150

stability and low NO_x emissions. The experimental results obtained with No. 2 oil combustion have shown that by varying the burner geometry through the adjustment of the positions of the primary air swirler, the atomizing nozzle and the secondary air annuli it is possible to influence the position of the flame front, the length of the flame and the emission levels of NO_x .

Section 4

4.0 Coal Water Fuel Combustion Tests

4.1 Introduction

The combustion experiments with No. 2 fuel oil showed that highly stable flames could be obtained with the HEACC burner; however, it was expected that the configuration which was best for the oil would not necessarily be the optimal one for coal water fuel combustion. Hence, a parametric combustion study using CWF was carried out in which the combustion conditions were varied and at the combustion tunnel exit measurements were made of gas composition and fly ash particle size distribution, composition, and extent of carbon burnout.

Since the atomization quality of the CWF spray can influence the burner performance, an atomization study using the fine grind (MMD ~ 21 μm) and the ultrafine (MMD ~ 9 μm) coal water fuels was carried out to determine the best atomization conditions for achieving fine sprays.

4.2 Combustion Variables

The major input parameters which were found to affect the characteristics of CWF flames, are:

(1) CWF atomization quality as affected by:

- fuel nozzle - (OR-KVB vs. CE swirl jet)
- fuel temperature 22- 110°C
- coal mean particle size - 9 μm vs. 21 μm
- atomizing air/fuel ratio - 0.10 - 0.30
- fuel dilution level - 0.55 - 0.65

(2) Combustion air staging as affected by:

- primary/secondary combustion air mass flow ratio (0.22- 0.43)

- secondary air swirl degree
- fuel equivalence ratio of primary stage in a two stage system (rich-lean configuration)

(3) Sorbent injection and Ca/S ratio

$\text{Ca}(\text{C}_2\text{H}_3\text{O}_2)_2$ vs $\text{Ca}(\text{OH})_2$, at $0.0 < \text{Ca/S} < 2.1$

4.3 Experimental Conditions

4.3.1 Combustion Tests

The three fuels used in the combustion experiments included the fine grind, the base ultrafine grind, and the ultrafine grind CWF mixed with two types of sorbents. The input conditions maintained in these tests are listed for each fuel in Tables 4.1 - 4.3.

Measurements of gas composition including O_2 , CO, CO_2 , NO_x and SO_x were made in the flue gas. Solids samples were collected at the same location and analyzed for elemental composition and particle size distribution

4.3.2 Atomization Tests

After the conclusion of the combustion tests, atomization measurements were made for the fine and ultrafine grind CWFs as well as, for one of the $\text{Ca}(\text{OH})_2$ doped ultrafine coal water fuels. Both the atomizing air/fuel ratio and the fuel temperature were varied and measurements of the spray size distribution were made using a laser diffraction instrument.

4.4 Results

4.4.1. Ignition and Flame Stability

Sustained ignition in turbulent diffusion flames takes place as a result of convective and radiative heat feedback to the cold incoming fuel. Earlier studies of CWF flames at this facility (2, 3) have indicated that convection is the predominant mechanism of energy feedback in high swirl CWF flames. Radiation from the flame front and surroundings to the cold fuel

Table 4.1
Combustion Conditions of the Ultrafine Coal Water Fuel Flames

Thermal Input	Fuel Nozzle	Atomizing Air/ Fuel Ratio	Mass Fraction of Coal in Fuel	Fuel Temp °C	Primary/Secondary Air Ratio	Primary Stage Ratio Fuel Equivalence	Overall Excess Air Level %	Secondary Air Swirl Setting
(1)	OR-KVB	0.24	0.60	22	0.29	0.82	20.4	0
(2)	OR-KVB	0.20	0.60	22	0.28	0.83	22.2	0
(3)	OR-KVB	0.19	0.60	22	0.29	0.82	20.8	0
(4)	OR-KVB	0.23	0.60	22	0.29	0.83	20.8	1/2
(5)	OR-KVB	0.24	0.60	22	0.28	0.83	22.2	3/4
(6)	OR-KVB	0.29	0.60	22	0.26	0.82	21.5	1
(7)	OR-KVB	0.21	0.60	22	0.22	0.82	20.8	0
(8)	OR-KVB	0.22	0.60	22	0.27	0.82	22.2	0
(9)	OR-KVB	0.23	0.60	22	0.30	0.83	22.2	0
(10)	OR-KVB	0.22	0.60	22	0.43	0.82	21.5	0
(11)	C.E.	0.19	0.60	22	0.27	0.82	22.2	0
(12)	C.E.	0.21	0.60	22	0.27	0.82	22.9	0
(13)	C.E.	0.25	0.60	22	0.27	0.81	22.9	0
(14)	C.E.	0.25	0.60	22	0.30	0.81	22.6	0
(15)	C.E.	0.22	0.60	116	0.30	0.82	22.6	0
(17)	C.E.	0.25	0.60	22	0.61	1.21	22.9	0
(18)	C.E.	0.25	0.60	22	0.42	1.40	22.9	0
(19)	C.E.	0.25	0.60	22	0.61	1.40	22.9	0
(20)	C.E.	0.25	0.60	112	0.62	1.21	22.9	0
(21)	C.E.	0.25	0.60	113	0.51	1.25	22.6	0
(22)	C.E.	0.25	0.60	112	0.51	1.65	22.6	0

Table 4.2
Combustion Conditions of the Find Grind Coal Water Fuel Flames

Thermal Input	Fuel Nozzle	Atomizing Air/ Fuel Ratio	Mass Fraction of Coal in Fuel	Fuel Temp °C	Primary/Secondary Air Ratio	Overall Excess Air Level %	Secondary Air Swirl Setting
(1) 1.56	C.E.	0.12	0.625	111	0.30	22.9	0
(2) 1.56	C.E.	0.15	0.625	110	0.29	22.6	0
(3) 1.55	C.E.	0.23	0.625	110	0.29	23.7	0
(4) 1.55	C.E.	0.15	0.620	111	0.31	21.8	0
(5) 1.55	C.E.	0.19	0.620	111	0.31	22.2	0
(6) 1.56	C.E.	0.11	0.610	110	0.31	22.9	0
(7) 1.56	C.E.	0.14	0.610	111	0.31	22.9	0
(8) 1.56	C.E.	0.16	0.610	112	0.31	22.9	0

Table 4.3
Combustion Conditions of the Sorbent-doped Ultrafine Coal Water Fuel Flames

Fuel	Fuel Temperature °C	Solids Mass Fraction	Coal Mass Fraction	Thermal Input (MW)	Primary Stage Fuel Equivalence Ratio	Overall Excess Air (%)	Sorbent	Ca/S
Ultra-Fine	92	0.57	0.56	1.47	0.81	22.9	Ca(OH) ₂	0.52
Ultra-Fine	88	0.57	0.56	1.53	0.81	23.7	Ca(OH) ₂	1.05
Ultra-Fine	97	0.55	0.54	1.44	0.81	22.9	Ca(OH) ₂	1.26
Ultra-Fine	89	0.53	0.51	1.37	0.79	26.8	Ca(OH) ₂	1.58
Ultra-Fine	87	0.52	0.50	1.34	0.81	22.9	Ca(OH) ₂	2.10
Ultra-Fine	111	0.55	0.54	1.45	0.81	22.9	Ca(OH) ₂	1.26
Ultra-Fine	112	0.55	0.54	1.49	1.57	22.9	Ca(OH) ₂	1.26
Ultra-Fine	92	0.59	0.58	1.47	0.81	22.9	Ca(C ₂ H ₃ O ₂) ₂	0.62
Ultra-Fine	92	0.59	0.55	1.42	0.81	22.9	Ca(C ₂ H ₃ O ₂) ₂	1.24
Ultra-Fine	92	0.55	0.51	1.38	0.81	23.7	Ca(C ₂ H ₃ O ₂) ₂	1.86

jet appears to account for only about ~10-20% of the total energy (~90 KW) required to heat the fuel to ignition temperature.

Convective heating of fuel spray in highly swirled CWF turbulent diffusion flames is brought about by the backmixing of hot combustion products via recirculation zones established both internally and externally to the flame. Factors in convectively sustained-ignition include the water and volatiles content of the fuel, ignition temperature of the coal particles, the recirculated mass flow rate of the hot combustion products and their temperature.

Also important is the droplet size distribution of the CWF spray, since it determines the effective surface available for heat transfer. It plays an important role in the ratio of inertial to drag forces acting on the particle which, in turn, have an effect of increasing the concentration of fine droplets in the central region of the flame thereby promoting ignition.

A parameter which was found to significantly affect ignition and flame stability is the coal particle size. The flames studied using the HEACC show that when the "ultrafine" CWF was used a stable flame was obtained even without fuel preheating. In the case of the fine grind CWF, however, a stable flame could not be obtained unless the fuel was preheated to secondary atomization levels ($> 100^{\circ}\text{C}$). It was observed that even at that temperature the flame became unstable if the atomizing air/fuel ratio exceeded ~ 0.25.

Since the mean droplet size of the "fine grind" CWF spray is larger than $21\text{ }\mu\text{m}$, it is considered that the large droplets pass through the internal recirculation zone in a time less than that required to evaporate the water and to ignite the coal agglomerates close to the fuel nozzle. Indeed, an unstable, lifted flame was observed for this case. As the fuel

was heated above 100°C the fraction of the small droplets increased and the flame was stabilized at the burner.

On the other hand, the fraction of the small droplets for the ultrafine CWF (mean coal particle size ~ 9 μm) was high enough even for a fuel temperature of 22°C to sustain a stable flame in the vicinity of the burner. The flame became unstable, however, if the atomizer air/fuel ratio was raised beyond a value of 0.35.

4.4.2. Carbon burn-out, fly ash formation and pollutants emission

The dependent variables which were used as indicators on how well the burner performed and which were monitored during the combustion tests included carbon burnout levels and NO_x and SO_x concentrations in the flue gas.

The results obtained are discussed in terms of the effects of burner operating variables such as atomization quality, combustion air staging, and sorbent injection.

4.4.2.1 Carbon Burnout

(1) Effect of Atomization Quality Upon Carbon Burnout

The parameters which were found to influence atomization quality are:

- (a) atomizer type
- (b) air/fuel ratio
- (c) fineness of coal particle size distribution
- (d) fuel preheating level
- (e) dilution of CWF with water

The effect of these parameters on carbon burnout are discussed next.

(a) Atomizer Type

It is an advantage of both the OR-KVB and the CE-swirl atomizer designs, that the fuel spray pattern is a solid cone centered on the jet

axis. The fuel is thus injected directly into the central recirculation zone reverse flow region where the drag forces acting on the fuel droplets/particles will be the greatest. In the case of CWF combustion in which ignition times are longer than for others, e.g. liquid fuels, it appears particularly advantageous to have a fine spray with a long near-field residence time.

While no difference was observed between the stability of flames produced by the CE and OR-KVB nozzles, the carbon conversion efficiency was better in the flames produced with the CE swirl jet nozzle as illustrated in Figure 4.1. A possible reason for this is that the CE nozzle spray is finer despite the lower pressure drop of this nozzle on the atomizing air side.

(b) Atomizing Air to Fuel Mass Flow Ratio

From the spray testing experiments it was clear that as the air/fuel ratio increased, the atomization quality of the ultrafine and fine grind CWFs improved (see Figure 4.2). However, during the combustion tests it was found that if this ratio was higher than 0.20 for the fine grind CWF, carbon burnout level determined in the flames dropped (see Figure 4.3). It was observed that higher air/fuel ratios were required to sustain a flame in the case of the ultrafine CWF. Figure 4.3 shows that as the A/F ratio was raised from 0.20 to 0.26 the carbon conversion efficiency increases ~ 2%. However, if this ratio was raised beyond 0.35 fly ash collected at the exit of the combustor containing a larger fraction of char particles indicating lower carbon burnout levels. Visual observations of these latter flames showed that they were unstable, and two detached luminous regions could be seen close to the burner Figure (4.4)). As the air/fuel ratio was further increased only the small luminous zone close to the atomizer remained; the larger luminous zone moved further downstream.

Figure 4.1 Effect of atomizer type upon carbon burnout for three levels of atomizing air/fuel ratio

Figure 4.2 Effect of atomizing air/fuel ratio upon CWF atomization quality for the ultrafine and fine grind CWFs

Figure 4.3 Effect of atomizing air/fuel ratio upon carbon burnout in the ultrafine and fine grind CWF flames

Figure 4.4 Effect of atomizing air/fuel ratio upon flame envelope

It could be inferred from the measurements and the visual observations that for fully stable flames, the major fraction of the droplets do not have enough momentum to penetrate the reverse flow region and, hence, devolatilize and ignite in the upstream stagnation region of the central recirculation eddy. However, as the atomizing air flow rate is raised an increasing fraction of the CWF droplets penetrate the internal recirculation zone and cause the formation of two flame fronts detached from one another, one sustained by the reverse flow region and the other developing downstream of the central recirculation zone. The latter blows out at higher air/fuel ratios.

(c) Fineness of the Coal Particle Size Distribution

Closely related to atomization quality in impact upon carbon burnout is the fineness of the coal particle size distribution used in the formulation of the coal water fuel. The lower limit to which the spray droplet sizes can be reduced is a function of the coal particle sizes, since these, in turn, set the lower limit for the size of the fuel nozzle and the thickness of the liquid sheet issuing from the nozzle exit ports. Increasing coal fineness by its effect of raising the CWF viscosity may adversely influence the quality of atomization. Small dilution of the CWF by water may, however, help to reduce the fuel viscosity and permit full advantage to be gained by finer coal sizes (see Section e).

A comparison of the flames obtained with the ultrafine grind and the fine grind CWFs respectively showed that higher carbon burnouts were achieved with the ultrafine grind CWF (Figure 4.3).

(d) Fuel Preheating Level

The preheating of the CWF was observed to improve flame stability and carbon burn-out. Figures 4.5, 4.6 and 4.7 show O_2 , CO_2 , gas temperature and

Figure 4.5 Effect of secondary atomization upon the concentration profiles of O_2 and CO_2 along the furnace axis in ultrafine CWF flames:

- (a) flame No. 1 $T_{fuel} = 22^\circ C$, (a/f) ratio 0.25
- (b) flame No. 2 $T_{fuel} = 111^\circ C$ (a/f) ratio 0.22

Figure 4.6 Gas temperature profiles along the furnace centerline in flames HEACC 1 (fuel temperature 20°C, (a/f) ratio 0.25) and HEACC 2 (fuel temperature 110°C, (a/f) ratio 0.22)

Figure 4.7 Carbon burnout profiles along the furnace centerline in flames HEACC 1 (fuel temperature 20°C, (a/f) ratio 0.25) and HEACC 2 (fuel temperature 110°C, (a/f) ratio 0.22).

carbon burnout profiles along the axis of two 1.5 MW ultrafine grind coal water fuel flames which differed only in the level of fuel preheat and the atomizing air/fuel ratio. As the fuel temperature was increased from 20°C to 111°C, significant improvement in the carbon burnout was observed. The improved carbon burnout with increasing temperature is also reflected by the axial profiles of gas temperatures, O₂ and CO₂ concentrations. The earlier ignition for the case of the highly preheated fuel (111°C) results in a faster rise of the gas temperature and CO₂ concentration and a faster depletion of the oxygen present close to the burner compared to the case of no fuel preheat (20°C). It can be concluded that shorter residence times are required for complete combustion of superheated ($T > 100^{\circ}\text{C}$) coal water fuels.

It is noteworthy that although high final burnout levels were achieved also in the unpreheated fuel flame, the atomizing air/fuel ratio (a/f) required for this case was higher than the ratio maintained in the preheated fuel flame (a/f) = 0.25 vs 0.22). This indicates that fuel preheating permits a relaxation of the pump pressure as well as the atomizing air/fuel ratio without a penalty in carbon conversion efficiency.

The effect of fuel preheating, was even more dramatic for the fine grind CWF. When the fuel temperature was maintained at 20°C, a stable flame could not be sustained unless natural gas was injected coaxially with the fuel. As the fuel temperature was raised to 110°C, a stable flame was obtained without feeding natural gas. However, the carbon burnout achieved in this case (~ 98%) was lower than that obtained in the ultrafine CWF flame (~ 99.95%). These results clearly demonstrate the utilization of thermal atomization for improving CWF flame stability and combustion efficiency.

(e) Dilution of CWF with Water

Past experiments at MIT have shown that adding small amounts of water to the base fuel can significantly reduce the viscosity and thus improve carbon burn-out through finer atomization. The results shown in Figure 4.8, however, show that for this particular fuel, the combustion efficiency did not increase when the fuel was diluted.

Figure 4.8 shows that initially the carbon conversion efficiency improves with increasing atomizing air/fuel ratio. However, as the latter is raised the carbon conversion efficiency drops for the three diluted fuels. Visual observations of the flames indicate that as the atomizing air/fuel ratio is raised from 0.10 to 0.15, better atomization quality results in increasing carbon burnout levels. However, as the atomizing air/fuel ratio increases beyond 0.15 the flames become unstable, thus allowing the carbon burnout levels to drop. In fact the critical atomizing air/fuel ratio for an unstable flame is lowest for the fuel containing 61% solids followed by that containing 62% and 62.5% respectively. It can be concluded for this particular fuel that although water addition can improve the fuel spray quality, the aerodynamic flow field next to the burner is the major factor which determines flame stability and the final carbon burnout level to be achieved.

(2) Effect of Combustion Air Staging upon carbon burn-out

The effect of the mixing rate of the combustion air and fuel on carbon burnout levels was determined by varying the swirl degree (S) of the secondary combustion air, the burner configuration and the primary/secondary air ratio (a_p/a_s).

Since the primary combustion air is introduced through a fixed vane swirler, raising the a_p/a_s ratio increases the fraction of the combustion

Figure 4.8 Effect of coal content of CWF and atomizing air/fuel ratio upon carbon burnout for the fine grnd CWF.

air that has a tangential velocity component and increase the total pressure drop through the burner. For a fixed burner geometry, the carbon conversion efficiency was found to increase slightly as S and (a_p/a_s) were raised. Figure 4.9 indicates that the maximum improvement in carbon burnout levels were obtained for $(a_p/a_s) \sim 0.22$ and $S \sim 3/4$. No additional improvement could be observed at higher values of the swirl degree and the primary/secondary combustion air ratio. As S and (a_p/a_s) are raised, the internal recirculation zone becomes more intense, and the time of flight of the fuel droplets through the internal recirculation zone increases thereby promoting early ignition and more complete burnout within the available combustion space. However, as (a_p/a_s) and S are raised further, any additional benefit of increased turbulence in the recirculation zone diminishes as the fuel spray size distribution becomes the limiting factor in determining the final carbon conversion efficiency.

(3) Effect of Sorbent Injection upon carbon burn-out

Although the primary objective of introducing calcium hydroxide was to capture sulfur, its effect upon carbon burnout was also examined. A fraction of the base ultrafine CWF was mixed with a known quantity of Ca(OH)_2 forty-eight hours prior to combustion.

Ca(OH)_2 powder was first suspended in a water solution and then mixed slowly with the CWF. Consequently, the water content in the prepared batch was higher than in the base fuel (45% vs. 40%). In the combustion tests the CE atomizer was used to spray the CWF prepared with the Ca(OH)_2 into the combustion chamber. The difference in the water content caused finer atomization of the sorbent-containing fuel as will be discussed later in the section. During the experiments, in-flame solids samples were collected and analyzed for elemental composition and carbon burnout levels. The carbon

Figure 4.9 Effect of Secondary air swirl upon carbon burnout.

conversion efficiencies so determined were then compared with those of the base fuel flames without and with fuel preheat (22°C and 111°C respectively). The results shown in Figure 4.10 illustrate that the carbon burnout improved in the presence of the Ca(OH)_2 additive. Fig. 4.11 shows that the spray was finer in the CWF doped with the additive; this could explain the improved carbon burn-out. However, other research studies have shown that one of the elements that catalyzes char oxidation is calcium. The work done by Mcollor et al. (4) showed that when calcium was ion exchanged in the char, it enhanced the char burning rates. The results obtained showed that carbon dioxide was produced at the char surface by catalytic action of the char mineral matter. The experimental observation indicates that the improved carbon burnout levels seen in this study for the doped fuel case might be due to both the presence of calcium and the very fine atomization achieved with this fuel.

4.4.2.2. Fly ash Particle Size Distribution and Composition

According to our present understanding, the fly ash particle size that evolves when a coal particle burns covers a broad spectrum. If the coal does not burn completely, and there is usually some carbonaceous residue in the fly ash, these carbon containing particles represent the largest size fraction (50 μm plus). The rest of the fly ash consists of slag droplets formed from mineral inclusions (pyrites, clay minerals, etc), and from ash particles in atomic dispersion in the coal (Ca, Na, K). These latter form very small micrometer size droplets; their size range somewhat overlaps that of the vaporized fraction of the ash which forms a submicron size aerosol upon condensation as the flue gas is cooled.

Successive stages of fly ash evolution during coal combustion are illustrated by the cartoon in Fig. 4.12. The coal has a large number of

Figure 4.10 Carbon burnout levels along the flame for:

- (a) $\text{Ca}(\text{OH})_2$ -containing ultrafine CWF, $T_F = 111^\circ\text{C}$
- (b) Ultrafine CWF, $T_F = 111^\circ\text{C}$
- (c) Ultrafine CWF, $T_F = 22^\circ\text{C}$

Figure 4.11 Effect of temperature upon atomization quality for the ultrafine CWF and the Ca(OH)_2 -containing ultrafine CWF

Figure 4.12 Burnout and ash deposition mechanisms for bituminous coal-water fuel droplets

mineral inclusions on originating from the sedimentation processes during coalification. The inclusions are of specific composition such as pyrites, clay minerals, silica, alumina, etc. During combustion, as the coal water droplet (bituminous) is heated it becomes plastic in the temperature range of 300-600°C and forms a cenospheric (hollow sphere) agglomerate under the internal pressure of the coal volatiles. The volatiles break through the surface and when they reach a macropore they form a jet. After devolatilization the cenosphere wall burns through in positions where it has minimum thickness and the ash inclusion in the burned region forms a slag droplet which comes to the coal surface to which it lightly adheres. Slag does not wet the char surface and the droplets on the outer surface of the particle may be separated by the strong centrifugal forces. If the slag droplets do not separate from the char particle they may move on the surface and coagulate with others to form larger droplets.

While the "primary" slag droplets will have the chemical composition of the ash inclusion from which they are formed, the chemical composition of the coagulates will be closer to that of the average of the coal ash in the particle.

On the inside of the char cenosphere the slag droplets are trapped. Depending upon the temperature and the ash fusion/viscosity characteristics they either form clusters by sintering or melt into a large single droplet.

As the char particles burn they weaken structurally and break into fragments still relatively large. The crescents formed from char fragmentation upon their burn-out may lead to the formation of single slag droplets of corresponding size. These particles, while smaller than the cenospheres, have strong drag forces acting upon them and are carried over

incompletely burned if combustion conditions (O_2 , temperature) at the point of their breakup are not favorable.

In coal water fuel flames, several parameters, in particular atomization quality and sorbent types, which affect the combustion process and pollutants emission, may influence the fly ash size distribution and composition.

In order to study how these variables might influence fly ash, several samples were collected at the combustor exit and were analyzed for elemental composition and particle size distribution. Since the carbon content of all samples was less than 9% the particle size distributions determined for these samples represent the true ash particle size.

(1) Effect of Atomization Quality upon fly ash psd

In order to examine effects of atomization quality upon fly ash particle size distribution and composition, samples of fly ash were compared for flames in which the atomization quality was varied by raising the fuel temperature from 22°C to 111°C. Figure 4.13 shows that preheating the fuel to 111°C caused the fly ash psd to become finer in both single stage and two stage flames. The fraction of particles in the 0-2 μm size range increased while the number of 10 μm fly ash particles decreased when the fuel temperature was raised from 22°C to 111°C.

For coals of low ion exchangeable ash content there are two bounds of the fly ash particle size distribution. Assuming that mineral inclusions in the coal do not coalesce during combustion, each mineral inclusion will produce a fly ash particle upon the burn-out of the coal. This case constitutes the lower bound of the fly ash psd, i.e. the fine limit of the size distribution. Conversely, if all the mineral matter in a coal particle coalesces as the char particle burns to completion, one fly ash particle

Figure 4.13 Effect of fuel preheating upon fly ash size distribution in single- (lean) and two-stage (rich-lean) flames.

would result from each coal particle. This case constitutes the upper bound of the fly ash psd, i.e. the coarse limit of the size distribution.

In a separate study at MIT (4) it has been found that the fly ash psd in Eastern bituminous coals falls close to the lower bound, that is to the size distribution of the mineral inclusions in the coal. The fly ash psd found for the unheated CWF fell close, however, to the upper bound i.e. the size distribution from the "one fly ash particle per one coal particle model (Fig. 4.14a). It is considered that this was due to the exceptionally high sodium content introduced by the additive for the control of stability and rheological properties of the fuel. It is noteworthy that notwithstanding the high sodium content, disruptive atomization produced by fuel heating to 111°C reduced the fly ash size distribution close to that of the mineral inclusions in the coal (see Figure 4.14b).

The effect of fuel heating on the CWF atomization and droplet size distribution under furnace conditions might be stronger than under cold flow conditions. Radiation from the flame might further increase intensity of the microexplosions of CWF droplets when the fuel temperature was 110°C, but not when the fuel temperature was 20°C.

Although there was a large variation in particle size distribution for the two flames, morphology of the fly ash particles shown in Fig. 4.15 illustrates that fly ash particles mainly consisted of solid and cenospheric spherical particles; the particles were obviously molten in the flame and later solidified when the temperature decreased at the end of the furnace. Some angular shapes could also be seen, probably representing particles which remained solid throughout their history in the flame.

Microprobe analysis of the chemical composition of the fly ash particles showed that the particles from both flames were mainly

Mineral matter transformation in flame HEACC 1

Mineral matter transformation in flame HEACC 2

Figure 4.14 Comparison of measured fly ash particle size distribution with those of coal mineral inclusions and size distributions estimated based on one fly ash particle/coal particle for:

- (a) ultrafine CWF $T \sim 22^{\circ}\text{C}$
- (b) ultrafine CWF $T \sim 110^{\circ}\text{C}$

Figure 4.15 SEM pictures of fly ash particles collected at the end of the flame of the unheated ultrafine CWF ($T_F \sim 22^\circ\text{C}$)

aluminosilicates, many of them having significant amounts of iron and sodium; some quartz particles were also detected. The average chemical compositions determined in the two flames are given in Table 4.4. The high sodium content in the fly ash was due to the sodium-containing additive used in the fuel preparation. It is considered that the high sodium content in the fly ash has promoted the coalescence of mineral matter as has been suggested also by (Anjum et. al. (5))

(2) Effect of Combustion Air Staging upon fly ash psd

The two major methods which proved to be effective in reducing NO_x and which also affect fly ash composition and particle size distribution are internal and external "overfire air" flame staging. Due to the nature of these techniques the local reducing conditions close to the burner can create conditions favorable for lowering the softening temperature of mineral inclusions and increase the likelihood of coalescence. To examine this, fly ash samples obtained from two-stage flames were compared with those collected from single-stage ones. Figure 4.16 shows that the particle size distributions on a char-free basis in the two stage systems are coarser than in single-stage flames. The experimental observation indicates that fuel-rich conditions existing in the first stage are conducive to increasing the probability of mineral coalescence.

(3) Effect of Sorbent Injection upon fly ash psd

In this task sorbents were primarily mixed with the ultrafine CWF prior to combustion in order to capture the sulfur present in the coal. It was thought that the sorbents might act as binding agents for the mineral matter inclusions present within the burning char particles. To determine the extent of this problem, a study was conducted in which fly ash samples were collected from flames of sorbent-containing CWFs and analyzed for

Table 4.4 Microprobe analysis of fly ash chemical composition

Component	Flame No. 1	Flame No. 2
	$T_{\text{fuel}} \sim 22^{\circ}\text{C}$ wt %	$T_{\text{fuel}} \sim 110^{\circ}\text{C}$ wt %
SiO ₂	47.87	44.94
Al ₂ O ₃	30.72	30.90
Fe ₂ O ₃	9.51	9.90
CaO	2.10	2.36
MgO	0.13	0.17
Na ₂ O	6.21	7.45
K ₂ O	2.13	2.45
TiO ₂	1.26	1.60
MnO ₂	N/A	N/A
P ₂ O ₅	0.04	0.19
SrO	N/A	N/A
BaO	0.02	0.02
Total	99.99	100.00

N/A - not analyzed

Figure 4.16 Effect of fuel-rich conditions on fly ash particle size distribution:

- (a) $T_{\text{fuel}} \sim 22^\circ\text{C}$
 (b) $T_{\text{fuel}} \sim 110^\circ\text{C}$

composition and particle size distribution. The two sorbents used in these experiments were calcium hydroxide particles and calcium acetate, the latter of which was atomically dispersed within the coal water fuel droplets. The Ca/s ratio, during these experiments, was varied from 0.0 to 2.10. The results so obtained are shown in Figure 4.17 (a & b).

For the atomically dispersed calcium, as the Ca/S ratio is raised the number density of the 2 μm particles droplets decreased in favor of the 7-10 μm fly ash particles. It seems that the calcium present either acts as a binding agent for the mineral matter inclusions or it adds to the individual inclusions thus increasing their size. As for the calcium hydroxide sorbent, raising the Ca/S ratio causes an increase in both the 2 μm and the 7-10 μm particles. It is thought that since the mean diameter of $\text{Ca}(\text{OH})_2$ particles is around 5 μm , the addition of such particles would increase the fraction of particles that have diameters ranging between 1 and 10 μm even if the calcium hydroxide particles do not coagulate with fly ash.

4.4.2.3 NO_x Emission

The mechanistic pathways of nitrogen oxides formation in fossil fuel combustion are shown in Figure 4.18. 'Thermal' NO is formed from molecular nitrogen (N_2) in the combustion air via the Zeldovich mechanism, which involves the following set of 3 elementary reactions:

Rates of formation of NO by this mechanism become noticeable at about 1540°C; thermal NO also increases with increasing oxygen concentration. The Zeldovich mechanism has been found to adequately model NO formation in non-

Figure 4.17(a) Effect of Molar Ca/s feed ratio on fly ash particle size distributions in three calcium acetate-containing ultrafine CWF flames

Figure 4.17(b) Effect of Molar Ca/S feed ratio on fly ash particle size distributions in three calcium hydroxide-containing ultrafine CWF flames

Figure 4.18 Formation and Reduction of Nitrogen Oxides in Combustion: Mechanistic Pathways

hydrocarbon flames and also in fuel-lean and slightly fuel-rich (fuel equivalence ratio (ϕ_b) < 1.2) flames of nitrogen-free hydrocarbon fuels.

Fuel-derived NO is formed through a more complicated pathway. In the case of the homogeneous gas phase reactions (Fig. 4.18), heterocyclic nitrogen compounds which evolve from the fuel droplet rapidly decompose to cyanogens (HCN, CN). These in turn are oxidized to oxycyanogens (NCO, HNCO) which are then converted to the ammonia species of amines (N, NH, NH₂, NH₃). In the final steps of the bound nitrogen reaction sequence, the amines follow two competing parallel routes, one in which N₂ is formed by reaction with NO and the other in which they are oxidized by O or OH to NO. There are also a number of hydrocarbon-fragment/NO reactions which can result in the reduction of the latter to N₂.

In addition to the homogeneous gas phase reactions, a number of heterogeneous processes can take place which result in the conversion of the fuel-nitrogen to NO (e.g., oxidation of the fuel-nitrogen in the unburned residue) or to N₂ (e.g., reduction of NO in the gas phase by direct reaction with carbon in the residue or by various carbon-catalyzed gas phase reactions).

Finally, there is another mechanism for NO formation, which involves the fixation of atmospheric N₂ by hydrocarbon fragments to form cyanogens. The mechanism was first proposed by Fenimore (6) when he observed high rates of NO formation in fuel-rich hydrocarbon flames, which could not be accounted for by the Zeldovich mechanism alone. Once the molecular nitrogen has been fixed through reactions 4 & 5 in the form of HCN

its fate is indistinguishable from that of the fuel-derived bound nitrogen, i.e., the subsequent bound nitrogen chemistry is the same.

It is in terms of these mechanistic pathways that the effects of the major flame input variables on NO_x emissions could be best understood.

(1) Effect of Atomization Quality upon NO_x emissions

Two series of experiments with the ultrafine and fine grind CWFs were carried out in which the atomization quality was varied. In the first of these, the atomizing air/fuel ratio (η) was varied from 0.11 to 0.25 and NO_x emission levels were monitored at the combustion exit. In the second type of experiments, the fuel temperature was raised from 20°C to 110°C and measurements of NO_x concentration were made along the flame axis and in the flue gas. The results so obtained are shown in Figures 4.19 and 4.20.

In the ultrafine CWF combustion experiments, it was observed that the adjustment of either the atomizing air/fuel ratio or the fuel temperature did not have a significant effect upon NO_x emissions. Figures 4.21 and 4.22 show that for this fuel the NO_x concentration varied only by 50 ppm. It is noteworthy that the flames studied with this fuel were highly stable. In case of the fine grind CWF, however, when a stable flame front could be sustained close to the fuel nozzle, the NO_x concentration was relatively low (~ 675 ppm). As the atomizing air/fuel ratio increased, measured NO_x emission levels rose beyond 800 ppm as illustrated in Figure 4.21. During the tests, it was observed that as the atomizing air/fuel ratio increased, the flame became highly unstable and as the value of η increased beyond 0.2 the flame front moved further downstream.

Examination of the combustion data indicates that if the aerodynamic conditions generated by the burner are capable of decelerating the fuel droplets in the vicinity of the internal recirculation zone, nitrogen

Figure 4.19 Effect of atomization quality and atomizer type on NO_x emissions

Figure 4.20 Axial profiles of NO_x concentration in flames of unpreheated ($T_{\text{fuel}} \sim 22^{\circ}\text{C}$) and preheated ($T_{\text{fuel}} \sim 110^{\circ}\text{C}$) ultrafine CWFs.

Figure 4.21 Effect of CWF ignition and flame stability as influenced by atomizing air/fuel ratio on NO_x emission for three ultrafine CWFs.

evolution would primarily take place in the fuel-rich core of the flame. However, if the droplets start their flight with an initially high momentum, they would penetrate the fuel-rich internal recirculation zone and reach the fuel-lean zone of the flame where the fuel nitrogen would mainly convert to NO_x . Therefore, to achieve low NO_x emissions, flame stability limits have to be determined first for the burner. It is within these stability limits that any additional reduction of NO_x emission from the adjustment of other variables such as the staging of the combustion could be achieved.

(2) Effect of Combustion Air Staging upon NO_x emissions

The rate of mixing of the combustion air with the ultrafine CWF spray was varied by both internal and external flame staging. In internal flame staging this was accomplished by the adjustment of both the primary/secondary air ratio and the secondary air swirl degree. In external flame staging, on the other hand, this was achieved by introducing a fraction of the total air through the burner, and the rest was injected through tertiary air supply nozzles located 1.58 m downstream of the burner.

In case of internal flame staging as shown in Figure 4.22, the swirl degree of the secondary air was seen to have a minor effect upon NO_x emission; NO_x concentrations increased approximately by 25 ppm with increasing swirl degree.

As for the primary/secondary air ratio, it was observed that as this ratio was raised from 0.22 to 0.28 the NO_x concentration increased approximately by 65 ppm (see Figure 4.23). At ratios higher than 0.28 the measured NO_x concentration did not change significantly. The results of both experiments indicate that at low secondary air swirl degrees and low primary/secondary air ratios, fuel nitrogen as it evolves from the devolatilizing coal agglomerates is converted to molecular nitrogen due to

Figure 4.22 Effect of swirl degree on NO_x emissions in ultrafine CWF flames.

Figure 4.23 Effect of internal flame staging as adjusted by primary secondary/air) ratio on NO_x emissions.

Figure 4.24 Effect of primary stage fuel equivalence ratio on NO_x emissions in ultrafine CWF flames.

the fuel-rich environment surrounding the fuel spray. As these parameters are raised, more oxygen becomes available for the fuel nitrogen in that region and hence more NO is formed. At still higher ratios it is thought that the rate of nitrogen evolution is slower than the rate of mixing of the fuel with the combustion air; hence, no changes in NO_x emissions could be observed when the primary/secondary air ratio or the swirl degree of the secondary combustion air are varied.

As for the external air staging, if fuel-rich conditions are maintained across the entire flame cross section by introducing some of the combustion air further downstream, a significant effect upon NO_x emission is observed as illustrated in Figure 4.24. As the fuel equivalence ratio (ϕ) of the primary stage increases from 0.81 to 1.40 NO_x concentration drops by 240 ppm; from 640 to 400 ppm. At $\phi = 1.65$, NO_x emission levels decrease to 348 ppm indicating that only a marginal benefit could be obtained by raising ϕ from 1.4 to 1.65. Hence, it can be concluded that the optimum equivalence ratio is between 1.2-1.4. At these conditions the fuel nitrogen evolves from the coal particles in an environment rich in hydrocarbon radicals essential to the reduction of HCN and NH₃ to N₂.

(3) Effect of Sorbent Injection upon NO_x emissions

As mentioned earlier, the introduction of the sorbent into the combustion chamber was done primarily to capture the sulfur present in the fuel. However, the effect the sulfur capturing method might have upon NO_x reduction was evaluated by monitoring the concentration of NO_x in the flue gas of the sorbent-containing CWF flames.

The results obtained are listed in Table 4.5. All of the flames investigated except for Case 7 were generated in a single stage mode of operation, i.e.: all of the combustion air was introduced through the

Table 4.5
Effect of Sorbent Type and Ca/S ratio upon NO_x Emission Levels

Flame No.	<u>Sorbents</u>		
	Sorbent	Ca/S	NO _x Concentration (ppm)
1	Ca(OH) ₂	0.52	634
2	Ca(OH) ₂	1.05	644
3	Ca(OH) ₂	1.26	680
4	Ca(OH) ₂	1.58	686
5	Ca(OH) ₂	2.10	712
6	Ca(OH) ₂	1.26	640
7	Ca(OH) ₂	1.26	405
8	Ca(C ₂ H ₃ O ₂) ₂	0.62	580
9	Ca(C ₂ H ₃ O ₂) ₂	1.24	580
10	Ca(C ₂ H ₃ O ₂) ₂	1.86	624

burner. In flame 7 only a fraction of the air was introduced through the burner; the rest was injected 1.58 m downstream. The resulting fuel equivalence ratio in the first stage was 1.57 and the overall equivalence ratio was 0.81. It can be seen from Table 4.6 that the NO_x concentrations measured in both the single- and two-stage flames are similar to those measured in the base-fuel flames. This illustrates that sulfur capture techniques do not have any effect upon the efficiency of conversion of fuel-nitrogen to N_2 . However, the reducing conditions needed for the combustion of fuel-nitrogen to N_2 might enhance the sulfur capture process as will be discussed next.

4.4.2.4. SO_x Emission

In pulverized coal or coal water fuel combustion fuel-sulfur is primarily converted to SO_2 . In contrast to NO_x , SO_x emissions are not affected by the combustion variables that influence NO_x emissions levels. Therefore, sulfur-capture agents such as calcium oxide and calcium carbonate have been used to remove the sulfur from combustion gas mixtures.

The possible Ca-S-O species which can be formed from the reaction of coal-sulfur with a calcium sorbent include CaS , CaO and CaSO_4 . The rates of formation of these species and their final yield depend on the thermodynamics of the system as well as the local flame conditions. To determine the extent to which coal-sulfur reacts to form these species, an understanding of the formation and destruction mechanisms of CaS , CaO and CaSO_4 is first required. In this study, two types of agents were introduced with the fuel to capture sulfur from within the flame envelope, a water soluble calcium acetate and insoluble calcium hydroxide particles. An in-flame scheme for the formation and destruction of these species is proposed.

In the first step of the mechanism shown in Figure 4.25 water surrounding the CWF droplet evaporates allowing particles lying next to the periphery of the droplet to heat up. Once these particles are heated up beyond their plastic temperature, they coalesce trapping Ca(OH)_2 particles or atomically dispersed calcium within the agglomerate. Upon further heating, in step 2 the temperature of the CWF agglomerate reaches devolatilization temperature. The organic sulfur present in the coal reacts to form H_2S and SO_2 vapors. As these species are released and come into contact with the solid calcium, they react with the calcium to form mainly calcium sulfide or calcium sulfate. Since the combustion conditions at the surface of the coal-agglomerate and within the particle are fuel-rich, it is thought that CaS would be the primary product at this stage (step 2). Once the devolatilization process is completed char oxidation follows. If at this stage (step 3) the combustion gas mixture within the pores structure of the char is fuel-rich, calcium sulfide would remain unreacted. However, as the char particles become highly porous due to the oxidation of the carbon matrix, CaS reacts with the readily available O_2 to form CaSO_4 . If the local temperature at this step exceeds 1460 K, calcium sulfate decomposes to CaO . However, even under such conditions the extent of conversion of CaSO_4 to CaO depends on the local turbulence intensity of the flame as well as the degree of ash coalescence. Although the mean temperature might be higher than 1460 K, the turbulence intensity causes the temperature to fluctuate above and below 1460 K thus allowing the survival of calcium sulfate particles. In addition, the reactions of CaS and CaSO_4 with the liberated mineral matter present in the reacting char lead to the formation of highly stable complex mixtures (calcium alumina silicates) thus enhancing the

Figure 4.25 Schematic of in-flame sulfur capture processes

- (a) Using calcium hydroxide additive, and
- (b) Using calcium acetate additive

probability of survival of these sulfur compounds even under severe high temperature conditions.

At the end of the char oxidation step (step 4) only fly ash and fragmented char particles survive and leave the combustion chamber. It is thought that in this region of the furnace if the temperature is below 1460 K, the captured sulfur remains in the solid phase and therefore could be removed by electrostatic precipitators or by baghouse filters.

In the mechanism proposed, similar steps apply for both the atomically dispersed calcium and the suspended calcium particles. It should be pointed out, however, that the ion exchanged calcium is more uniformly distributed within the coal agglomerate than the calcium hydroxide particles and the retention of the sulfur in this case is expected to be more effective.

The results which show the difference between the two sorbents are plotted in Figures 4.26 and 4.27. All of the investigated flames except for the staged flame were generated by introducing all of the combustion air through the burner. In the staged flame, 2/3 of the air was fed through the burner while the rest was introduced through air nozzles located 1.58 m downstream of the burner. Therefore, the fuel equivalence ratio in the first stage, in this case, was 1.57 while the overall fuel equivalence ratio was maintained at 0.81 similar to the other flames.

It is in light of the mechanism discussed above the experimental data should be interpreted.

(1) Effect of Atomization quality upon SO_x emissions

The quality of atomization of the sorbent-containing CWF might play an important role in defining the flame envelope through which the sorbent containing particles have to pass through. However, this was beyond the objectives of this study and thus was not pursued.

EFFECT OF SORBENT IN FUEL UPON SULFUR CAPTURE

Figure 4.26 Effect of molar Ca/S feed ratio upon sulfur removal from flue gas in:

- (a) Calcium hydroxide-containing ultrafine CWF flame
- (b) Calcium acetate-containing ultrafine CWF flame

Figure 4.27 Effect of molar Ca/S feed ratio upon the sulfur content of fly ash in:

- (a) Calcium hydroxide - containing ultrafine CWF flame
- (b) Calcium acetate-containing ultrafine CWF flame

(2) Effect of Combustion air staging upon SO_x emission

It is considered that combustion air staging is beneficial to both NO_x reduction and SO_x capture. The fuel-rich conditions existing in the first stage are thought to enhance the formation of CaS whose decomposition temperature is higher than that of CaSO_4 and therefore can withstand the high flame temperatures. Since the objectives of the project was more oriented towards the burner development, a detailed investigation regarding this effect was not carried out.

(3) Effect of Sorbent Injection upon SO_x emissions

The efficiency of sulfur removal from the flue gas was determined from exit SO_2 concentrations measured for the base fuel flame and for the calcium acetate-containing and calcium hydroxide-containing CWF flames. The results shown in Figure 4.26 indicate that calcium acetate was more effective than calcium hydroxide in capturing the sulfur. At 2/1 ratio it seems that a sulfur capturing efficiency of 85% could be obtained in the former case as compared to 50% in the latter. It is thought that the ability to disperse the calcium uniformly among the coal particles results in a higher sulfur removal efficiency. It is noteworthy, that the sulfur removed from the flue gas is captured by the fly ash as can be seen in Figure 4.27. The mass fraction of sulfur in the fly ash samples collected in the calcium acetate case is much higher than that in the calcium hydroxide case. It should be pointed out that as the Ca/S ratio for the latter compound exceeds 2, the capture efficiency approaches a limit of 55 - 60%, thus reducing the Ca(OH)_2 utilization efficiency. On the other hand it was observed that when the calcium is atomically dispersed the asymptote could be at a much higher value of Ca/S ratio. These results show that calcium acetate is superior to calcium hydroxide in removing the sulfur from the combustion products gas

mixture. It is thought that the removal efficiency for this sorbent would be much higher for coals that have higher sulfur contents (i.e. coal sulfur fraction > 0.89%).

To get information regarding the mechanism of sulfur removal in the flame envelope, solids samples were collected at several axial locations in a flame which was generated burning a Ca(OH)_2 -containing CWF. In addition, SO_2 concentrations measured along the flame length and carbon burnouts determined for in-flame solids samples were compared with those measured in a base CWF generated flame. The mass percentage of sulfur on a calcium free basis determined for the flame solids samples and its axial profiles for the base case as well as for the sorbent-containing fuel flame are shown in Figure 4-28. The results show that sulfur is captured easily in the fuel-rich flame core. Although the mass fraction of sulfur in the solids samples increases, SO_2 concentrations along the flame axis also rise. This phenomenon could be due to the entrainment of SO_2 from the periphery lean flame zones towards the furnace axis. Moreover, it is also possible that some of the captured sulfur is released from the coal agglomerates, increasing the SO_2 concentration on the axis.

Figure 4.28 Sulfur content of flame solids samples and SO_2 concentration along the furnace axis in flames of:

- (a) Ultrafine CWF, $T_F = 111^\circ\text{C}$
- (b) Calcium hydroxide-containing ultrafine CWF.

Section 5

5.0 CWF Flame Structure Studies

After the completion of the parametric study with coal water fuel, a flame characterization study was carried out by means of measurements of temperature, gas velocity, gas composition, carbon burnout levels and particle size distribution in two coal water fuel flames. The only parameter varied in the two flames was the fuel preheating level, i.e., in one case (Flame No. 1) the fuel temperature in the atomizer was maintained at 22°C while in the second flame (flame No. 2) the fuel was preheated to 116°C just before injection into the furnace. The input conditions maintained in these experiments are given in Table 5.1. In conjunction with this flame study using the spray rig test facility, the spray size distribution was determined under conditions similar to those maintained in the atomizer during the combustion tests, and the results so obtained are presented in the following section.

5.1 Atomization Tests

To evaluate if the atomization quality varied with fuel heating, spray droplet size distribution measurements were carried out in cold flow with the Malvern Particle Sizer (MPS). Because of multiple scattering effects, some effort was needed to find a reliable interpretation for the results.

To get a general idea of the shape of the distribution, all measurements were first analyzed with the MPS model independent technique. As the effects of multiple scattering can not be corrected when this technique is used, the distributions were expected to appear finer (smaller mean size) and broader (larger spread of sizes) than they actually were (Felton et. al. (6)). Nevertheless, it was believed that the overall shape of the distribution would not be seriously distorted.

Table 5.1
A list of Input Combustion Conditions maintained in the Flame Characterization Experiments

Thermal Input	Fuel Nozzle	Atomizing Air/ Fuel Ratio	Mass Fraction of Coal in Fuel	Fuel Temp °C	Primary/Secondary Air Ratio	Primary Stage Fuel Fuel Equivalence	Overall Excess Air Level %	Secondary Air Swirl Setting
(1) 1.55	C.E.	0.25	0.60	22	0.30	0.81	22.6	0
(2) 1.54	C.E.	0.22	0.60	116	0.30	0.82	22.6	0

Distributions obtained with the model independent technique were found always to be unimodal, and the log-normal distribution function fit the results reasonably well. The Rosin-Rammler distribution function was found to be less useful; the best-fit Rosin-Rammler distribution always underestimated the fraction of large droplets in the spray. This observation is somewhat surprising, since the Rosin-Rammler distribution function has been widely used in spray studies. However, a similar conclusion was reached by Meyer and Chigier (7) in their study of coal water fuel sprays. It can be speculated, that the Rosin-Rammler distribution function is perhaps more appropriate when low viscosity liquids are sprayed and good atomization is easily achieved, than when high viscosity slurries are sprayed and poorer atomization is expected.

As the droplet size distributions seemed to obey the log-normal distribution function, the measurements were reanalyzed with the MPS log-normal model, and the equations of Felton et. al. (8) were used to calculate corrections for multiple scattering. These results probably give the best quantitative basis for comparisons of spray droplet sizes under different atomization conditions.

Spray droplet size distributions at two different fuel temperatures obtained with the MPS model independent technique are shown in Fig. 5.1. The MPS log-normal analysis with multiple scattering corrections resulted in a volume mean diameter of 40.7 microns for fuel temperature of 22°C and volume mean diameter of 36.3 microns for fuel temperature of 116°C. In both cases, the logarithmic standard deviation of the distribution was found to be 2.0. Fuel heating thus clearly improved atomization, and corresponding improvements in flame quality are to be expected.

Figure 5.1 Droplet size distributions in the fuel spray as measured at the Spray Test Facility. The ordinate represents the volume-based probability density and the abscissa represents the logarithm of the particle diameter.

5.2 In-Flame measurements

Data obtained in the experiments show that the flow pattern is similar in the two flames. Profiles of axial gas velocity along the furnace centerline are shown in Fig. 5.2. Velocities were very similar in both flames, and the velocity decay could be described with the equations for a fully developed turbulent jet (Beér & Chigier (9)). Radial profiles of axial gas velocity at different axial locations are shown in Fig. 5.3. The decay of the jet and the development of a flat velocity profile can be clearly seen. Velocity profiles show no indication of an internal recirculation zone of combustion products back to the incoming fuel jet; external recirculation zones existed, however, in the corners of the furnace: i.e., in the region which surrounds the air jet.

Although the flow field was the same in both flames, the preheating of the CWF was observed to improve flame stability and combustion efficiency. Figures 5.4 and 5.5 show the O_2 , CO_2 , carbon burnout and gas temperature profiles along the axis of the two flames which only differed in the level of fuel preheat. As the fuel temperature increases from $20^\circ C$ to $111^\circ C$ significant improvement in carbon burnout was observed. The improved carbon burnout with increasing temperature is also reflected by the axial profiles of gas temperatures, O_2 and CO_2 concentrations. The earlier ignition for the case of the highly preheated fuel ($111^\circ C$) results in a faster rise of the gas temperature and CO_2 concentration and a faster oxidation of the coal agglomerates present on the furnace axis as compared to the case of no fuel preheat ($20^\circ C$). Further downstream from the nozzle the gas temperature decreased more rapidly in the preheated-fuel flame case, reflecting perhaps more effective heat transfer from the flame to the furnace walls; no measurements of radiative heat transfer were made, and the explanation

Figure 5.2 Gas velocity profiles along the furnace centerline in flames HEACC 1 (fuel temperature 20°C) and HEACC 2 (fuel temperature 110°C)

Figure 5.3 Radial profiles of gas velocity in the furnace in flames HEACC 1 (fuel temperature 20°C) and HEACC 2 (fuel temperature 110°C).

Figure 5.4(a) Oxygen concentration profiles along the furnace centerline in flames HEACC 1 (fuel temperature 20°C) and HEACC 2 (fuel temperature 110°C).

Figure 5.4(b) Carbon dioxide concentration profiles along the furnace centerline in flame HEACC 1 (fuel temperature 20°C) and HEACC 20°C) and HEACC 2 (fuel temperature 110°C).

Figure 5.4(c) Carbon burnout profiles along the furnace centerline in flames HEACC 1 (fuel temperature 20°C), (A/f) ratio 0.25) and HEACC 2 (fuel temperature 110°C, (a/f) ratio 0.22).

Figure 5.5 Gas temperature profiles along the furnace centerline in flames HEACC 1 (fuel temperature 20°C) and HEACC 2 (fuel temperature 110°C).

remains speculative. From these results, it can be concluded that shorter residence times are required for complete combustion of superheated ($T > 100^{\circ}\text{C}$) coal water fuels.

A close examination of the radial flame properties will bring to mind the structure of the flame. Viewing the gas composition profiles in the two flames, the O_2 concentration in the center of the jet, at axial positions very close to the burner where combustion has not yet ensued, is seen to be high and the concentration of the products of combustion low. Traversing the flame in the highly luminous region (e.g. .80 m from the burner) the O_2 is depleted in the center due to the intense combustion. In this fuel-rich combustion zone, CO concentrations are relatively high and NO_x concentrations low, as would be expected. Moving radially outward the stable species concentrations again approach their tail-end values. The carbon burnout profiles show the regions where the unburnt fuel concentration is highest (centerline, near the burner) and where the major proportion of it is burnt away (away from the centerline and/or downstream of the burner at distances > 1 m). Beyond about 1 m from the burner the radial gradients in the jet become negligible and the flow field enters a plug flow regime.

5.3 Flame Samples: Char particle size distributions

Scanning electron microscope photographs of char particles collected from the furnace are shown in Fig. 5.6. Many of the char particles were observed to be much larger than the coal particles in the fuel, indicating that the individual coal particles inside each droplet agglomerated during the devolatilization stage and formed single large char particles.

The evolution of char size distributions along the furnace centerline is shown in Fig. 5.7 for both flames, i.e. for the flames in which the fuel

Figure 5.6 SEM Photographs of char particles collected from flame HEACC 1.

Figure 5.7 The evolution of char size distribution at different axial locations along the furnace centerline in flames HEACC 1 (fuel temperature 20°C) and HEACC 2 (fuel temperature 110°C).

temperature was 20°C and 110°C, respectively. In both flames, char size distributions are initially unimodal (0.99 m axial distance), but become bimodal at locations further downstream. The transformation of a unimodal size distribution into a bimodal one can not be explained with simple combustion of particles, and may be a consequence of fragmentation of char particles during combustion.

To find the relationship between the droplet size distribution in the CWF spray and the initial size distribution of char particles in the flame, a log-normal distribution function was fitted on the char size distributions at an axial distance of 0.99 m. Very good log-normal fit with a mean of 54 microns and a standard deviation of 2.2 was observed for the char particle size distribution from flame No. 1. For the char size distribution from flame No. 2, log-normal fit was less good; best fit was obtained with a mean of 40 microns and a standard deviation of 2.2.

The mean diameters and standard deviations of the char size distributions at 0.99 m axial distance were in both flames higher than the mean diameters and standard deviations of the CWF droplets in the fuel sprays. The difference may be due partly to particle swelling in the flame, partly to turbulent diffusion of particles radially away from the furnace centerline which is more efficient for small particles, and partly to combustion which most rapidly destroys the smallest particles. Based on single droplet studies we may assume that each char particle has a 10 % larger diameter than the original droplet; thus we would expect to see a char distribution with a mean of 41 microns for flame No. 1 and a char distribution with a mean of 37 microns for flame No. 2. The remaining discrepancy is probably due to turbulent diffusion and combustion.

In some studies it has been found that the aerodynamic forces on fuel droplets tend to produce sprays in which small droplets are concentrated in the region near the spray axis, and large droplets are concentrated in the region in the perimeter of the spray (Breña de la Rosa et. al. (10)). If this is the case, we expect to find finer char particles on the furnace axis, and large char particles at increasing radial distances. No evidence for such segregation was found in this study. The char particle size distributions in flame No. 1 at an axial distance of 1.29 m and at different radial locations are shown in Fig. 5.8 and can be seen to be very similar to each other.

From the flame structure study we may conclude that CWF heating above 100°C would be of significant value in aiding combustion efficiency and flame stability in short residence applications.

Figure 5.8 Radial profile of char size distribution at an axial distance of 1.29 m in flame HEACC 1 (fuel temperature 20°C).

Section 6

6.0 Mathematical Modeling of Coal Char Combustion and Fragmentation

6.1 Modeling of Char Combustion

Using the formalism of Field et al. (11), the reaction between char (carbon) and oxygen can be written as:

where the reaction factor $\gamma = 1$ if the reaction product is pure CO_2 and $\gamma = 2$ if the reaction product is pure CO . Reverse reaction needs not to be considered at typical combustion temperatures (Walker et al. (12)); reactions of char with other gaseous species in the furnace (such as CO_2 and H_2O) are slow and can be ignored (Field et al. (11), Laurendeau (13)).

The reaction factor γ increases with temperature, and at typical combustion temperatures we may assume that $\gamma = 2$ (Walker et al. (11), Field et al. (11), Laurendeau (13), Smith (14)).

The combustion of char can be divided into the following five steps:

- 1) diffusion of oxygen from the bulk gas to the surface of the particle across the boundary layer surrounding the particle;
- 2) diffusion of oxygen through the porous structure of the particle;
- 3) reaction of oxygen with char at the solid surfaces of the particle;
- 4) diffusion of reaction product (CO) through the porous structure of the particle; and
- 5) diffusion of reaction product from the particle surface to bulk gas across the boundary layer surrounding the particle.

All five steps are sequential and have their own characteristic times; the step with the longest characteristic time will determine the carbon oxidation rate. It is commonly assumed, that steps 4 and 5 are fast

compared with the first three steps. Depending on the magnitudes of the characteristic times for boundary layer diffusion of oxygen (τ_D), for pore diffusion of oxygen (τ_p), and for chemical reaction (τ_c), different combustion regimes can be distinguished (Walker et al. (16), Laurendeau (17)). Two cases will be considered in this study:

- a) $\tau_D \gg \tau_c$, $\tau_p \gg \tau_c$. The reaction is so rapid, that all oxygen will be consumed at the external surface of the particle; the particle burns with constant porosity and decreasing size. Combustion rate is only controlled by the diffusion rate of oxygen through the boundary layer. This type of combustion is usually called zone II combustion.
- b) $\tau_D \sim \tau_c$, $\tau_p \gg \tau_c$. The reaction is fast compared with the pore diffusion of oxygen, but of comparable speed with the boundary layer diffusion of oxygen. The reaction takes place in a thin layer near the particle surface, and the particle burns with decreasing size and almost constant porosity. Boundary layer diffusion and chemical rate are of equal importance in the control of the combustion rate. This type of combustion is usually called zone III combustion.

The molar flux of oxygen through the boundary layer is

$$j = h_D (C_b - C_s) \quad (6.2)$$

where h_D is the mass transfer coefficient, C_b is the oxygen concentration in the bulk gas, and C_s is the oxygen concentration at the external surface of the particle. For zone III combustion, we have $C_s = 0$ and eqn. (6.2) becomes:

$$j = h_D C_b \quad (6.3)$$

Mass transfer coefficient can be solved from the correlation for Sherwood number (Laurendeau (13)):

$$Sh = \frac{h_D x}{D_A} = 2 (1 + 0.3 Re^{1/2} Sc^{1/3}) \quad (6.4)$$

where x is particle diameter and D_A is the bulk diffusivity of oxygen. For small particles in furnace atmosphere, Reynolds number $Re \ll 1$ and Schmidt number $Sc \sim 1$. Thus, we can solve (6.4) to obtain

$$h_D = \frac{2D_A}{x} = \frac{D_A}{R} \quad (6.5)$$

where R is particle radius.

Substituting into eqn. (6.3) gives

$$j = \frac{D_A C_b}{R} \quad (6.6)$$

The rate expression for char consumption (kg char/m² sec) is

$$q = \gamma M_c j = \frac{\gamma M_c D_A C_b}{R} \quad (6.7)$$

and the mass loss from a particle is

$$Q = -q A_p = - \frac{\gamma M_c D_A C_b}{R} \cdot 4 \pi R^2 \quad (6.8)$$

For a spherical particle which burns with decreasing diameter and constant porosity, we may write

$$Q = \frac{dm}{dt} = \rho (1-\epsilon) \frac{dV}{dt} = \rho (1-\epsilon) 4 \pi R^2 \frac{dR}{dt} \quad (6.9)$$

where ρ is the true density of the material and ϵ is the porosity. Setting eqns. (6.8) and (6.9) equal, we obtain

$$\frac{dR}{dt} = - \frac{\gamma M_c D_A C_b}{\rho (1-\epsilon)} \cdot \frac{1}{R} \quad (6.10)$$

Eqn. (6.11) can be easily integrated if we assume constant γ , D_A , C_b , and ϵ .

The result is

$$R^2 = R_o^2 - \frac{2\gamma M_c D_A C_b}{\rho(1-\epsilon)} t \quad (6.11)$$

Eqn. (5.34) is one of the alternative forms of the well-known "diameter squared" law. In this study, however, eqn. (6.10) will be solved numerically to allow changes in D_A and C_b and to allow the addition of fragmentation effects. Approximating $(\frac{dR}{dt})$ of eqn. (6.10) as a delta function gives

$$\Delta R = - \frac{\gamma M_c D_A C_b}{\rho(1-\epsilon)} \cdot \frac{1}{R} \Delta t \quad (6.12)$$

The dependence of bulk diffusivity of oxygen on temperature can be expressed as (Laurendeau (17)):

$$D_A = D_o \left(\frac{T}{T_o} \right)^{1.75} \quad (6.13)$$

where T_o is standard temperature (298°K) and D_o is diffusivity of oxygen in air at standard temperature ($0.206 \cdot 10^{-4} \text{ m}^2/\text{sec}$).

Oxygen concentration can be solved from the ideal gas law:

$$C_b = \frac{Xp}{R_g T} \quad (6.14)$$

where X is the mole fraction of oxygen, p is the absolute pressure in the furnace (100 kPa), R_g is the gas constant (8.314 kJ/kmol°K), and T is the absolute temperature.

Constant values are assumed for the remaining variables in eqn. (6.12): reaction factor $\gamma = 2$, molecular weight of carbon $M_c = 12 \text{ kg/kmol}$, char true density $\rho = 1400 \text{ kg/m}^3$, and char porosity $\epsilon = 0.7$. Char porosity was not measured, but can be estimated if we assume that each char particle has a diameter which is 10% larger than the diameter of the original droplet due to swelling, and if we assume that the true (void-free) volume of solid material equals the volume of the fixed carbon in the original droplet.

Eqns. (6.12) - (6.14) and measurements of gas temperature and gas composition inside the furnace can now be used to calculate changes in the sizes of char particles with time under zone III combustion.

For zone II combustion, we have $C_s > 0$ (finite oxygen concentration at the particle surface). Char consumption can then be described in terms of chemical rate expression:

$$q = kC_s = Ae^{-E/R_g T_p} C_s \quad (6.15)$$

where k is the rate coefficient, A is the frequency factor, E is the activation energy, and T_p is the temperature of the particle. The reaction is assumed to be of first order in oxygen, which is a good approximation at temperatures above 1500°K (Laurendeau (13)).

The mass loss from a particle can now be written as

$$\dot{Q} = -q A_p = kC_s \cdot 4\pi R^2 \quad (6.16)$$

It is assumed here that the mass loss can be correlated with the external surface area of the particle. Theoretical analysis of char combustion under zone II conditions (Laurendeau (13)) justifies this assumption, and it has also been successfully used to explain experimental observations (Field et. al. (11), Cooper (15), Wells et. al. (16)).

The surface concentration of oxygen can be solved by matching the chemical reaction rate with the oxygen diffusion rate:

$$\begin{aligned} kC_s &= \gamma M_c j = \gamma M_c h_D (C_b - C_s) \\ &= \frac{\gamma M_c D_A}{R_g} (C_b - C_s) \end{aligned} \quad (6.17)$$

Solving C_s from eqn. (6.17) gives

$$C_s = \frac{1}{1 + \frac{kR_g}{\gamma M_c D_A}} C_b = \frac{1}{1 + Da} C_b \quad (6.18)$$

The dimensionless group $Da = kR_g/\gamma M_c D_A$ gives the ratio of the characteristic diffusion time to the characteristic chemical time, and is called the Damköhler number. When $Da \gg 1$, diffusion is slow compared with chemical reaction and $C_s \sim 0$; when $Da \ll 1$, diffusion is fast compared with chemical reaction and $C_s \sim C_b$.

* R_g is the gas constant (8.314 kJ/kmol K),

The value for C_s from eqn. (6.18) can now be substituted into eqn. (6.16) to solve for the mass loss from a char particle:

$$\dot{Q} = -kC_b \cdot \frac{1}{1 + Da} \cdot 4\pi R^2 \quad (6.19)$$

For a particle burning with constant porosity and decreasing diameter, we can use eqn. (6.9) to obtain:

$$\frac{dR}{dt} = -\frac{kC_b}{\rho(1-\epsilon)} \cdot \frac{1}{1 + Da} \quad (6.20)$$

or, after discretization:

$$\Delta R = -\frac{kC_b}{\rho(1-\epsilon)} \cdot \frac{1}{1 + Da} \cdot \Delta t \quad (6.21)$$

To calculate the rate coefficient k , the kinetic parameters given by Field et. al. (11) were used: an activation energy $E = 35.7$ kcal/mol = 149400 kJ/kmol and a frequency factor $A = 8710$ g/cm² sec atm = 862 kg/m² sec kPa. As oxygen concentration rather than partial pressure was used, the frequency factor had to be modified to

$$A'' = AR_g T = A' T \quad (6.22)$$

where R_g = gas constant = 8.314 kJ/kmolK and T is the gas temperature. Hence, $A' = AR_g = 7170$ kg/m² secK (kmol/m³) and

$$k = A' T_e^{-E/R} \exp\left(\frac{T_p}{T_g}\right) \quad (6.23)$$

The particle temperature T_p could be solved using the energy balance between heat generation within the particle due to chemical reaction and heat losses from the particle due to convection and radiation. Calculations by Field et. al. (11) and experimental observations by Pourkashanian and Williams (16) and by Murdoch et. al (18, 19) suggest that the temperature diffusion between the particle and the surrounding gas may be several hundred degrees K. However, to avoid the computational work and uncertainties associated with energy balance calculations, the particle temperatures will be assumed equal to the gas temperature. Similar approach was successfully used by Srinivasachar (20) in modeling of char combustion in coal-water fuel flames and by Walsh et. al (21) in modeling of char combustion in heavy fuel oil flames.

Equations (6.14), (6.21) and (6.23) can now be used to calculate changes in the sizes of char particles with time under zone II combustion.

To study the combustion of a distribution of char particles with different sizes, four computer programs were developed using an IBM XT compatible microcomputer and Turbo Pascal programming language. Two programs were used to calculate char burning under zone III conditions, and the remaining two were used to calculate char burning under zone II conditions. Two programs were needed for each case, because two different scenarios for char fragmentation were included in the programs.

The programs were developed to calculate the combustion of char particles as they travel along the furnace centerline. No slip between the gas and the particles is assumed. In principle, the programs could be used to calculate char burning at any part of the furnace, but slight

modifications would be necessary to take into account different gas velocities, temperatures, and oxygen concentrations.

The starting point for the calculations was chosen to be at a distance of 0.99 m from the fuel nozzle. At this distance, carbon burnout is already fairly high (63.5% for flame No. 1 and 80.2% for flame No. 2), and devolatilization effects need not be considered. The initial size distribution of the particles was assumed to be log-normal, and the parameters $\bar{x}$ and σ were selected to provide best fit to experimentally determined size distributions.

The calculations were carried out in 61 discrete size classes. The boundaries of each size bin were not fixed, but changed as the particles burned. In the initial distribution, size class 0 was used to describe the volume fraction of particles with diameters between 0 and $\bar{x}/\sigma^3$, and size classes 1-60 were used at geometrical spacing to describe the volume fractions of particles with diameters from $\bar{x}/\sigma^3$ to $\bar{x}\sigma^3$. Particles with diameters larger than $\bar{x}\sigma^3$ were ignored in calculations; in a log-normal distribution they only form 0.13 % of the total volume of particles.

6.2 Modeling of Char Fragmentation

In an earlier study by Srinivasachar (20), char fragmentation calculations were based on a detailed analysis of the changes in the physical structure of the particles. In this study, a simplified approach will be used to save computation time. Two semi-empirical equations will be used to describe fragmentation processes; one equation to give the fragmentation rate of the particles, and one equation to give the size distribution of the fragments.

As the char burning calculations will be performed using a number of discrete size bins, a discrete expression has to be developed for the fragmentation rate. We are looking for an expression of the type

$$\Delta V_i = f(x_i, t, \dots) \quad (6.24)$$

where ΔV_i is the volume lost in bin i due to fragmentation, x_i is the average diameter of particles in bin i , and t is time. We can assume that the fragmentation rate of particles is also affected by other variables, such as conversion, porosity, temperature, etc., but those variables will not be considered here.

When short time intervals are considered, eqn. (6.24) can be linearized to give

$$\Delta V_i = g(x_i) \Delta t \quad (6.25)$$

Dunn-Rankin and Kerstein (22) have suggested the following functional form for $g(x_i)$:

$$g(x_i) = k x_i^\alpha \quad (6.26)$$

where fragmentation coefficient k and fragmentation exponent α are adjustable and can be chosen to fit the experimental results. Eqn. (6.26) was used in this study, so that the volume lost from bin i during time interval Δt due to fragmentation can be expressed as

$$\Delta V_i = k x_i^\alpha \Delta t \quad (6.27)$$

When volume ΔV_i is lost from bin i due to fragmentation, an equal volume has to be added to bins $0 \dots i-1$ to fulfill mass conservation law. Several different ways to distribute the volume between different size bins have been suggested. Srinivasachar, et al., (23) assumed in his calculations that all fragments are very small and burn very rapidly. The generation of small, rapidly disappearing particles will increase the

burning rate of char, but is not likely to change char size distribution very much. This assumption will therefore not be considered.

Based on their calculations on the percolative fragmentation of char particles, Dunn-Rankin and Kerstein (22) suggested that the size distribution of the fragments obeys a power-law distribution function which is given in eqn. (6.28).

$$v(x) = c \ln \left(\frac{x}{x_{\min}} \right) \quad (6.28)$$

Therefore in the first fragmentation scenario, a power-law distribution function is used to calculate the size distribution of the fragments.

Sundback et al. (24) found that coal particles fragmented during devolatilization stage of fluidized bed combustion, and that the size distribution of the fragments was log-normal with a mean of 43 % of the diameter of the original particles. Lawn et. al. (25) studied char combustion in heavy fuel oil flames and show that the size distribution of char fragments has some resemblance to log-normal size distribution. Consequently, in the second fragmentation scenario, a log-normal distribution function was used to calculate the size distribution of the fragments.

6.3 Comparison of theory and measured data

The combustion of char particles without any fragmentation was calculated first, and the results are shown in Fig. 6.1. The two plots in the top row show the log-normal distribution function fit to the measured char particle size distribution at a distance of 0.99 m from the burner nozzle. In the plots in the middle and bottom rows, the calculated size distributions are compared with the experimentally measured distributions at 1.29 m and at 1.90 m.

In the plots in the middle and bottom rows, the solid lines correspond to combustion calculations in zone II; (both boundary layer diffusion and chemical kinetics are assumed to be important), and the dashed lines correspond to combustion calculations in zone III (only boundary layer diffusion is assumed to be rate-controlling). The graphs are normalized in such a way that at the starting point of the calculations (0.99 m axial distance), the area under each curve equals unity. At subsequent axial locations, the area under each curve equals unburned char at that location divided by unburned char at 0.99 m; for the experimental curves, the calculations were performed using ash as tracer, and for the theoretical curves, the remaining unburned char was directly related to calculated changes in char volume.

In Fig. 6.1, it can be seen that the distribution preserves its shape during combustion, and that, as expected, the smallest particles burn most rapidly. For particles with diameters above 200 μm , the combustion rate is mainly controlled by boundary layer diffusion, and zone II and zone III calculations give similar results. For smaller particles, zone III calculations predict fast burnout. The calculated char burnout (average values for complete distributions) are given in Table 6.1; when compared with experimentally determined burnout values, zone III calculations predict faster initial burnout when a large number of small particles are still present, but the burnout rate later slows down because only large particles remain during the oxidation process. Zone II calculations predict that the carbon burnout rates are very slow throughout the entire range of axial distances.

Because the predicted carbon burnout of the larger particles appeared to be low, it was assumed that fragmentation of char particles increased the

Figure 6.1 Comparison between calculated and measured char particle size distributions. No fragmentation of char assumed in calculations.

Table 6.1: Comparison of experimentally observed and calculated char burnout values

	<u>Char burnout (%)</u>			
	HEACC 1		HEACC 2	
	1.29 m	1.90 m	1.29 m	1.90 m
<u>Experimental values</u>	73.6	90.2	85.1	94.1
<u>Zone III calculations:</u>				
No fragmentation	79.8	90.3	91.2	96.5
Scenario 1, $\alpha = 0.0$	83.5	97.7	92.9	99.2
Scenario 1, $\alpha = 0.5$	82.7	97.3	92.6	99.2
Scenario 2, $\alpha = 0.0$	81.7	97.2	91.9	98.9
Scenario 2, $\alpha = 0.5$	81.6	96.9	92.0	99.0
<u>Zone II calculations:</u>				
No fragmentation	67.4	74.2	83.2	87.7
Scenario 1, $\alpha = 0.0$	69.7	90.1	84.7	95.8
Scenario 1, $\alpha = 0.5$	68.9	85.6	84.1	93.8
Scenario 2, $\alpha = 0.0$	67.7	77.3	83.2	88.6
Scenario 2, $\alpha = 0.5$	67.7	77.5	83.3	89.0

char burnout rate in the furnace. Fragmentation also seemed to be a plausible explanation for the evolution of bimodal char size distributions, which could be seen at 1.90 m axial distance in both flames. Calculations were first performed with fragmentation scenario 1 (power-law distribution of fragment sizes), and different values for fragmentation coefficient k and fragmentation exponent α were tested. Calculations were found to be fairly insensitive to the particular value of α , which has also been observed by Dunn-Rankin and Kerstein (22). Results for $\alpha = 0$ and for $\alpha = 0.5$ are shown in Figs. 6.2 and 6.3. The effect of the fragmentation is to remove volume from the large particles, and to bring an equal volume to small particles. Under zone III combustion, the small particles burn very rapidly, and the shape of the distribution does not change very much from what was obtained in calculations with no fragmentation. Under zone II combustion, the small particles burn more slowly due to the finite rate of the chemical reaction, and the volume of particles with diameters below 10-20 μm is actually increasing.

Fragmentation scenario 1 was able to produce the high carbon burnout values which were observed in the experiments, but the calculated distributions was still unimodal. It was felt that fragmentation scenario 2 (log-normal distribution of fragment sizes) would be more likely to produce a bimodal char size distribution, and the calculations were repeated with the scenario 2. The best fit with experimentally determined size distributions was were obtained by assuming that the fragments had a mean of 30 μm and a standard deviation of 1.5. It is not clear, why such a mean and a standard deviation would be most appropriate, but it can be speculated that 30 μm perhaps represents the size of some kind of structural unit, of which the large char particles are formed. The results of the calculations

Figure 6.2 Comparison between calculated and measured char particle size distributions. Char fragmentation calculated according to scenario 1 with $\alpha = 0.0$.

Figure 6.3 Comparison between calculated and measured char particle size distributions. Char fragmentation calculated according to scenario 1 with $\alpha = 0.5$.

are shown in Figs. 6.4 and 6.5. The calculated size distributions now have a peak at 30 μm but are still unimodal. The calculated burnout rates are too fast for zone III combustion and too slow for zone II combustion (Table 6.1).

Several factors may contribute to the discrepancies between the calculated results and the experimental observations. The kinetic parameters of Field et. al. (10) might not be valid for this particular char; a small scale experiment to determine the reactivity of char would be useful to check the kinetic parameters. The particle temperatures were assumed equal to the gas temperature; a more realistic analysis would include energy balance calculations for each particle size class to determine the temperature difference between the particles and the gas. It was assumed that the particles travel with the gas in plug flow region along the furnace centerline; aerodynamic effects, such as the turbulent diffusion of particles radially away from the furnace centerline and the deceleration of the particles due to drag force, tend to be favorable for the survival of large particles at the furnace centerline. The equations which were used to describe particle fragmentation were not verified theoretically or experimentally; a more detailed theoretical analysis on the fragmentation mechanisms and small scale experiments on size graded char would be useful to check the validity of the approach used here. In particular, we may expect that other factors besides char particle size also affect the fragmentation rate of the particles; such factors might include temperature, oxygen concentration, and the burnout of the particles. However, it is very difficult to include any dependence on particle burnout in a model of the type used here, because particles are not traced on an individual basis. Thus, particles in any given size class will include some unfragmented

Figure 6.4 Comparison between calculated and measured char particle size distributions. Char fragmentation calculated according to scenario 2 with $\alpha = 0.0$.

Figure 6.5 Comparison between calculated and measured char particle size distributions. Char fragmentation calculated according to scenario 2 with $\alpha = 0.5$.

particles which were initially slightly larger and which already have been burned out to a considerable extent, but there is also going to be some newly formed fragments from particles which were initially significantly larger, and which have not been burned out very much because of the high boundary layer diffusion resistance of large particles. In the present model, the history of each particle will be lost, and the burnout in each size class will be difficult to follow. For the same reason, the model can not be easily adapted to calculations of mineral matter coalescence inside char particles.

From the mathematical modeling of the two flames, we may conclude that:

- (1) The model which included both boundary layer diffusion and chemical kinetics performed better.
- (2) When negligible fragmentation was assumed, both models predicted lower carbon conversions and coarser particle size distributions than were experimentally observed.
- (3) When fragmentation was included in the calculations, closer agreement with experimental results was achieved.

Section 7

7.0 Conclusions

The studies carried out under this contract have indicated that the new burner can be successfully used to burn coal water fuels. Pilot scale tests with the prototype burner illustrate that:

- o In No. 2 oil combustion tests, through burner adjustments it was possible to sensitively influence the position of the flame front, combustion length of the flame and NO_x emissions. Very low NO_x emission levels were obtainable (~ 125 ppm).
- o In the CWF combustion tests the burner proved to be capable of stable operation, with high carbon conversion efficiency ($> 99\%$) and moderate NO_x emissions without over fire air (600-700 ppm).
- o With over fire air it was possible to reduce NO_x emission levels from ~ 700 ppm to 350 ppm.
- o With addition of calcium acetate to the CWF, high in-flame sulfur capture efficiency was obtained (71% removal for $\text{Ca/S} = 1.86$).
- o With the addition of calcium hydroxide to the CWF, 50% sulfur removal was observed for a Ca/S ratio of 2.1.
- o The very high sulfur capture efficiency was a result of a combination of the sorbent-containing fuel and pyrolyzation in a fuel-rich flame zone.
- o Fuel heating in the atomization process proved to be beneficial for better flame stability and carbon burnout. The experimental studies showed that the HEACC design has a potential for becoming a high efficiency clean combustion device.
- o When the atomization quality improved as in disruptive atomization ($T_{\text{fuel}} = 116^\circ\text{C}$), the fly ash particle size distribution resembled that of the individual mineral inclusions.

Section 8

8.0 References

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Appendix

EXPERIMENTAL APPARATUS AND PROCEDURES

A.1 Combustion Research Facility (CRF)

The Combustion Research Facility, shown schematically in Figure A.1, was designed to facilitate detailed experimental investigations of industrial-type turbulent diffusion flames; it is a 10 m long combustion tunnel with 1.2 m x 1.2 m cross-section, and has a single burner with up to 3 MW thermal input and multi-fuel firing capability. The tunnel is normally configured with two chambers of square cross-section connected by a cylindrical section that can be used in an afterburner mode. The (upstream) experimental chamber is assembled from modular furnace sections, each 0.30 m wide; all sections are water-cooled, but the interior surfaces may be either bare metal or refractory-lined. For simulation of utility boiler flames the chamber walls in the vicinity of the burner are always refractory-lined, so that the radiation field in the near-burner region is equivalent to that in an individual flame within a multi-burner unit. Further downstream the mix of hot and cold wall sections can be adjusted to reproduce the desired heat extraction from the flame.

The CRF is similar in design to an International Flame Research Foundation combustion tunnel at IJmuiden, in the Netherlands. Much of the in-flame instrumentation used in the CRF, and described below, is based on designs originated at the IFRF.

A.1.1 Instrumentation and Measuring Equipment

The Suction Pyrometer

The drawing of the standard suction pyrometer used at the MIT-CRF and at IJmuiden is given in Figure A.2. The purpose of the suction pyrometer is to measure as accurately as possible the combustion gas temperature at a particular position in the flame. The suction pyrometer consists of a

Figure A.1 Furnace Assembly and Air Staging System

Figure A.2 Suction Pyrometer

platinum/platinum-10%-rhodium thermocouple protected by a fused alumina sheath, placed in a series (usually two) of concentric refractory shields. Once the probe is positioned in the flame, the combustion gases are drawn over the thermocouple and through the refractory shields by a powerful vacuum pump. The system of refractory tubes and the thermocouple are mounted onto a hollow, water-cooled shaft through which the combustion gas vacuum line and the thermocouple wire are passed. The thermocouple is connected to a potentiometer in the control room which gives a temperature read-out corresponding to the voltage differential across the thermocouple junction.

The principles behind the suction pyrometer design are discussed in detail by Chedaille and Braud (1). Basically, the design is aimed towards minimizing errors in temperature readings due to radiation interactions between the thermocouple and its surroundings (this is the purpose of the refractory shields), and to insufficient convective heat transfer from the sample gases to the thermocouple (which is the reason for implementing a rapid rate of gas suction over the thermocouple).

The Gas Sampling Probe

A drawing of the gas sampling probe and a schematic of the entire gas sampling and analysis system are given in Figures A.3 and A.4 respectively. In simplest terms, the gas sampling probe consists of a water-cooled tube to which is applied vacuum for the purpose of drawing in combustion gases for analysis of the concentrations of their constituents. The combustion gases move under vacuum through the probe and a sample transport line to a set of continuous on-line gas analyzers (for NO_x , CO, CO_2 , and O_2), as shown in Figure A.4.

One of the primary functions performed by the probe is to cool the sample combustion gases with sufficient rapidity that the constituents in

Figure A.3 Gas Sampling Probe, with Detail of Probe Tip

Figure A.4 Schematic of Gas Sampling and Analysis System

the gas are preserved in their original concentration. Combustion reactions are extremely rapid; Chedaille and Braud estimate that the gases must be cooled by the probe at least 300°C within 3 msec to obviate the effects of continuing reaction kinetics once the gas sample is drawn in.

It is also desirable that the probe disturb as little as possible the flow field of the jet flame. The gas sampling probe is inserted with the intake facing the direction of overall combustion gas flow, and preferably the sample is drawn into the probe at a rate equal to that of the combustion gas velocity so as not to distort the flow streamlines (isokinetic sampling).

The probe itself is constructed from stainless steel. The probe is cooled by means of high pressure (150-220 psig) cooling water, and is mounted into a heavier, hollow, water-cooled shaft through which water-cooled lines and gas sample line are passed to the top (see Figure A.3).

Impaction Tube Velocity Probe

A drawing of the impaction velocity probe is shown in Figure A.5. The probe consists simply of two open ended stainless-steel tubes which have been welded together in the manner shown in the figure. At the probe tip the tubes have been cut back to form a full angle of ~ 60°.

A device similar to this was used by the Central Testing Laboratory of the Beijing Electric Power Bureau for the measurement of flowrates of dust-laden air; it is described in the handbook prepared by the Thermal Power Engineering Research Institute (2). The probe was calibrated by comparison of its differential pressure with the axial component of the gas velocity indicated by a five hole Pitot probe in a natural gas flame. The factor correcting the velocity calculated using the pitot/static equation is 0.7; this factor was independent of gas velocity in the range 5 to 8 m/s. The uncertainty in the gas velocity is estimated to be ± 5 m/s. This

Figure A.5 Schematic of the Impaction Tube Velocity Probe.

uncertainty arises from the inability of the probe to discriminate the axial from other velocity components, and the difficulty of obtaining accurate time-averaged gas velocity using impact methods in regions of high turbulence intensity. One advantage of the probe is that due to its symmetry it does not need to be rotated to measure negative velocities. Another advantage is that the orifices are large and the tip is hot so the probe is not quickly clogged when making measurements in the fuel spray. The probe is withdrawn into the water-cooled support to protect it between measurements.

The Hollow Ellipsoidal Radiation Probe

A drawing of the ellipsoidal radiometer is given in Figure A.6. This instrument is used for measuring the radiative flux passing through an element of a plane surface. The probe has a hemispherical field of view; incoming radiation of varying incident angles passes through a small orifice (~ 2-5 mm) and is focused by the polished gold plated surfaces of an ellipsoidal cavity (see Figure A.6) onto a thermopile.

The thermopile consists of a hemispherical receiving pellet, a cylindrical portion AB, and a cooled metal mass, M, all made of stainless steel (25% nickel and 25% chromium). Constantan wires are soldered at the base of the receiving pellet and at the base of the cylindrical portion AB, as shown in Figure A.6. A thermocouple is in effect formed, which produces an electrical potential that is proportional to the amount of radiant energy received by the hemispherical pellet, provided that the temperature of the thermopile remains relatively constant and low (e.g., at room temperature). If the thermopile were to rise in temperature, radiative and convective heat losses would cause inaccuracies in the measurements. The probe and thermopile are designed so as to maintain a constant, relatively low temperature at all times.

Figure A.6 Hollow Ellipsoidal Radiation Probe with Detail of Probe Tip

Dry nitrogen is injected into the ellipsoidal cavity through a number of tiny holes for the purpose of preventing entry of combustion gases and particulates. These tend to form deposits which lower the reflectivity of the cavity surfaces, and alter the performance of the probe.

The ellipsoidal cavity and thermopile are housed in a water-cooled stainless steel shaft. The probe is calibrated by means of black body furnaces which have surfaces of known emissivity and which can be varied in temperature.

The Narrow Angle Radiation Pyrometer

A drawing of the narrow angle radiation probe is given in Figure A.7. This probe measures the intensity of the radiation received at a small surface element from a specified direction. The solid view angle of the instrument is very narrow (~ 0.02 steradians); in the case of radiation measurements at the MIT-CRF, the viewing path-length is normally on the order of 1.2 m and the diameter of the area 'seen' by the probe on the order of 20-40 mm.

The narrow angle radiation probe is used at the MIT-CRF primarily in the determination of flame emissivities by the Schmidt method. The emissivity is determined on the basis of three radiation measurements as follows:

$$\epsilon_F = 1 - \frac{R_2 - R_1}{R_3}$$

where R_1 - the radiative flux measured by viewing a cold target through the flame

R_2 - the radiative flux measured by viewing a hot target (of emissivity ~ 1) through the flame, and

R_3 - the radiative flux due to the hot target alone, as calculated from its measured temperature.

The narrow angle radiation pyrometer consists of a spherical concave mirror which focuses radiation received through the length of the sighting

Figure A.7 Narrow Angle Total Radiation Pyrometer

tube onto a thermopile. The mirror is pierced at its center to facilitate aiming of the probe at a desired radiation target. The sighting tube is purged of combustion gases which contain radiating/absorbing species by means of dry nitrogen injection. The probe is calibrated in a manner similar to the ellipsoidal probe, by means of black body furnaces.

The Particulate Sampling Probe

Drawings of the water quench, gas and solids sampling probe are shown in Figures A.8a and A.8b. Combustion gases along with particulates are drawn under vacuum through the probe and into a sampling train. A controlled flow of water is sprayed at the tip of the probe in order to quench the reactions occurring in the sample tube walls. The probe is constructed of stainless steel and is water-cooled.

The sample contains the quench water, particulates and gases. This is run through a sampling train which consists of: 1) a filter paper for collection of solids, 2) absorption traps for various constituents of interest in the combustion gases, e.g., XAD-2 (polystyrene) traps for polycyclic aromatic hydrocarbon (PAH), and 3) a water trap for retention of any organics of interest that may have been dissolved in the quench water.

The total gas drawn through the sampling train is measured with a volumetric gas flow meter so that the constituents of interest may be quantified as well as identified.

Fly Ash Sampling System

A newer addition to flame solids sampling apparatus is an ash particle size sampler. In this system, the particles are withdrawn from the flame through a sampling probe having both a water-cooled shell, and a steam heated sampling line to prevent condensation. The steam flowrate and pressure are adjusted to maintain the temperature of the gas/particle stream leaving the probe at 150°C. Particles are separated from the gas in a

Figure A.8a Water Quench Sampling Probe

Figure A.8b Detail of the Water Quench Sampling Probe Tip

cyclone followed by a cascade impactor (Pollution Control Systems, Mark III). The cyclone and cascade impactor are enclosed in an oven maintained at 160°C. The mass distribution of "free ash" is determined by weighing the different size fractions collected.

Analysis of Chemical Composition of Fly Ash Particles by Electron Microprobe

Fly ash particles are analyzed by automated image analysis using a Joel 733 Superprobe with a Tracor Northern TN5500 Minicomputer as a controller. Samples of fly ash are mixed with epoxy resin. After hardening, the sample pellet is polished and then carbon coated, ready for microprobe analyses.

The microprobe analysis consists of running the Particle Recognition and Characterization (PRC) program on the Tracor Northern computer. The Tracor Northern PRC manual provides a detailed description of the program. Fields 0.42 by 0.42 mm at 200 X magnification are set up in the software to analyze the stub from the bottom of the 1/2 inch cross sectioned pellet to the top. Complete passes across the sample are made only to insure a representative analysis.

The microprobe is operated using the backscattered electron detector which provides the best contrast between the mineral inclusions or fly ash and the carbon or epoxy. The beam is operated with a 15 KeV potential. The PRC program scans the beam across the field until a particle is found, one with higher contrast than the background. The area, perimeter, shape factor, and the minimum, maximum and average diameters for the particle are determined. After the particle is measured, the beam is placed at the centroid and energy dispersive X-ray spectrum (EDS) counts are accumulated for about 5 seconds. Total counts of 15 elements (Na, Mg, Al, Si, P, Zr, S, Cl, Ca, K, Ba, Ti, Cr, Fe, and Zn) are normalized to 100%. The information acquired by the Tracor Northern computer is sent to an IBM microcomputer where at a later date the data are processed.

A.2 Spray Test Facility

A schematic diagram of the spray test facility (STF) used to characterize CWF sprays at atmospheric pressure is shown in Figure A.9. CWF is delivered to the spray nozzle through a flowmeter (Micro Motion Model C 25) by a Moyno pump that can provide injection pressure up to 550 psig. Fuel pressure and temperature are measured at the atomizing gun entrance. Atomizing air is supplied at pressures up to 2200 psig. It passes through a pressure regulator, flow meter, and flexible stainless steel hose, to a spray nozzle. Atomizing air pressure and temperature are measured at the entrance of the fuel gun. A spray gun transporting the CWF and the atomizing air can be adjusted vertically and horizontally to permit the traversing of different segments of the conical spray by the laser beam of an optical spray analyzer.

Two sides of the 49 in. x 18 in. x 40 in. chamber are made of plexiglas for optical observation and measurement. Honeycomb sections, through which air to be entrained by the spray can pass, comprise about half the area of the other side walls. The supply of outside air is necessary to suppress the recirculation of small particles into the path of the laser beam.

Air at room temperature enters through the honeycomb sections when the exhaust fan is switched on. This entrained air flow and the atomizing air stream are separated from the fuel at the exit from the spray chamber and then flow through a filter and a flexible hose en route to the exhaust system. The used fuel is collected in a storage tank.

For the CWF heating, steam-heated lines connecting the fuel pump to the spray test facility are used to preheat the experimental CWF to the desired temperature. Each line is about 12 m long and equipped with gauges for monitoring pressures and temperatures of both steam and CWF.

Figure A.9 Schematic Diagram of Spray Test Facility

A.3 Laser Diffraction Droplet Size Analyzer

The spray test facility is equipped with a laser diffraction size analyzer (Figure A.10) for droplet size measurements. The operational principle of the laser diffraction analyzer (3) is based on the relationship between the droplet sizes along the laser beam as it traverses the spray and the radial energy distribution of light in a Fraunhofer diffraction pattern (alternate bright and dark rings). This analyzer (Type 2600 HSD), manufactured by Malvern Instruments Inc., allows a laser light source to pass light through the two plexiglas plates perpendicular to the fuel spray flow. A 31-annular-element photodetector receives the laser light diffracted by the spray droplets from the other side of the chamber. A control terminal processes the signals from the photodetector and feeds them into a minicomputer. The computer is programmed to yield the particle size distribution, in various different functional forms, such as Normal, Log Normal, Rosin-Rammler, or Model Independent.

In the experiments, a 300-mm focal length lens was used for the laser diffraction particle size measurements. This gave an observable size range between 5.8 and 564 μm . The laser light transmissivity of the spray was monitored, and measured average droplet sizes were corrected to account for multiple scattering effects in the measurement according to the empirical calibration technique developed by Dodge (4). The laser beam was aimed perpendicular to the spray centerline, at a distance of 10 in. from the nozzle tip. A laser beam guide tube (3/4 in. O.D.) was placed coaxially with the laser beam between the laser source and the center of the spray so as to reduce the path length of the laser beam crossing the spray, and hence the effects of multiple scattering.

Figure A.10 Schematic Diagram of Laser Diffraction Analyzer

A.4 Capillary Tube Viscometer

A capillary tube viscometer developed at MIT (5) was used to measure viscosities of CWF at shear rates up to 10^5 sec^{-1} . The essential feature of this device is the measurement of a frictional pressure drop associated with the laminar flow of fluid at a given rate through a long, smooth, cylindrical tube of known dimensions. Under conditions of steady, fully developed flow through a capillary tube, the shear stress at the tube wall can be expressed as

$$\tau_w = \frac{D\Delta P}{4L} \quad (1)$$

where ΔP is the pressure drop associated with the laminar flow of fluid through a tube of diameter D and length L . The shear rate at the tube wall for a steady, laminar flow of time-independent fluid can be expressed as

$$\dot{\gamma}_w = \frac{3n+1}{4n} \frac{8V}{D} \quad (2)$$

where V is the average flow velocity in the tube, and

$$n = \frac{\Delta[\ln(D\Delta P/4L)]}{\Delta[\ln(8V/D)]} \quad (3)$$

By analogy with Newtonian fluids, an apparent viscosity is defined as

$$\mu_a = \tau_w / \dot{\gamma}_w \quad (4)$$

for the corresponding shear rate.

When the measurements made on the capillary tube viscometer are converted into a logarithmic plot of $D\Delta P/4L$ versus $8V/D$, n is evaluated as the slope of the curve at a particular value of τ_w . The corresponding wall shear rate and apparent viscosity are found from Eq. (2) and Eq. (4), respectively. Eq. (3) shows that it is also possible to write

$$\tau_w = \frac{D\Delta P}{4L} = K \left(\frac{8V}{D} \right)^n \quad (5)$$

where K is the intercept at an $8V/D$ of unity on the logarithmic plot of $\Delta P/4L$ versus $8V/D$. Since Eq. (2) is based on the assumption of laminar flow in the tube, this condition can be confirmed by checking that the generalized Reynolds number is less than 2100:

$$Re_{gen} = \frac{D^n v^{2-n} \rho}{K 8^{n-1}} < 2100 \quad (6)$$

where ρ is the fluid density.

In practice, the pressure drop measured over the capillary tube can be expressed as

$$\Delta P_T = \Delta P + \Delta P_{excess} \quad (7)$$

where ΔP is the frictional pressure drop in fully developed flow and ΔP_{excess} is the excess frictional pressure drop because of entrance losses and additional friction effects. The excess frictional pressure drop should be constant when measurements of ΔP_T are made for two tubes of different lengths, L_1 and L_2 , but with the same diameter and at the same flow rate (i.e., same average velocity). Therefore, the excess frictional pressure drop can be cancelled out from Eq. (7), if the pressure drops measured with tubes of different lengths but with the same diameter and at the same flow rate are subtracted, to yield

$$\Delta P_{21} = \Delta P_{T2} - \Delta P_{T1} = (\Delta P)_2 - (\Delta P)_1$$

The values of ΔP_{21} and $L_{21} = L_2 - L_1$ can then be used in place of ΔP and L , respectively, in Eqs. (1) through (5) to determine the apparent viscosity and shear rate.

A schematic diagram of the capillary tube viscometer is presented in Figure A.11. A cylindrical pressure vessel, 2 ft long and 0.5 ft inside diameter, designed for a maximum working pressure of 2000 psia, is used to store CWF. When the cylindrical vessel is pressurized by compressed air,

Figure A.11 Schematic Diagram of Capillary Tube Viscometer

CWF in the vessel is forced to flow through a capillary tube to a Micro Motion flow meter. The applied pressure is measured by the pressure transducer and recorded together with the CWF mass flow rate on a minicomputer through an A/D converter. The capillary tubes used have an inside diameter of 1.5 mm and a length of 1.0 to 10.0 cm.

A.5 Combustion of Single CWF Droplets or Agglomerate Particles

The processes of particle agglomeration, particle rotation, and fragmentation during devolatilization and char combustion were studied in laminar flow reactors (LFRs) by two experimental procedures. In the first of these, a new CWF droplet generator was developed and was used to feed CWF droplets directly into the LFR. The droplet generator, which consists of a twin fluid atomizer and a series of skimmers to reduce the feed rate of droplets into the LFR, is capable of producing CWF droplets in the size range of 5-500 μm , and at feed rates less than 3 mg/s.

In a parallel study, solid samples were withdrawn from a CWF flame in the CRF, from stations close to the atomizing nozzle. The samples were size-graded and fed into the LFR in low particle concentrations. Their combustion history in the LFR was determined by monitoring the intensity of radiation emitted by individual particles during combustion (by two-color pyrometry) and by the use of high speed cinematography.

The experimental apparatus for CWF droplet injection will be discussed in Section A.5.1, and that for CWF agglomerate (solid sample) injection will be discussed in Section A.5.2.

A.5.1. Experimental Apparatus for CWF Droplet Injection

The experimental apparatus for CWF droplet injection, schematically shown in Figure A.12, consists of a CWF droplet generator, a laminar flow

Figure A.12 Schematic Diagram of Experimental Apparatus
(CWF Droplet Injection)

reactor, a feeding probe, a sample collection system, a fuel supply tank, a fuel waste tank, and a photographic recording system.

A wide angle CWF spray, generated from an atomizer, was discharged through a series of three cone-shaped skimmers with progressively larger openings to chop most of the CWF spray. This produced a narrow dilute stream of CWF droplets which was fed directly to the LFR. The remainder of the CWF spray was discharged to a waste fuel collecting tank. The range of the opening diameters of the first skimmer was 0.3 cm to 0.6 cm, that of the second skimmer was 0.4 cm to 0.7 cm, and that of the third skimmer was 0.5 cm to 0.8 cm. The opening sizes of the skimmers used for a particular experiment were chosen based on the desired skimmed CWF flowrate to the laminar flow reactor.

A twin-fluid, internally-mixed, single-exit atomizer was developed to generate a stream of CWF droplets in the size range of 5 to 500 μm . This atomizer was tested in the Spray Test Facility described in Section A.2.

The laminar flow reactor was manufactured by Astro Industries, Inc. (Santa Barbara, CA). Overall furnace dimensions are 25.4 cm diameter by 111.7 cm length. Two windows, 1.3 cm wide by 30.5 cm long, are located on opposite sides of the furnace and symmetrically centered about the hot zone. The windows are sealed with 0.3 cm thick quartz plates. A port is provided at the center of the hot zone in a plane perpendicular to that of the windows for a Graphite/Boronated Graphite thermocouple (Astro BGT-2). A water-cooled 5.1 cm diameter O-ring seal assembly is provided at each end of the furnace to support a quartz tube that extends the length of the furnace.

The graphite heating element is supported from two power feed-throughs at one end of the furnace. This configuration limits the furnace orientation to a length-wise vertical position. The heating element is

located between the quartz tube and the graphite radiation shield. Power for the heating element may be manually adjusted or automatically adjusted by a digital control programmer (Honeywell DCP-7700).

The signal for the programmer is produced by the Graphite/Boronated Graphite thermocouple and transformed to a compatible programmer input by a signal transmitter (Rochester Instrument Systems, Model SC-1304). The BGT-2 thermocouple has an exceptionally high output and sensitivity throughout its entire operating temperature range, providing stable long-time operation to 2250 K. All designs of this type of thermocouple have appreciable thermal mass and conduction losses along the graphite supporting elements to the water-cooled cold-junction and thus must be calibrated.

A narrow stream of CWF droplets was fed into the laminar flow reactor through a feeding probe whose inside-diameter may be varied between 0.8 cm and 2.4 cm. The feeding probe was kept cool in the combustion zone by circulating cooling water.

The water-cooled sample collection probe was connected to the bottom of the furnace. A vacuum pump pulled the exhaust gases and particles through the probe to a filter which removed the solid particles. The pressure inside the furnace (monitored by a water-column manometer) could be changed by adjusting bleed valves between the sample collection filter and the vacuum pump. The sample collection filter could be replaced by a cascade impactor to measure ash particle size distribution.

A high speed cinematographic camera (HYCAM) equipped with a microscope (HEERBRUGG MDG 13) was used for observing and recording the combustion process through the quartz window on the furnace. The microscope provided magnification of the burning CWF droplets in the range of 0.3 X to 3.7 X. A

light source was located opposite the camera to give the background light for the transmission photographic study.

A.5.2. Experimental Apparatus for CWF Agglomerate Injection

The experimental apparatus for CWF agglomerate (solid-sample) injection, schematically shown in Figure A.13, consists of a laminar flow reactor, a solid-sample feeding system, a collection system, a two-color pyrometer, and a photographic recording system. For these experiments the laminar flow reactor used was an Astro Model 1000A. The furnace has electrically heated graphite elements, the temperature of which is regulated with an automated current controller. In order to protect the graphite heating elements from the oxidizing environment, the elements are isolated from the central combustion zone by an alumina muffle tube. Due to the thermal limitation imposed by the alumina, the maximum operating furnace temperature is 1800 K. The main gas, a pre-mixed oxygen/inert gas, enters at 10^{-4} m³/s through the top of the furnace where it flows through an alumina honeycomb at the top of the hot zone, an isothermal region of 0.15m. The honeycomb serves as both a flow straightener and preheater, delivering the main gas at the specified furnace temperature with a uniform laminar velocity. The composition of the oxygen-nitrogen gas mixture is regulated by dual mass flow controllers. Size-graded CWF agglomerates are fed through a narrow water-cooled feeder tube and injected axially into the main gas stream just below the honeycomb. The CWF agglomerates are rapidly heated and combustion begins. Radial dispersion of the particles is minimized by the stable laminar flow field.

The CWF agglomerates are entrained by the inert carrier gas, which flows over the surface of an agitated coal bed and into stationary fine gauge tubing. The gas velocity in the fine gauge tubing is sufficient to keep the particles in suspension. The rate of entrainment is established by the rate

Figure A.13 Schematic Diagram of Experimental Apparatus
(CWF Agglomerate Injection)

at which a coal feed vial is driven towards the stationary fine gauge tubing by a syringe pump. A range of feeding rates from 1.7×10^{-4} grams/s to 1.7×10^{-3} grams/s is obtainable by changing the speed of the syringe pump. For a given syringe setting, a fixed clearance between the top of the coal bed and the fine gauge tube will be established after an initial transient. One to three grams of CWF agglomerates are normally fed per experiment.

All the combustion products, both gaseous and solid, are collected at a given height in the furnace by a water-cooled probe which is inserted through the bottom of the furnace. The probe position is adjustable to enable time-resolved studies. The inner core of the probe is fitted with a stainless steel porous tubing through which gas is transpired. The 1.27 cm ID porous tubing is constructed from fused five micron stainless steel spheres. In the top 2.5 cm section of the probe the combustion products are rapidly quenched, at a rate of 1.0×10^{-4} C/s, by a flow of 3.0×10^{-4} m³/s of nitrogen. A minimal inward radial gas flow of 6.6×10^{-5} m³/s of nitrogen which corresponds to a gas velocity of 3.5×10^{-3} m/s is maintained through the subsequent section of porous tubing to counter the thermophoretic velocity of the particles (e.g., 1.8×10^{-4} m/s), thereby preventing particle deposition on the inner wall of the probe.

A two-color pyrometer was used to measure the radiation from the burning particles. A lens located at the bottom of the laminar flow reactor is used to focus the radiation from the burning particles. The particles are viewed against a dark background consisting of a water-cooled collection probe. The signals are measured by individual photomultiplier tubes, after passage through filters with effective wavelengths of 450 and 550 nm and band widths of 5 and 7 nm. The system was calibrated with a tungsten strip lamp, and provides a temperature resolution of 30 K at 3500 K.

Additional information on the LFR experimental apparatus may be found in Reference 6.

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