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PROGRESS IN THE DEVELOPMENT OF CWF BURNERS FOR BOILER AND PROCESS COMBUSTOR APPLICATIONS

K.V. Thambimuthu and H. Whaley

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Reprinted from the Proceedings of the American Flame Research Committee
Spring Technical Meeting, Toronto, Canada. May 1988.

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PROGRESS IN THE DEVELOPMENT OF CWF BURNERS FOR BOILER AND PROCESS COMBUSTOR APPLICATIONS

by

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ABSTRACT

The Canadian program of coal-water fuel (CWF) technology development has been in progress since 1980. The main emphasis has been on CWF manufacturing technology and burner development. In the latter area, the commercial burner manufacturers have been involved in the program, but have not been too successful in achieving reliable wear resistant atomizers that were durable and burners which gave good combustion.

For this reason, a research program was undertaken by the Energy Research Laboratories, Canada Centre for Mineral and Energy Technology (CANMET) in collaboration with the National Research Council to design and develop a dual oil/CWF burner based on the basic principles of atomization and combustion air mixing. The burner has been scaled up from a pilot-scale (5 GJ/h) to a commercial scale (55 GJ/h) prototype and has been tested on a 20 MWe compact oil-designed utility boiler in Charlottetown, Prince Edward Island.

In a similar development, durable burners were developed for a cement kiln which enabled a cement manufacturing company in Richmond, B.C., to convert its operations economically from natural gas to CWF.

Details are given of the respective programs, the development of burners and their impact on operation, since it is clear that oil-replacement combustion technologies will be in great demand when the price of oil escalates again as it has done in the past. Furthermore, the Canadian experience indicates that this is a new coal burning technology that gives compact flames, a benign ash behaviour with reduced erosion and deposition on heat transfer surfaces, more rapid char combustion due to differences in morphology which combined with the ease of handling a liquid fuel will eventually enable it to compete with oil and pulverized coal firing technology.

INTRODUCTION

Coal-water fuels (CWF) may be used as a replacement for oil, natural gas and pulverized coal in utility and industrial boilers and process combustors. The advantages of fuel substitution are that the change-over to coal can be attempted with minimal modifications to hardware in existing oil firing plants. These benefits which eliminate the need for bulk coal transportation, storage, handling and conveying equipment also engender the application of CWFs from environmental considerations. Preliminary results from a CWF demonstration program(1) in a tight oil-designed boiler without evidence of convective tube erosion, or maximum capacity reductions (derating), show that CWFs may also usher a new era in the design of more compact boilers for clean coal combustion(2).

Despite these potential benefits and attractions, CWF deployment, after almost a decade of R & D, continues to be hampered by the poor availability of efficient and reliable CWF burners. The common difficulties encountered include an inability to efficiently atomize the fuel, erosive wear in two fluid atomizers, poor ignition stability and turn-down in burners. Many of these problems can be attributed to the almost universal adaptation and use of oil-designed fuel nozzles and burner registers for CWF combustion(2,3). The difficulties in this approach are that CWFs, due to their two-phase (solid-liquid) nature and high (nominally 30 wt%) moisture content, are mis-matched to oil-designed burner equipment, because of fundamental differences in their atomization behaviour and burning profiles in comparison to oil. In addition, it is also clear that there is a poor understanding of fuel properties, burner operation and control parameters critical to good atomization and combustion of CWFs(2).

The present paper briefly reviews fuel properties and fundamental design principles which govern atomization and combustion of CWFs, and describes a dual CWF/Oil, front wall fired burner that was developed from an application of these principles. Results from a single burner demonstration test undertaken in a 20 $MW_{(e)}$ oil-designed, utility boiler in Charlottetown, Prince Edward Island, are presented. Brief details of a program to evaluate a full complement of 5 burners in the the Charlottetown utility boiler in the summer of 1988, are also described. In another development, the conversion of a wet process cement kiln from natural gas to CWF is described together with the development of a wear resistant atomizer and the impact of CWF utilization on cement kiln operation (4).

THE PERFORMANCE OF TWO-FLUID CWF ATOMIZERS

The following is a brief summary of the main parameters which govern atomization quality that has been developed in detail elsewhere (5).

Y-jet atomizers are commonly used in oil firing practice, and the example presented in this section illustrates its performance with CWFs. The adaptation to CWFs usually involves modifications to increase the fuel and outlet orifices to prevent blockage by coal particles, and atomizer fabrication with hardened materials such as tungsten carbide or specialized steels, to minimize erosion by the coal and ash particles(2).

Figure 1 shows the dependence of the spray droplet diameter on the air-liquid ratio (ALR) for a Y-jet CWF atomizer. A number of different operating regimes can be identified for the spray data shown in Figure 1. A schematic illustration of the Y-mixing, and its preceding co-axial mixing regime at ALR < 0.45 for the Y-jet atomizer is shown in Figure 2. These mixing regimes were identified from the relative values of the liquid and air pressures in the atomizer, and from radial traverses of the spray.

Figure 3 shows a plot of the pressure measurement for the Y-jet CWF atomizer. The data were obtained at a variable air flowrate, and a constant liquid rate of 0.038 kg/s. Two curves are shown for the liquid pressures in Figure 3. These were obtained in repeat experiments, and show that the shear dependent rheology of the CWF incurs a variable pressure loss from viscous flow in the atomizer. The air pressures, P_g, on the other hand are independent of P_L, and fall on an identical curve for the two sets of repeat measurements. In view of the variation in P_L, two different transition points for the Y-mixing regime were identified from the intersection of P_g and P_L. The change-over at ALR > 0.45 was measured for the spray data shown in Figure 1, and the second value at ALR > 0.62 was obtained for the repeat experiment. Due to a change in the spray quality with the fuel-air mixing configuration noted above, it is evident that the atomizer performance is affected by the shear dependent rheology and bulk viscosity of the CWF. For the liquid pressures shown in Figure 3, a 20% increase in the viscous pressure loss due to an equivalent change in the CWF bulk viscosity requires a 40% increase in the ALR in order to achieve the same flow mixing regime in the atomizer. This example gives a clear illustration of the variability in nozzle performance, often encountered when atomizing CWFs.

Figure 4 shows a plot of the spray droplet diameter as a function of P_o for the Y-jet atomizer. Values of Po where obtained by subtracting the liquid pressure intercepts at the ordinate from the measured values of P_L in Figure 3. The data shown generally correspond to measurements obtained in the sonic regime, and with co-axial mixing in the atomizer. The Sauter mean droplet diameters, d_{32}, are correlated by;

$$(d_{32}/D_o) = 230.9\ P_o^{-0.78} \qquad (1)$$

Since $P_o = 0.5\ \rho_g U_g^2$, Equation 8 may be expressed in terms of the Weber Number;

$$(d_{32}/D_o) = 17.8\ We^{-0.78} \qquad (2)$$

where the Weber number is defined as;

$$We = \{\ \rho_g\ U_g^2\ D_o/\ \sigma_L\ \} \qquad (3)$$

In which ρ_g is the gas density, Ug the gas velocity, σ_L is the interfacial surface tension, and Do is the outlet diameter of the atomizer orifice. The Weber Number represents the ratio of the disrupting aerodynamic force (kinetic energy) of the atomizing fluid, to the consolidating surface tension force that opposes CWF surface disintegration at the solid-liquid interface. The same group is also used to correlate surface tension effects for liquid atomization(6).

BURNER DESIGN FOR CWF 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. For a low momentum fuel spray, the aerodynamic flow patterns established in the burner near-field mixing zone are shown schematically in Figure 5. Flow mixing induced by the swirling air jet creates a large, torroidal vortex, internal recirculation zone (IRZ) at the flow axis. 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 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(7). This exchange of gas promotes mixing which affects the temperature and oxidant concentrations 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 in the fuel spray, the convective heat necessary 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 CWFs stem from the longer heating and ignition times of the coal particles and CWF droplets(2). Compared to oil which heats and ignites virtually instantaneously with the first evolution of volatiles, the CWF droplets experience a finite heating and ignition delay due to moisture evaporation and volatiles evolution which occurs at a much slower rate for coals. These problems may be overcome by an increased residence time combined with increased convective heat transfer rates for the drying and ignition of the spray droplets in the IRZ. These requirements are usually achieved by;

i) minimizing momentum penetration of the spray which affects the droplet residence times, and disrupts the flow in the IRZ,

ii) increasing the size and strength of flow recirculation in the IRZ,

iii) decreasing swirl induced mixing or by employing staged combustion to reduce gas dilution and increase the temperature of the recirculating gases in the IRZ.

The impact and improvement of the ignition stability of CWF flames due to the above, and the influence of burner design and operating parameters is illustrated by the following examples.

In pilot-scale, 2.5 $MW_{(th)}$ input, CWF flame trials at the International Flame Research Foundation (IFRF), it was found that the type and spray angle of the two-fluid atomizer used in the burner had a significant impact on the flow patterns established in the IRZ(8). Multi-orifice, two-fluid atomizers of the Y-jet and T-jet type, in which the angular disposition of the outlet holes was varied, produced stable flames with minimal disruption of the flow patterns in the IRZ. For a burner with a divergent quarl of 35° half angle (Figure 5), an 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 latter into the forward flow in the swirling combustion air. In this way, the heat to dry 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 as the IFRF study at a 1.8 $MW_{(th)}$ input scale, investigations with a conical spray 'prefilming' atomizer of a design similar to that described in the next section, revealed that the optimum spray angle was one which maximized initial penetration of the spray close to the IRZ flow boundary(9). Penetration of the spray at this location was found to maximize the residence time in the recirculating gases, and the intense turbulent mixing provided a higher oxygen availability which facilitates rapid flame propagation(2). In contrast to the behaviour of narrower angle sprays, the spray momentum at this location also has a minimal impact in modifying the extent of the induced gas flow patterns established within the IRZ. For CWF, this spray angle of 50° was similar to that identified in the IFRF study. However, the flow patterns for oil using an identical burner and atomizer, required an optimum spray angle that was 10° larger than that used for the CWF. This difference in the spray angle was attributed to the greater momentum penetration and radial dispersion of the heavier and coarser CWF droplets(2,9). This characteristic feature is often ignored when oil-designed burners are modified for CWM combustion.

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 preheat, and staging on CWM flame stability(8). An increasing L/D ratio and half angle increase flow recirculation and the size of the IRZ(7). Increasing the swirl has the same effect on the IRZ due to a higher negative pressure gradient (suction) that is created at the flow axis. The IFRF study found that a 35° quarl was mandatory for the stable combustion of CWFs containing 30 wt% moisture and 18-36 wt% d.a.f volatile matter. This may be compared with a 25° quarl typically used to sustain stable combustion of oil or high volatile pulverized coals(8). At the optimum quarl 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 CWFs made from low volatile coals. The improved ignition stability with increased quarl half angle and length, stems from the increased residence times for CWF droplet heating in the IRZ.

The effect of staged combustion by diverting some of the air normally admitted to the swirling air jet through outer tertiary air ports has been evaluated(8). Increased staging, increased temperatures uniformly in the swirling jet and the IRZ. However, the increased temperatures and flame stability with reduced gas dilution was off set by poorer carbon burnout, due to a reduced oxygen availability in the early stages of combustion. Higher swirl numbers relative to those used in unstaged flames, tended to improve carbon burnout by improved mixing and a higher oxygen availability, but this reduced the IRZ temperatures and the flame stability.

In view of the trade-off between flame stability and carbon burnout, staging is marginally beneficial as a design tool. A review of the operating characteristics of swirl burners, particularly pulverized coal burners, showed that the increased quarl dimensions played a more effective role in increasing the size of the IRZ, while maintaining high gas temperatures(2). This occurs because the increased dimensions of the quarl are accompanied by lower rates of mixing between streams in the near-field zone, compared to those attained when the swirl number is increased. The IFRF study has also shown that high swirl numbers are not an effective tool to improve the ignition stability of CWF flames due to a tendency to decrease the temperature of the recirculating gases in the IRZ by increased gas dilution(8).

DUAL FUEL BURNER DEVELOPMENT FOR FRONT WALL FIRING.

Figure 6 shows a schematic diagram of the spray head of the 55 GJ/h, National Research Council (NRC) dual fuel (CWF/Oil) two-fluid atomizer. An outer annulus develops the CWF into a thin liquid sheet which is brought into contact with the atomizing fluid at sonic velocity. A wear resistant ceramic cone and matching ring forms the final discharge annulus or mixing chamber, where the aerodynamic and hydrodynamic pressures are controlled to yield a spray of fine droplets. The ceramic components are selected to reduce erosion of the mixing chamber dimensions which would otherwise result in a rapidly deteriorating spray quality. The angle of the mixing chamber relative to the axis of the nozzle determines the spray angle of the atomizer. Different spray angles by replacing the ring and cone are often used in field trials to optimize the spray trajectory, and hence the ignition stability and compactness of the flames. As outlined previously, the optimum spray angles may also differ for CWF and Oil combustion.

The atomizer discharge area is adjustable, and is controlled by an external micrometer with low and high gap settings on a graduated scale. This adjustable feature permits fine tuning of the nozzle to maintain throughput, sonic discharge velocities and a spray quality independent of the variable shear dependent rheology of the CWF. The latter avoids difficulties due to changes in the flow mixing regimes similar to that described earlier for the fixed geometry Y-jet atomizer. Thus, the nozzle adjustment essentially provides a method of controlling the aerodynamic and hydrodynamic pressure ratio in the mixing chamber. The same adjustable feature also permits a convenient means of fuel switching to oil, by closing down the discharge gap. The latter reduction is necessary due to large differences in the viscosity of oil and CWF, which would otherwise cause a higher oil throughput to the burner during fuel switching.

The schematic in Figure 6 shows that the mixing chamber is essentially an annular Y-jet design. The major difference between this and the circular orifice Y-jet design described previously, is that the annular configuration offers a significantly larger mixing volume. Using the present 55 GJ/h atomizer as a basis, the annular design is roughly comparable in volume to 100 circular Y-jets of a more conventional design. The greater volume, and hence surface area, is thus beneficial for the primary separation of coal particles from the liquid surface during fuel atomization. An additional benefit of the annular design is that it develops a hollow cone spray discharge with an induced recirculation of fine droplets and particles at the spray axis. This pattern is compatible with the recirculation flow also established in the IRZ. The presence in the flame core of fine droplets and particles that heat and ignite more rapidly are generally beneficial to the overall ignition stability of the flame.

Figure 7 shows a schematic illustration of the Canada Centre for Mineral and Energy Technology (CANMET) burner register. The burner design comprises of two parts; a mechanical register assembly of swirl vanes, flow separation ducts and control dampers, and a refractory quarl. The burner register is basically configured to generate two concentric primary and secondary swirling air jets, with independent control of the swirl level and mass flow in the respective streams. The latter feature provides a method of sustaining different gas dilution and mixing intensities in the IRZ, for the stable ignition and combustion of CWF and Oil which differ significantly in their chemical reactivity. As outlined in the section on combustion aerodynamics, lower swirl levels and mass flows are generally employed in the primary air flow during CWF combustion. Critical quarl design parameters in accordance with the guidelines mentioned previously are also maintained for CWF combustion. The NRC atomizer is located in a central guide tube in the register, and final flame shaping and ignition stability is achieved by adjustment of the register settings in combination with the atomizer spray angle and the nozzle outlet gap settings.

The above atomizer and burner register combination was demonstrated on CWF and Oil during summer 1987 in the Unit No. 10, oil-designed utility boiler at the Maritime Electric Company's, Charlottetown Generating Plant. A schematic of the boiler is shown in Figure 8. The prototype was developed and tested at its 55 GJ/h design rating on CWF, but an upper limit of 80 GJ/h and a lower limit of 30 GJ/h was also demonstrated. These results demonstrate a minimum 2:1 turn-down ratio without loss of flame stability or deterioration in combustion efficiency due to poor atomization. The latter was confirmed by the noticeable absence of sparklers in the flame, or any significant drop-out of large unburnt fuel aggregates in the furnace bottom. Fly ash samples recovered from the boiler indicated a 96 % fuel burnout efficiency. However, due to mixed firing with oil in a boiler which was operating at 40% MCR, it is thought that this efficiency is a conservative estimate of the actual burnout efficiency. The difficulty in estimating the actual burner performance stems from the oil-carbon contamination of the coal flyash. The best comparable performance test with the 5 commercial CWF burners at 93% MCR in the same boiler indicate a fuel burnout efficiency of 93%. In addition to the lower combustion efficiency, the commercial CWF burners showed poor turn-down stability. The oil combustion tests on the CANMET/NRC burner demonstrated an 8:1 turn-down ratio, but higher firing rates beyond the 55GJ/h design capacity were limited by poor oxygen availability in the flame. The latter is anticipated due to the lower rates of mixing and gas dilution in the IRZ that is a feature of the different quarl design employed in the burner.

The prototype versions of the NRC atomizer used alumina ceramics as a wear resistant component for the cone and ring assembly(10). Field experience with the NRC atomizer has shown that the high erosion resistance was compromised by poor thermal shock and toughness of alumina. While ceramic components as a class are known for their extreme hardness (erosion resistance), the severe high velocity, sonic conditions and the abrasive coal and ash particles, present an environment that few materials are able to withstand. Silicon nitride ceramics due to their improved thermal shock resistance were tested in the current burner program, but had an erosion life of less than 500 h. Partialy stabilized zirconia and zirconia toughened alumina are candidate materials that will be evaluated in future tests for their improved erosion resistance.

UTILITY AND CWF AND BURNER DEMONSTRATION PROGRAMS

The CANMET/NRC burners will be tested in a full, 5 burner conversion in the Unit 10, boiler at the Charlottetown Generating plant in the summer of 1988. The purpose of this trial is to demonstrate burner and boiler performance on CWF. Most of the large utility CWF demonstrations to date while positive on the lack of ash induced erosion or capacity reductions, have turned in poor combustion efficiencies and burner performance characteristics on CWFs. Reliability from the latter perspective is a primary consideration which will be addressed in a 1400 tonne CWF combustion test and boiler performance evaluation.

CEMENT KILN DEMONSTRATION

The manufacture of cement is very energy intensive. A typical wet process kiln uses 6 GJ/t of clinker, a dry process up to 4 GJ/t. Larfage Canada Inc. has been exploring options for converting its western Canadian kilns to coal, the bulk of its eastern operations already using pulverized coal (PC). In Alberta and B.C. the dominant fuel is natural gas, even though both provinces have abundant reserves of coal. An esclating natural gas price in B.C. caused the company to explore options for coal conversion, of which CWF was one, particularly for the Richmond wet process plant (see Figure 9.)

This plant has two kilns which can produce 650 and 750 t/d of clinker and will consume in total 375 GJ/h. A simple economic analysis showed that if capital costs were reasonable, coal was about half the cost of gas on a thermal basis. However, a dry PC system would cost $6.8 million and this was regarded as too high due to the age of the plant. An examination of the excess milling capacity at the plant showed that this could be utilized to produce CWF using the same technology that was used to produce the kiln cement slurry feedstock. This reduced the capital costs of conversion to $850,000 with a pay back period, if successful, of less than six months. This attractive option prompted the company to undertake a joint program with Energy, Mines and Resources Canada in which partial funding and technical assistance on burner technology was provided by Canmet. The overall project objectives were;

i) To develop and optimize the CWF preparation process

ii) To develop the burner technology for the utilization of CWF in the kiln

iii) To maximize the utilization of coal (at least 80% natural gas replaced by coal) and to assess the impact of coal combustion and ash on the kiln operation

iv) To develop a practical handling and piping system for CWF

v) To assess various coals and coal reject options as feedstocks for CWF

The manufacturing process and simple burner concept is shown schematically in Figure 10. After completing the two year program, the company has been able to replace 95% of the plant gas requirement by coal and although it is feasible to entirely replace gas with coal, the latter is not often done because of a minimum use clause in the gas supply contract. Several coal and tailings feedstocks have been evaluated and the most economical choices made. Negligible impact of the ash on kiln operation was observed. The kilns have been converted to CWF commercially and represented the first industrial CWF conversion in North America. At the present time, the low natural gas prices make CWF operations uneconomic.

ACKNOWLEDGEMENTS

Excerpts in this paper have been previously published in reference 5 by Thambimuthu et al. at the 50th American Power Conference, April 18-20, 1988, Chicago, Illinois.

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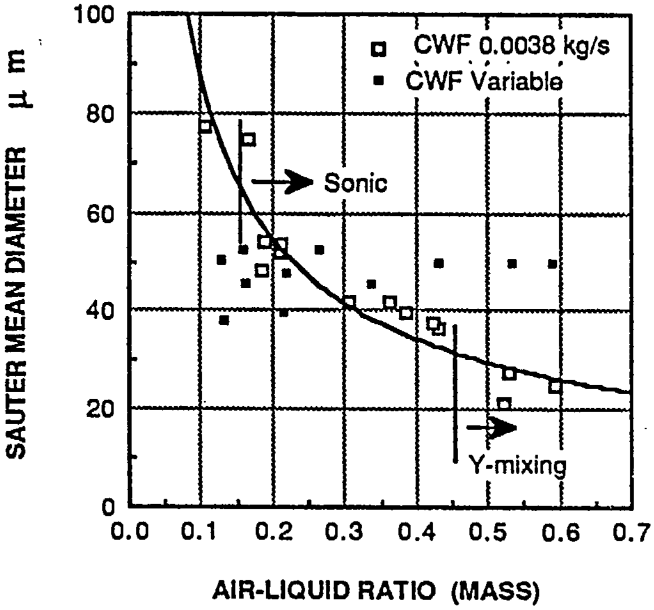

Figure 1 - Influence of Air-Liquid Ratio on the Spray Droplet Diameter

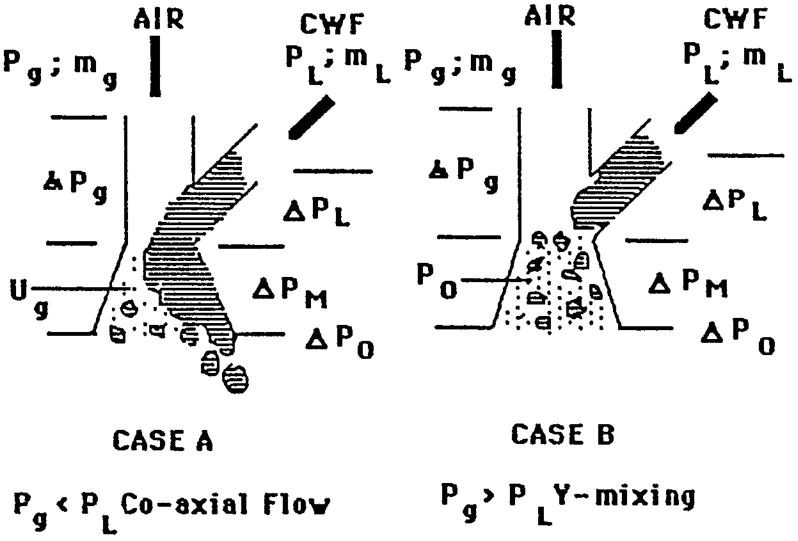

Figure 2 - Flow Mixing Regime Regimes in a Y-Jet Atomizer

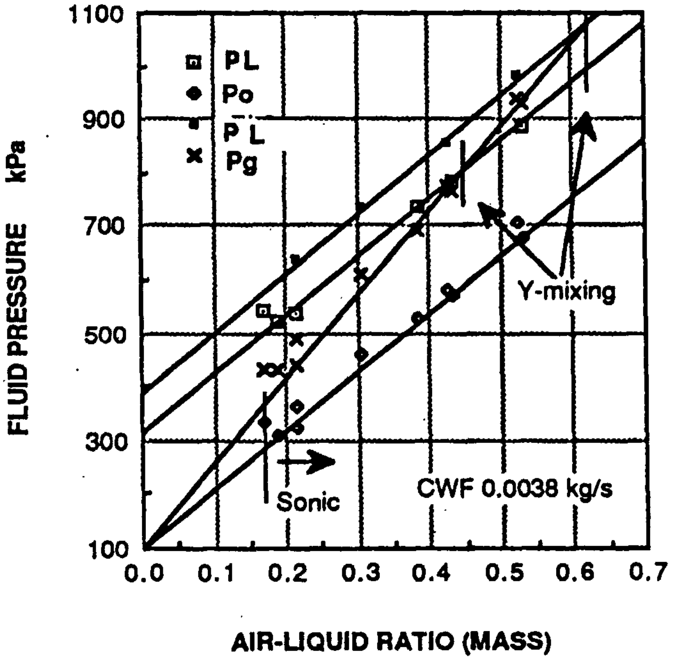

Figure 3 - Fluid Pressures in a Y-Jet Atomizer

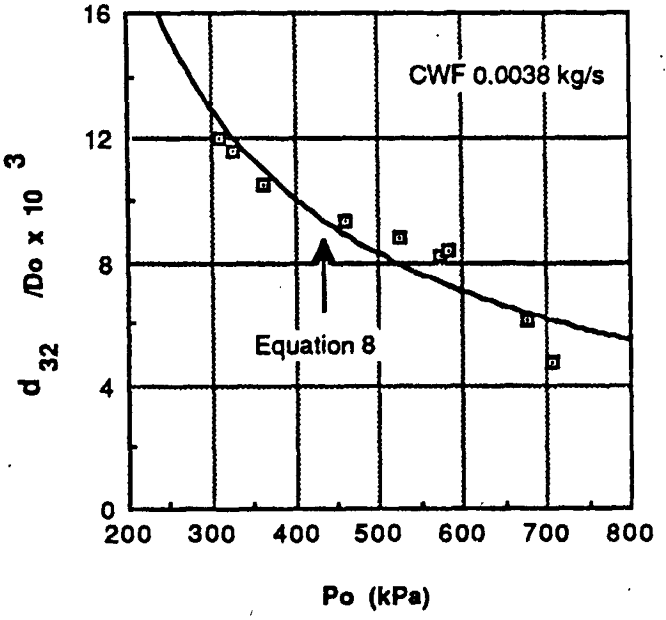

Figure 4 - Spray Droplet Correlation with Co-axial Mixing in a Y-Jet Atomizer

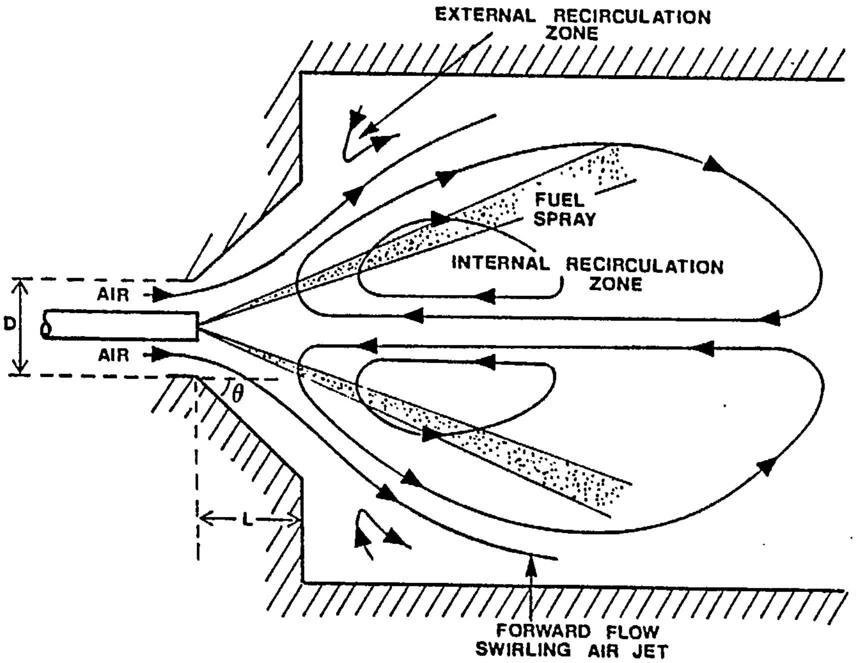

Figure 5 - Flow Mixing in Swirl Burners with Spray Injection

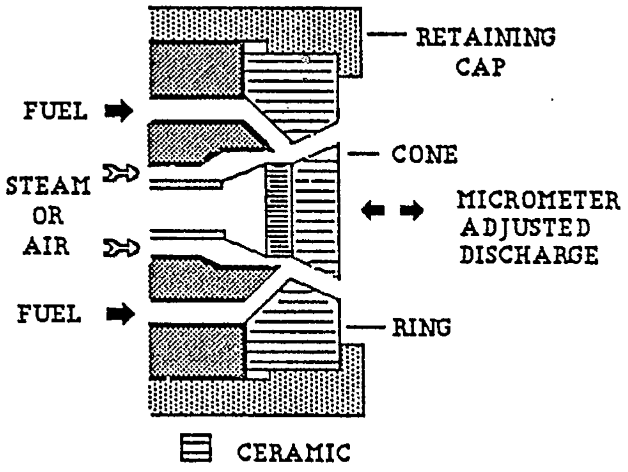

Figure 6 - Schematic of the NRC CWF-Oil Dual Fuel Atomizer

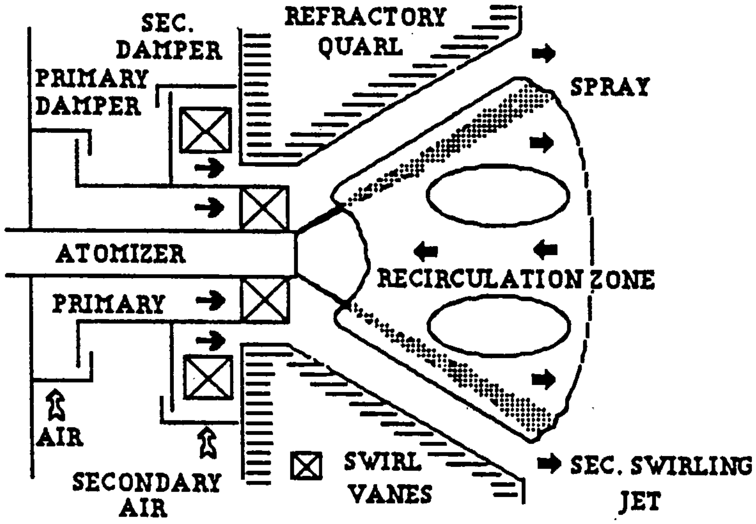

Figure 7 - Schematic of the CANMET CWF Burner Register and Aerodynamic Flow Mixing

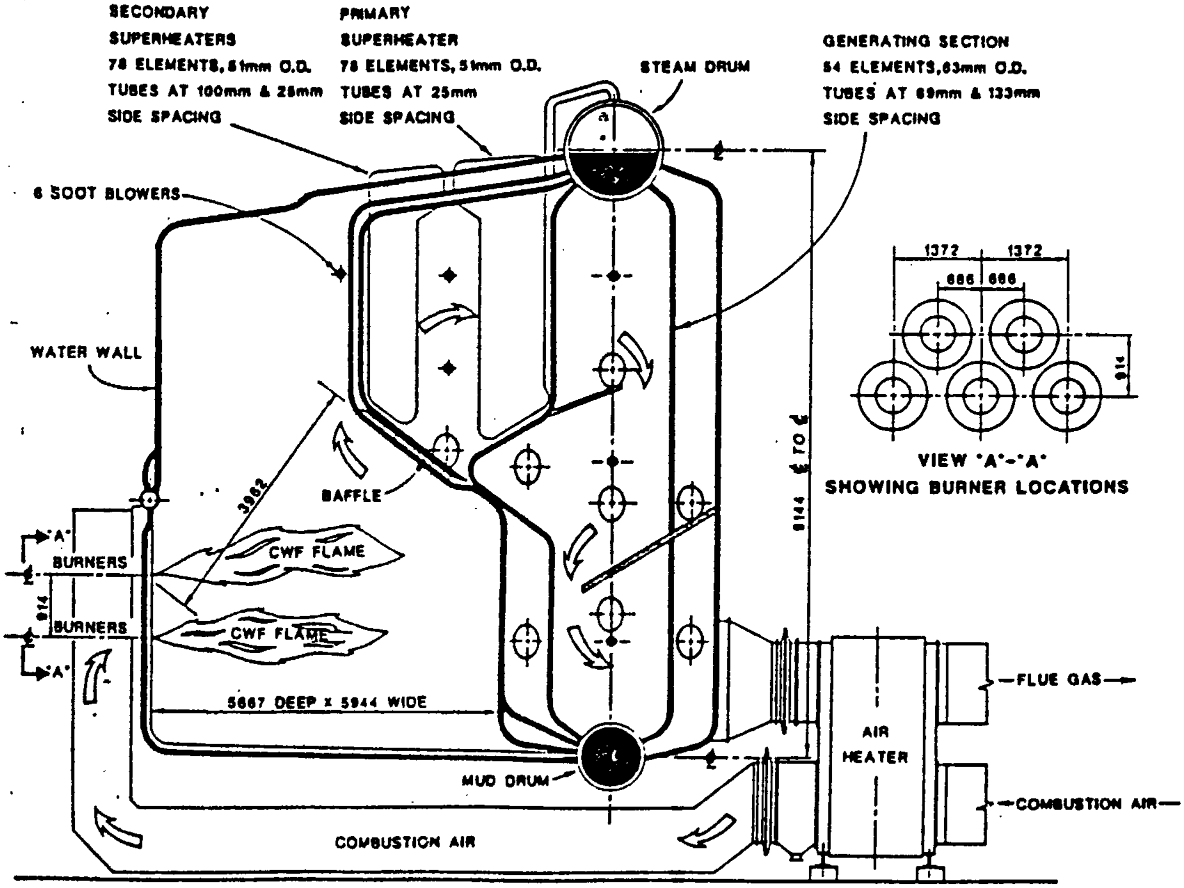

Figure 8 - Schematic of the Charlottetown, Unit 10 Oil-designed Utility Boiler

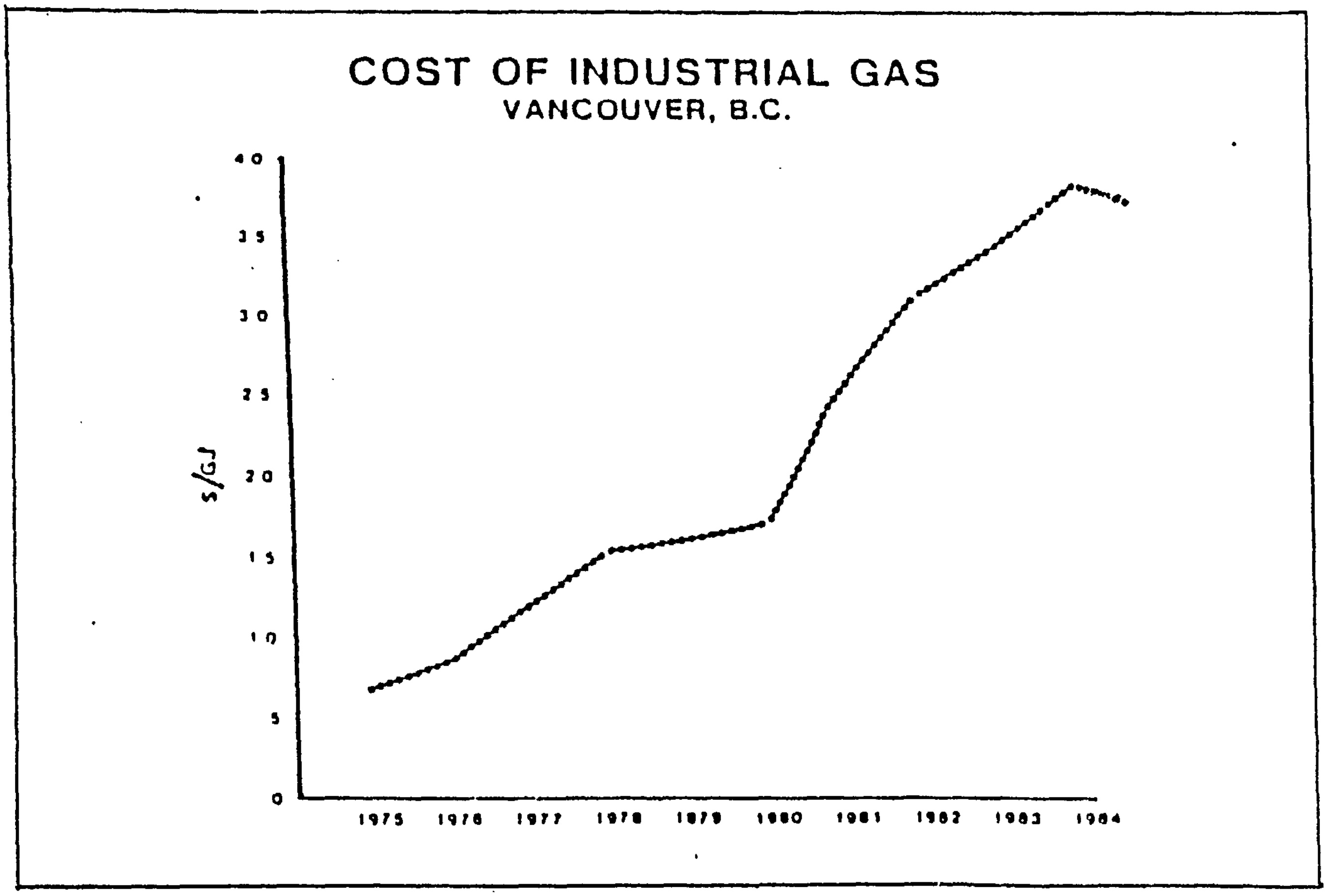

Figure 9 - Natural Gas Prices

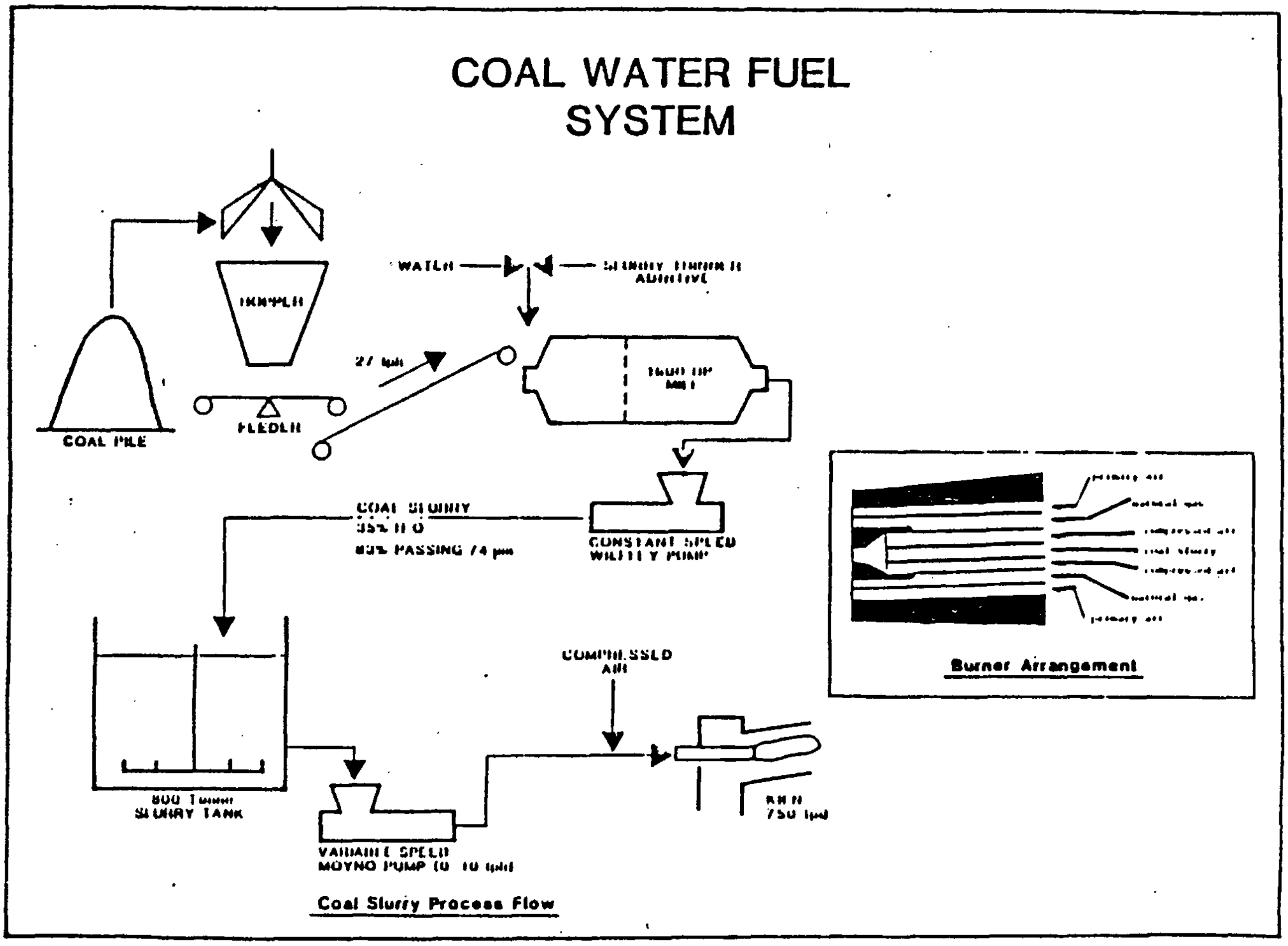

Figure 10 - Schematic of Cement Kiln Conversion to CWF