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DEVELOPMENTS IN ATOMIZATION AND BURNER DESIGN FOR COAL-WATER MIXTURE COMBUSTION

K.V. Thambimuthu, H. Whaley and G.K. Lee
Combustion and Carbonization Research Laboratory

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DEVELOPMENTS IN ATOMIZATION AND BURNER DESIGN FOR COAL-WATER MIXTURE COMBUSTION

K.V. Thambimuthu, H.Whaley and G.K. Lee
Energy Research Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada

ABSTRACT

Experimental data from coal-water mixture (CWM) spray atomization studies have been interpreted according to a new theory for the mechanism of atomization recently proposed in the literature. Measurements of combustion aerodynamics and ignition behaviour in pilot-scale CWM flames were used to identify burner design and operating parameters critical to the flame stability and burnout. For CWM atomization in two-fluid atomizers, it is proposed that the surface tension, coal particle size distribution and the aerodynamic shear force are controlling parameters. CWM spray data correlated well with the Weber Number, and the performance of two-fluid atomizers was found to be dependent on the atomizer geometry and its operating flow regime. Burner design and operating parameters to optimize flow recirculation for convective heating, and to maximize the residence time of the spray in the Internal Recirculation Zone were found to be critical for the stable combustion of CWM. Significant process parameters include the degree of combustion air preheat and swirl, the half angle and length to diameter ratio of the burner quarl and the spray injection angle and momentum of the two-fluid atomizer. Many of the characteristics governing the atomization and combustion of CWM were found to be incompatible with the same parameters affecting oil combustion. This explains why the adaptation of oil-designed burners to CWM applications has proven to be unsatisfactory.

NOMENCLATURE

ALR	- Air liquid W_g/W_l, dimensionless
CWM	- Coal-water mixture(s), abbreviation
d_m, d_{32}	- Mass mean diameter of a droplet; Sauter or surface area mean diameter
D, D_o	- Diameter of throat in burner quarl; outlet orifice diameter in an internally-mixed atomizer, or liquid orifice diameter in an externally-mixed atomizer
ERZ	- External Recirculation Zone, abbreviation
IRZ	- Internal Recirculation Zone, abbreviation
L	- Length of a burner quarl.
P	- Supply pressure of air or steam in an atomizer
PSD	- Particle size distribution of coal, abbreviation
S	- Swirl Number or ratio of angular to axial momentum in combustion air flow
SR	- Ratio of secondary combustion and atomizing air to the stoichiometric air requirement for coal combustion
U_g	- Velocity of atomizing fluid (air or steam)
U_l	- Exit or efflux velocity of liquid or CWM in an atomizer liquid orifice
We	- Weber Number, dimensionless, equation (2)
W_g	- Atomizing medium flowrate (air or steam)
W_l	- Liquid, fuel or CWM flowrate
θ	- Half angle of divergent section of burner quarl, degrees
μ_l, μ_s	- Viscosity of a liquid; apparent viscosity of CWM
ρg, ρl	- Density of atomizing fluid (air or steam); density of liquid
σ_l	- Interfacial surface tension of a liquid

INTRODUCTION

The successful deployment of 70/30 Wt% coal-water mixtures (CWM), as a substitute for oil in industrial and utility boilers has been hampered by inefficient atomization and unstable combustion. These problems can be attributed to the ad-hoc modification of conventional oil-designed burners for CWM combustion[1]. For example, conventional oil-designed burner registers and quarls are retained, and two-fluid oil atomizers are adapted to CWM by widening fuel and atomizing medium orifices to prevent blockage and erosion by coal particles.

The above approach is contrary to atomization and combustion concepts. Firstly, the modifications undertaken on two-fluid oil atomizers violate salient design principles which require an increased surface area to volume of the liquid exposed to the atomizing fluid, and an increased aerodynamic shear force, for an improved spray quality. Coupled with improper material selection and design to prevent nozzle erosion, and a poor understanding of the CWM properties affecting atomization, there is a tendency to generate poor quality sprays. Typical CWM sprays have a high concentration of coarse droplets that subsequently burn as large aggregates of coal fines with poor carbon burn-out[2]. Secondly, there is a fundamental difference in the burning profile of the CWM relative to oil, owing to the slower reactive properties of the coal, and the CWM moisture content. These two fuel properties delay devolatilization and ignition of the fuel droplets[3]. Thus oil burners which are designed to promote near-field aerodynamic mixing patterns for more reactive fuels are unable to sustain stable combustion with CWM.

This paper describes the critical influence of fuel atomization and burner design and combustion operating parameters on the burning profile of CWM. Although the data examined are based largely on published literature, the results have been reinterpreted to clarify salient issues that were either not understood or not well defined.

MECHANISM OF CWM ATOMIZATION AND CONTROLLING FUEL PROPERTIES

The flow properties of CWM are similar to those of viscous liquids due to a high apparent fluid viscosity, μ_s. Values of μ_s in the 100-1000 mPa.s range are typical, being one to two orders of magnitude greater than the viscosity of oils and water. These high values of μ_s stem from the inter-particle collisions and surface friction between particles in relative motion, and from the resistance to motion due to particle slip relative to the aqueous phase in the CWM[1]. CWM also exhibit non-Newtonian behaviour, with dilatant and pseudoplastic properties, that are shear rate and time dependent. In view of the 'apparent liquid' properties of CWM, the accepted view in the technical literature is that CWM behave like viscous liquids in their atomization behaviour[4,5,6,7]; however, this proposed dependence remains largely unproved[1].

Due to the heterogeneous nature of CWM, it has been proposed that their atomization under the influence of the aerodynamic shear force from the atomizing fluid will likely arise from liquid separation at a solid-liquid interface, or from the breakup of the interstitial liquid layer between dispersed solids[1]. For liquid separation at a solid-liquid interface, the separation process is governed by the interfacial surface tension of the liquid, σ_1. The breakup of the liquid phase between solids, on the other hand, is a phenomenon identical to that encountered in the atomization of homogeneous liquids, and is determined by σ_1, and its viscosity, μ_1 (8). For the latter phenomenon, it is highly likely that the liquid phase viscosity, μ_1, as opposed to the apparent viscosity, μ_s, has more influence on CWM atomization.

For the proposed mechanism of atomization described above, the resistance to surface breakup is lowest at the solid-liquid interface[1]. This is due to the controlling influence of surface tension as opposed to the combined influence of the surface tension and viscous forces resisting interstitial liquid atomization. With this surface tension dominated separation process, the particle size distribution (PSD) of the coal also plays a key role in the atomization process. The appearance of a wave instability on the CWM surface will first expose the surface of the coarsest particles to frictional drag from the air blast[1]. This initially favours the separation of the CWM into coarse particles and an interstitial liquid layer of fines. This mechanistic process becomes a repetitive one, eventually promoting phase separation at finer particle nucleation sites. Atomization efficiency is also dependent on the scale of the wave disturbance created on the liquid surface relative to the particle dimensions. The aerodynamic shear force required to promote separation at finer particle nucleation sites is higher in order to facilitate the complete separation of an aggregate surface into discrete particles. Thus, the overall atomization process is governed by an instability criterion determined by the amplitude of the aerodynamically induced wave disturbance, the surface tension, and the PSD of the coal as a measure of the size and frequency of active particle nucleation sites.

In terms of the CWM properties, the apparent viscosity would appear to play an insignificant role in atomization; however inter-particle friction and resistance to flow embodied in the measured value of μ_s are dependent on the PSD and degree of wetting (determined by the surface tension) of the dispersed solids[1]. Furthermore, the flowrate of CWM through the liquid orifice in the atomizer is governed by the pressure loss in viscous flow. With the inter-dependence of the fuel and atomizing medium flowrates and pressures in internally-mixed atomizers, the atomizing medium flowrate becomes dependent on the apparent viscosity of the fuel. Thus, μ_s as a secondary dependent property, also plays a role in the overall atomization process.

PERFORMANCE OF TWO-FLUID ATOMIZERS

The spray characteristics of CWM have been evaluated in an externally atomized 'plain jet' atomizer[9] so termed because of a flow configuration involving a 'liquid jet' subjected to the aerodynamic action of an externally co-flowing air blast[8]. Figure 1 shows the effect of the Air-Liquid Ratio (ALR) and the CWM flowrate on the spray droplet diameter. The mean spray droplet diameter decreases with the ALR at a constant CWM flowrate, but becomes independent of ALR when the liquid flowrate is varied at a constant air flowrate. This behaviour is unlike the trends reported for 'plain jet' liquid atomizers which show a marked deterioration of the spray quality with an increasing liquid flowrate[8], and those found for CWM by other investigators[10]. In view of the independence of the spray quality on the liquid flowrate, CWM atomization is assumed to be mainly governed by the aerodynamic energy of the atomizing air and to be correlated by an equation of the form [9];

$$d_{32} = 8200\ P^{-0.934} \tag{1}$$

Based on the mechanism of CWM atomization described above, the spray data may be correlated by the Weber Number[1];

$$We = \frac{\rho_g\, U_g^2\, D_o}{\sigma_1} \tag{2}$$

which represents the ratio of the disrupting aerodynamic force relative to the surface tension force that opposes the disintegration of the CWM surface at the solid-liquid interface. Calculations of the air orifice exit velocities also identified two flow regimes corresponding to sub-sonic and critical sonic flow for the data[9], and two correlations corresponding to these flow regimes have been derived[1]. For sub-sonic flow the dimensionless droplet diameters are correlated by:

$$\frac{d_{32}}{D_o} = 0.82\ We^{-0.36} \tag{3}$$

and for critical sonic flow which describes the bulk of the spray data, the dimensionless droplet diameters are correlated by:

$$\frac{d_{32}}{D_o} = 93.9\ We^{-0.92} \tag{4}$$

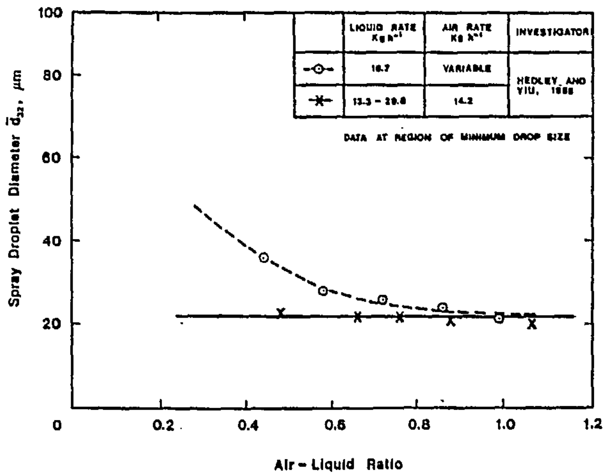

FIGURE 1

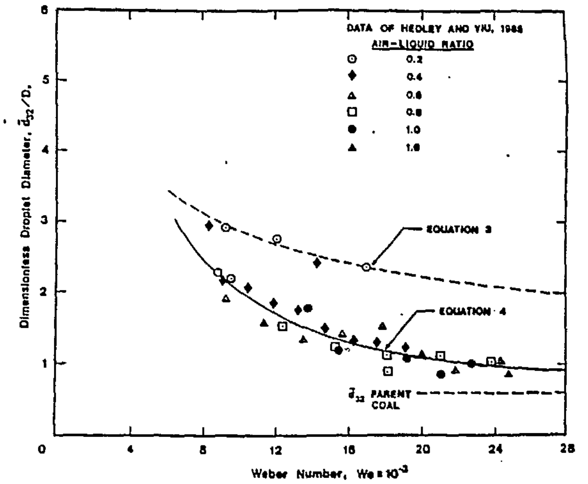

FIGURE 2

These correlations are independent of the ALR, and the dependence on the Weber Number; hence the pressure, shown by $d_{32} \propto P^{-0.92}$, for the bulk of the data represented by Eq. (4), is also virtually identical to that shown in Eq. (1).

Figure 2 shows the experimental results fitted by these correlations. For the spray data in sonic flow, the correlation shows more efficientatomization of the CWM with the spray droplet diameters approaching the mean coal particle diameter at high Weber numbers. Relative to the coarser droplets generated in subsonic flow, this behaviour appears reasonable, since the high energy, sonic shock waves from flow separation may be expected to enhance the break-up of the wave instabilities in a CWM jet with smaller amplitude vibrations at finer interfacial particle nucleation sites. Thus, the spray data are in general agreement with the proposed mechanism of CWM atomization.

For sub-sonic flow, a form similar to Eq. (3) may be derived[1] from the following correlation for a 'plan jet' liquid atomizer[11];

$$\frac{d_{32}}{D_o} = 0.877 \left[\frac{\sigma_1^{0.33}\, U_1^{0.33}}{\rho_g^{0.3}\, U_g\, D_o^{0.34}}\right]\left[1 + \frac{W_1}{W_g}\right]^{1.7} \quad (5)$$

$$+ 0.13 \left[\frac{\mu_1^2}{\sigma_1\, \rho_1\, D_o}\right]^{0.5} \left[1 + \frac{W_1}{W_g}\right]^{1.7}$$

Eliminating the redundant terms relating to the ALR and viscosity of the liquid, Eq. (5) becomes;

$$\frac{d_{32}}{D_o} = 0.877 \left[\frac{\sigma_1^{0.33}\, U_1^{0.33}}{\rho_g^{0.3}\, U_g\, D_o^{0.34}}\right] \quad (5a)$$

Eq. (5.a) with a reduced air velocity dependence of $U_g^{0.67}$ versus $U_g/U_1^{\,0.33}$ owing to a lower resistance encountered for liquid separation at the particle interface as opposed to a liquid-liquid separation becomes;

$$\frac{d_{32}}{D_o} = 0.877\ We^{-0.33} \quad (5b)$$

The atomization characteristics of CWM were evaluated in an internally-mixed turbulent chamber atomizer[12,13]. The atomization behaviour of CWM demonstrated that highest and lowest surface tension values generated the coarsest and finest sprays, respectively[12]. For CWM with identical surface tension values, a coarser grind in the particle size distribution produced finer spray droplets at comparable atomizing air flowrates[12], and these results are in agreement with the role of the PSD proposed in the CWM atomization model. Defining a Weber Number based on the droplet velocities and compressible flow conditions in the 'y-jet' mixing port upstream of the turbulent chamber enabled a correlation of the spray data for one of the lower surface tension CWM by the following expression[13];

$$\frac{d_m}{D_o} = 1.82\ We^{-0.57} \quad (6)$$

Similar to the behaviour for an externally-mixed plain jet atomizer, the droplet diameter is again independent of the ALR. For a conventional definition of the Weber Number based on the gas velocity, Eq. (2), Eq. (6) becomes[1];

$$\frac{d_m}{D_o} = 6.23\ We^{-0.57} \quad (6a)$$

The spray droplet diameters correlated by Eq. (6) also approach the mean coal particle diameter in the CWM at high Weber Numbers, and the measured pressure profiles confirm that sonic flow prevails at the nozzle exit[13]. However, unlike the independent air and liquid flowrates in externally mixed two-fluid atomizers, the inter-dependent liquid and air flowrates introduce difficulties in the correlation of the spray data based on the sonic flow conditions at the nozzle exit. If a correlation was possible, a higher proportionality constant and a Weber number exponent may be expected relative to the values shown in Eq. (6a). These differences would then be identical to the transition also noted between the sub-sonic and sonic flow correlations (Eq. 3 and 4) found for the 'plain jet' atomizer.

From photographic studies, two stages in the atomization process were identified for the turbulent chamber atomizer: initial breakup into largely coarse droplets in the 'Y-jet' upstream of the turbulent chamber and subsequent finer breakup in the turbulent chamber[13]. Fine droplets and particles with a lower inertia entrained by the gas flow escape through the exit ports, whereas coarse droplets and particles impinge on the internal surface of the turbulent chamber. These impinging slurry droplets form a thin liquid film that flows towards the exit ports, and is re-atomized at the inlet edge of the exit ports by a rapidly accelerating air flow. The improved spray quality generated from the re-atomization of the CWM in a pressure pre-filmed liquid surface in a turbulent chamber atomizer is also identical to that encountered in a pre-filming air blast liquid atomizer[1]. From a correlation proposed for the latter[8];

$$\frac{d_{32}}{D_o} = 0.073 \left[\frac{\sigma_1}{\rho_g U_g D_o}\right]^{0.6} \left(\frac{\rho_1}{\rho_g}\right)^{0.1} \left[1 + \frac{W_1}{W_g}\right] + 0.0006 \left[\frac{\mu_1^2}{\sigma_1 \rho_g D_o}\right]^{0.5} \left[1 + \frac{W_1}{W_g}\right] \quad (7)$$

Eliminating the redundant terms relating to the ALR, viscosity of the liquid and the liquid to gas density ratio, Eq. (7) becomes;

$$\frac{d_{32}}{D_o} = 0.073\ We^{-0.6} \quad (7a)$$

and this shows a dependence on the Weber Number virtually identical to that shown in Eq. (6) and (6a).

From a comparison of Eq. (3) and (5a), and Eq. (6) and (7a), the performance of two-fluid atomizers on CWM appears to be dependent on the geometry of the atomizer or more specifically the structure and orientation of the liquid surface exposed to the air flow[1,14]. A higher value of the exponent for the Weber Number shows that CWM atomization is finer in 'pre-filming' type atomizers as opposed to 'plain jet' atomizers. In the critical sonic flow regime, the nature of the wave instabilities induced by the aerodynamic energy of the atomizing fluid also affects the spray quality, with a higher value for the Weber Number exponent. Although these general trends are apparent in the spray droplet correlations, their universal application is limited, primarily due to the influence of the PSD of the coal on the atomization process. It may be assumed that the PSD among other factors[14] will influence the value of the proportionality constants in the spray droplet correlations. Intuitively, this conclusion is reasonable, because the spray quality generated cannot be finer than the PSD of the coal in the CWM.

COMBUSTION AERODYNAMICS, BURNER DESIGN AND OPERATING PARAMETERS FOR CWM COMBUSTION

In modern industrial burners, a swirling combustion air jet is used to promote fuel-air mixing and to improve the ignition stability and combustion intensity of flames. When the momentum of the fuel spray is low, the aerodynamic flow patterns established in the burner near-field mixing zone is shown schematically in Fig. 3. Flow mixing induced by the swirling air jet creates a large, torroidal vortex IRZ at the flow axis, and an ERZ at the outer jet boundary. The fuel spray from the atomizer is typically located within the IRZ, but its trajectory may also partially penetrate the IRZ with an increasing axial and radial distance downstream from the burner mouth. The IRZ at the flow axis basically recirculates hot combustion gases in closed streamlines between two flow stagnation points from the flame tip to its root. However, this flow is not totally isolated, and turbulent diffusion is intense at the flow boundary close to the swirling air jet[15]. This exchange of gas promotes mixing which affects the temperature and oxidant con-

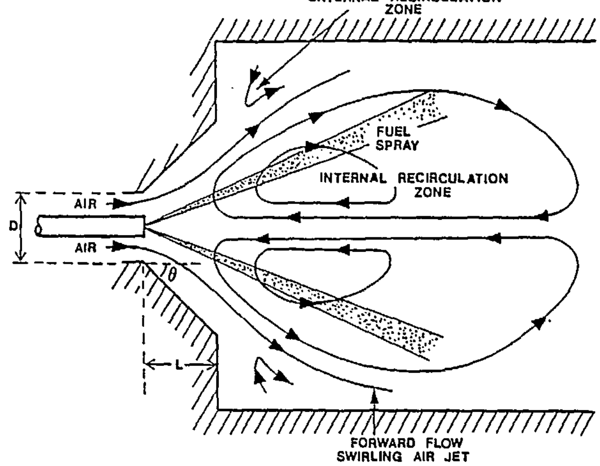

FIGURE 3

centrations in the IRZ. Over the bulk of the spray trajectory in the IRZ, the recirculating gases provide the aerodynamic drag which reduces the droplet and gas velocities of the fuel spray, the convective heat required to promote droplet evaporation and devolatilization, and the ignition energy and oxidant concentration necessary to propagate a flame front.

Problems related to flame stabilization with CWM may be overcome by an increased residence time and/or increased convective heat transfer rates for moisture evaporation and devolatilization of the spray droplets in the IRZ. These requirements in turn may be accomplished by;

(i) increasing the size and strength of flow recirculation in the IRZ,
(ii) decreasing swirl induced mixing or employing staged combustion to reduce gas dilution and to increase the recirculating gas temperature in the IRZ,
(iii) minimizing momentum penetration of the spray which affects the droplet residence times and disrupts the flow in the IRZ.

The improvement in the ignition stability of CWM flames by burner design and operating parameters is illustrated by the following examples.

In pilot-scale CWM flame trials at a 2.5 MW_{th} input carried out by the International Flame Research Foundation (IFRF) for the Canada Centre for Mineral and Energy Technology (CANMET) and the Netherlands Energy Development Corporation (NEOM), it was found that the type of two-fluid atomizer used in the burner had a significant impact on the flow patterns established in the IRZ[16]. With a single orifice 'plain jet' two-fluid atomizer, the narrow angle axial spray totally penetrated the IRZ, establishing gas mixing patterns that were external to the spray, and hence, unable to return sufficient convective heat to the bulk of the spray. The CWM flames for these conditions were generally unstable and required natural gas support. Multi-orifice, two-fluid atomizers of the Y-jet and T-jet type, in which the angular disposition of the outlet holes were varied, produced stable flames with minimal disruption of the flow patterns in the IRZ. For a diverging burner quarl with a 35° half angle, the optimum atomizer spray angle of 50° provided a trajectory that matched the flow patterns in the IRZ. For these conditions, fuel droplets initially travel through the IRZ, and later into the forward flow in the swirling combustion airjet. In this way, the heat necessary to evaporate, devolatilize and ignite the spray was provided by the recirculating gases in the IRZ. The higher oxygen availability further downstream was then able to sustain combustion.

Employing a similar burner quarl to the IFRF study but with a $1.8MW_{th}$ input, investigations on the effect of the spray angle with a conical spray, 'prefilming' type atomizer revealed that the optimum spray angle was one which maximized the initial penetration of the spray close to the IRZ flow boundary(2). Figure 4 shows the flow boundaries and the locations of the peak radial flame temperatures measured for air and steam atomized CWM flames. For most of the flame length the location of the peak radial temperatures, which corresponds to the fuel-rich zones near the spray trajectory, is also close to the IRZ boundary, and subsequently diverges with the swirling air jet and reconverges with the gas flow closer to the exit breeching from the furnace. Penetration of the spray at this location in the IRZ maximizes the residence time in the recirculating gases, and the intense turbulent mixing which promotes oxygen diffusion at the boundary facilitates flame propagation. In contrast to the behaviour of narrower angle sprays, i.e., the 'plain jet' atomizer, the spray momentum at this location has a minimal impact in modifying the extent or the induced gas flow patterns established within the IRZ. Figure 5 shows the corresponding flow patterns measured for air and steam-atomized heavy oil flames. The flow patterns for an oil burner with an identical geometry and 'pre-filming' atomizer required a spray angle that was 10° larger than that required for the CWM flames. This has been attributed to the difference in spray angles which causes greater momentum penetration and radial dispersion of coarse CWM droplets, and hence requires a smaller angle for optimum matching of the droplet trajectories with the IRZ flow boundary(1). This characteristic feature is often ignored when oil-designed burners are modified for CWM combustion.

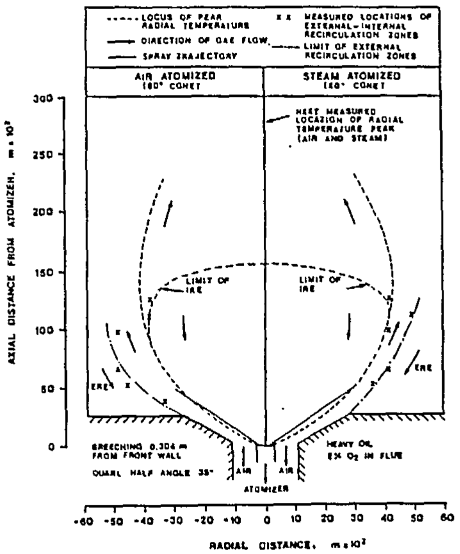

FIGURE 4

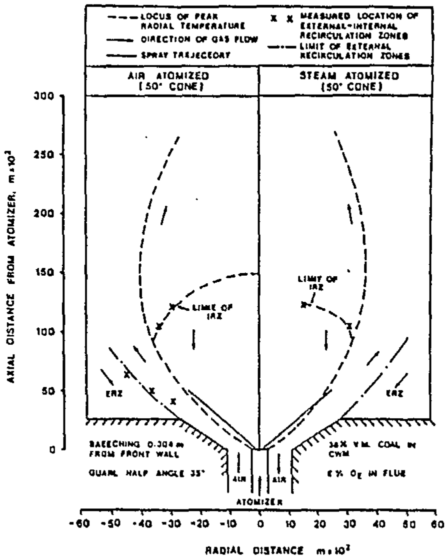

FIGURE 5

The flame trials at IFRF also evaluated the effect of burner design and operating parameters such as the L/D ratio and half angle of the divergent quarl, the swirl number and combustion air pre-heat, and staging on CWM flame stability(16). An increasing L/D ratio and half angle of the quarl increase flow recirculation and the size of the IRZ in the burner near-field mixing zone(15). Increasing swirl has the same effect on the flow induced in the IRZ. A 35° half angle was found necessary for stable combustion of CWM containing 30 wt % moisture and coals with 18-36 wt % d.a.f volatile matter compared to the 25° half angle quarl typically used to sustain stable combustion of oil or high volatile pulverized coals(16). At this optimum half angle, a long quarl (L/D = 1.1) as opposed to a shorter one (L/D = 0.7) was found to be necessary for the stable combustion of CWM made from the low-volatile coals. The promotion of ignition stability by an increasing quarl half angle and L/D ratio results from the increased residence times for droplet heating in the near-field mixing zone.

Figure 6 shows the influence of the swirl number on the radial temperatures measured in the near-field mixing zone of a CWM flame. Approximate locations of the ERZ, the swirling jet and the IRZ may be identi-

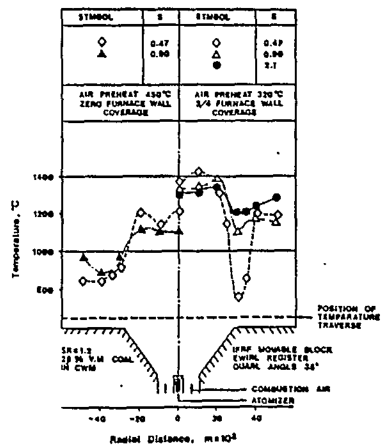

FIGURE 6

fied from the temperature profiles. The minimum temperatures correspond to the forward moving swirling air jet, and the maximum to the fuel-rich zone close to the IRZ flow boundary. For the cold wall and 3/4 refractory-lined furnace, the temperatures in the ERZ and the swirling jet increase with the swirl number while the IRZ temperatures decrease. This effect may be attributed to increased mixing between the streams due to a higher swirl in the combustion air jet. Besides the effect of an increasing swirl number in creating a larger IRZ[15], the increased mixing greatly reduces temperatures for spray heating. This may be detrimental to the flame stability. For the cold wall case at S = 0.9, where the IRZ temperatures had reached a low value of 1100°C, it was found that a further increase in the swirl number destabilizes the flame[16]. Hence, an upper limit exists for the swirl number in CWM flames beyond which they destabilize. This value is influenced by the degree of furnace heat extraction and combustion air pre-heat which also determine the temperatures established in the burner near-field mixing zone (Fig. 6). For the extreme cold wall case, operating parameters for CWM combustion can be stringent, because a minimum swirl number exists below which the axial negative pressure gradient induced by the swirling air jet will not establish an IRZ[15]. The upper limit on the swirl number will decrease with increased moisture content, a lower coal volatile content or a poorer spray. These factors introduce an ignition delay because the rate of heat generation by combustion may not be rapid enough to sustain the convective heat recirculated for droplet heating at the higher swirl number.

The effect of staged combustion by diverting some of the air admitted to the swirling air jet into the ERZ by tertiary air jets has been evaluated[16]. The effect of increased staging, increased temperatures uniformly in the ERZ, the swirling air jet, and the IRZ. However, the increased temperatures and flame stability with reduced gas dilution was off set by poorer carbon burnout due to reduced oxygen availability in the early stages of combustion. Similar to the trends shown in Fig. 6, the higher swirl numbers improved carbon burnout in staged flames by promoting mixing and by increasing the availability of oxygen in the primary combustion zone, but reduced the IRZ temperatures and the flame stability.

In view of the trade-off between flame stability and carbon conversion efficiencies, staging only marginally improved the overall performance. A review of the operating characteristics of swirl burners, particularly pulverized coal burners, showed that increased quarl dimensions such as a larger half angle or L/D ratio play a more effective role in increasing the size of the IRZ while maintaining high gas temperatures[1]. This occurs because the increased dimensions of the quarl are accompanied by lower rates of mixing between streams in the near-field mixing zone, compared to those attained when the swirl number is increased.

SUMMARY

1. The atomization characteristics of two-fluid CWM atomizers show no dependence on the apparent viscosity of the slurry.
2. Properly designed CWM atomizers can provide mean slurry droplet diameters approaching those of the coal component.
3. Stable CWM flames require deep quarls with wide half angles, air pre-heating and low to moderate swirl with an ability to independently adjust the swirl number in burners.
4. Atomizer spray patterns should remain in the IRZ and some flame staging can be used to improve flame stability.
5. The stoichiometry of the near-field mixing zone should be high enough to optimize carbon burnout.

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