

Optimization of a swirl burner for pulverized-wood fuels

Terry N. Adams, Delmar R. Raymond, and Christoph Schmid

Swirl burners can accommodate wood fuels with moistures up to 20% if the combustion air is staged properly.

Wood waste derived from manufacturing processes provides a substantial portion of the energy consumed by the forest products industry. Burning of wood waste was initially conceived as a housekeeping chore to eliminate the large volume of waste generated during manufacturing. Since then, economic factors have dictated the efficient use of this fuel as a substitute for fossil fuels in boilers. The cost and reliable availability of wood waste make it a valuable fuel resource for all mills. Environmental concerns make wood waste even more attractive because of its inherently low ash, sulfur, and nitrogen contents.

Most wood waste is burned in a bed or a pile in a boiler furnace. The advantage of this approach is the relatively limited processing of the raw, wet fuel. Only limited size reduction in a hammer hog is required to achieve fuel particles ranging in size from 100 μm to 2 in. (5 cm). Fuel moisture typically ranges from 45% to 60% on a wet basis.

There are advantages to using a fuel that requires only limited preparation, but there are also disadvantages. These include low combustion efficiency, low boiler efficiency, poor load following, environmental issues, and serious difficulty in retrofitting existing fossil fuel boilers. It is also virtually impossible to use wood waste as a fuel for lime kilns with this technology, and lime kilns consume more than half the fossil fuel used by a modern pulp and paper mill.

Firing wood waste in suspension, in a manner similar to pulverized coal, eliminates the disadvantages of bed-burning technology and extends the use of wood as a fuel to lime kilns and other direct-fired units. However, fuel preparation requirements increase substantially for stable and efficient wood-fines burning.

Unlike most coals, wood is a fibrous solid that cannot easily be reduced in size. Further, both pulverization and combustion requirements make it mandatory for the wood to be dried to a relatively low moisture content (15-20%). However, to be economically viable, stable and efficient

wood-fines combustion must be achieved with particles larger and wetter than is typical for any coal. A fuel preparation system specifically designed for wood waste and a burner specifically optimized for this fuel is needed.

Development and optimization of swirl burners has been the task of the International Flame Research Foundation (IFRF) for the past three decades. A wide range of optimization criteria, from stability, to efficiency, to environmental protection, has been applied by the IFRF to an even wider range of solid, liquid, and gaseous fuels. Recognizing this expertise, the International Energy Agency (IEA) funded an experimental program at the IFRF in 1984 to collect fundamental data for wood-fines burning. Five of the member countries of the IEA participated in this program: the United States, Canada, Norway, Sweden, and Finland. The contract was administered through Norsk Dampkjelforening of Oslo, Norway. The program's objective was to optimize a swirl burner for wood waste. This was done by identifying the burner aerodynamics that produced the most stable and efficient combustion for a range of wood fuel sizes and moisture contents.

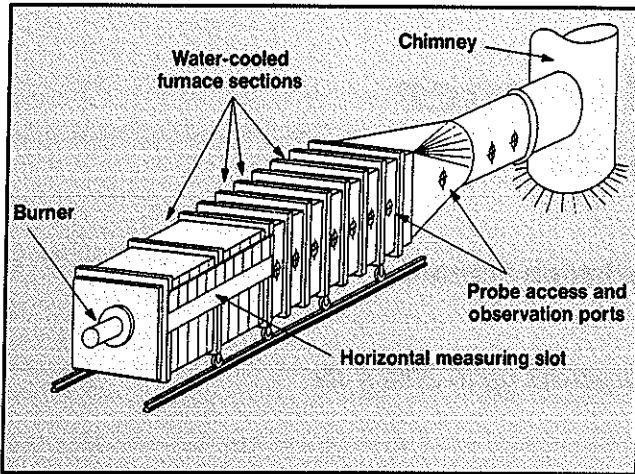
This article presents a summary of the IFRF program, test results, and significant findings. The full report (1) is available from the IFRF or the U.S. Department of Energy. The test facility and test data are described, followed by a discussion of the resulting stability maps for wood-fines fuel.

Test facility

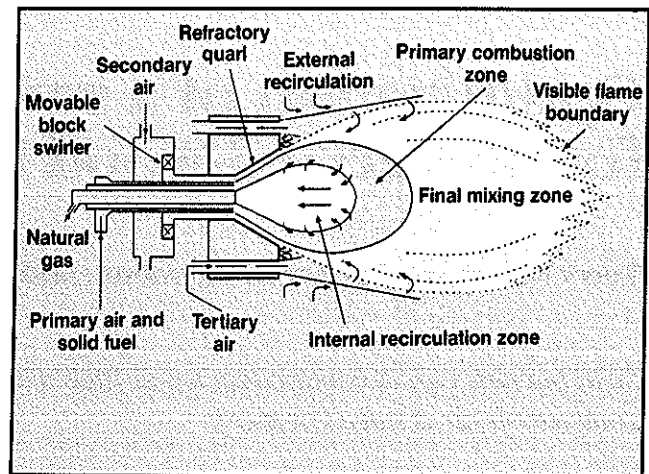
The wood-fines test program was conducted in IFRF's No. 2 furnace. This is a semi-industrial-scale furnace capable of continuous operation at a thermal input of 2 MW (6.8×10^6 Btu/h). A schematic diagram of the furnace is shown in Fig. 1. The interior dimensions of the furnace are 1.11 m $\times$ 1.05 m $\times$ 4.05 m (3.6 ft $\times$ 3.4 ft $\times$ 13.3 ft). The burner is installed on the centerline at one end, and combustion gases leave through a flue and chimney at the other end. The furnace is constructed of 17 water-cooled segments. The axial heat extraction is measured from the water flow and temperature rise. The furnace interior surface is 3/4-lined with refractory brick so that the thermal environment seen by the flame in this narrow furnace simulates the boiler furnace environment.

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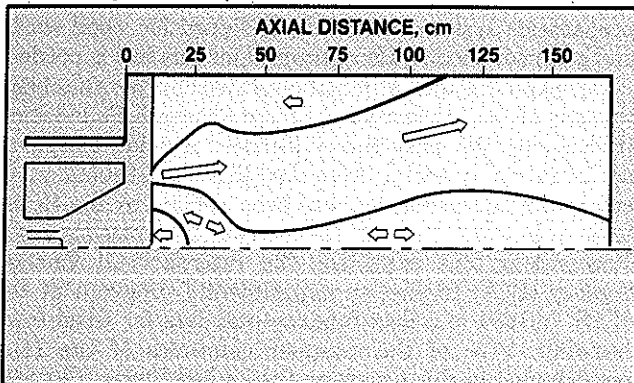
1. The No. 2 furnace is capable of continuous operation at a thermal input of 2 MW. The interior dimensions of the furnace are 1.11 m × 1.05 m × 4.05 m.



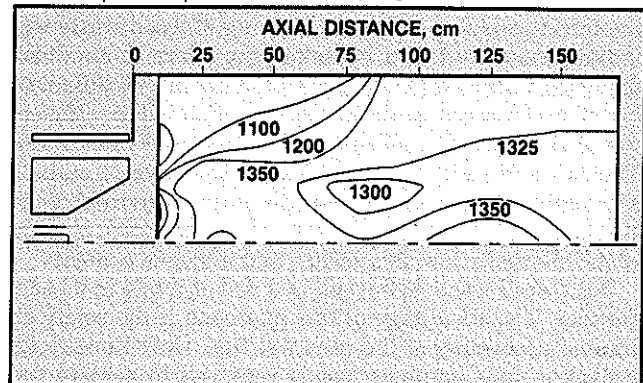
2. Circular swirl burner for pulverized wood



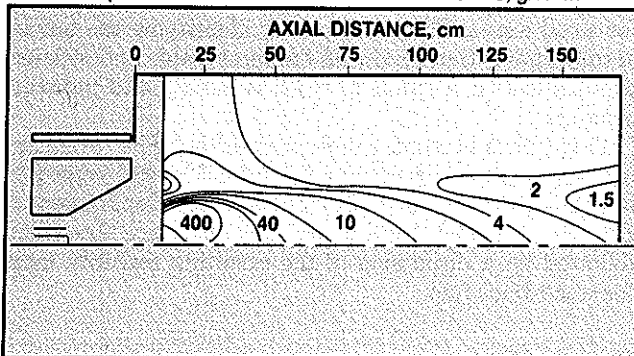
3A. Aerodynamic flow pattern for flame F-20-2/3



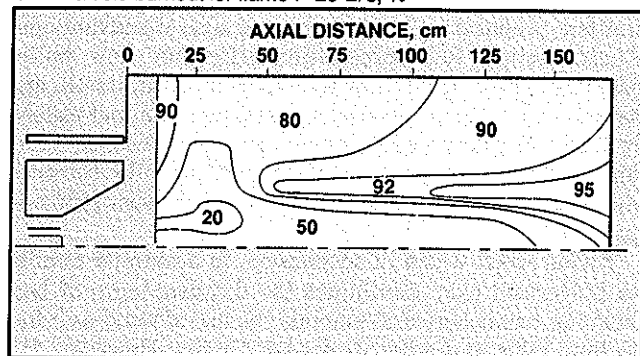
3B. Temperature profile for flame F-20-2/3



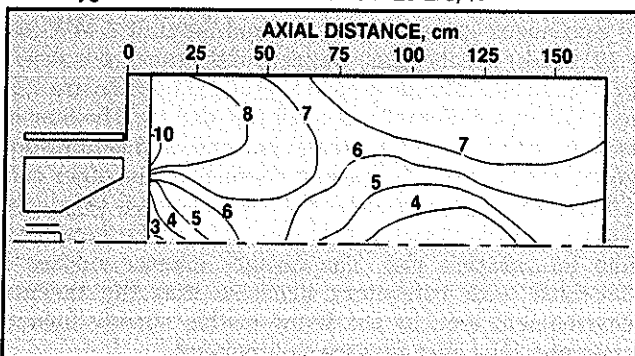
3C. Solid-particle concentration within flame F-20-2/3, g/N·m³



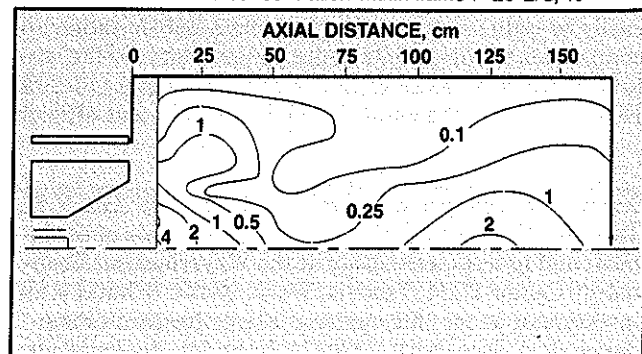
3D. Particle burnout for flame F-20-2/3, %



3E. Oxygen concentration within flame F-20-2/3, %



3F. Carbon monoxide concentration within flame F-20-2/3, %



I. Specifications for pulverized-wood fuel

	Fuel designation				
	Ebenol	Very Fine	Fine*	Coarse*	Sub-coarse
Approximate analysis					
Volatile matter, % daf	86.41	83.83	...	...	87.19
Fixed carbon, % dry-ash-free	13.59	16.17	...	...	12.81
Ash, % dry	1.28	1.4	...	...	0.49
Moisture, %	6.0	8.8	...	...	8.1
Lower heating value, MJ/kg/dry	17.75	16.95	...	...	17.34
Ultimate analysis					
Carbon, % daf	50.63	49.14	...	...	50.32
Hydrogen, % daf	6.11	6.0	...	...	6.0
Nitrogen, % daf	0.23	4.7	...	...	0.07
Oxygen, % dry	41.69	38.97	...	...	43.09
Sulfur, % dry	0.024	0.069	...	...	0.011
Size distribution, % less than					
1180 μm	99.2	100	100	100	100
560 μm	84.9	75.4	61.2	55.9	52.0
250 μm	52.3	40.8	35.7	22.2	11.1
100 μm	24.4	21.8	15.3	8.8	2.0

*Blended from very fine and subcoarse fuels.

II. Operating conditions during the pulverized-wood trials

	Feed rate, kg/h	Temperature, °C	Velocity, m/s
Wood fuel	400	Ambient	18
Primary air	400	Ambient	18
Secondary air	1400	150	40
Tertiary air	1100	150	59
Range of burner operating parameters			
Thermal input, MW		0.5 - 2.5	
Overall stoichiometry		1.1 - 1.3	
Primary-zone stoichiometry		0.6 - 1.3	
Quarl length/diam.		1	
Quarl angle		25°	
Blockage ratio		0.64 - 0.77	
Swirl number		0 - 1.6	
Air preheat temperature, °C		25 - 150	
Secondary/primary velocity ratio		0.68 - 3.06	
Furnace refractory lining		0 & 3/4	
Range of fuel parameters			
Fuel fineness, % < 100 μm		3 - 25	
Fuel moisture, %		6 - 20	

The 2-MW test burner designed by the IFRF is shown in Fig. 2. It is a circular swirl burner. Like most register burners used for gaseous, liquid, and solid fossil fuels, the air flow is basically axial with a strong swirl component. The various annuli are a fundamental aspect of the burner design.

Natural gas or fuel oil can be introduced to the pulverized wood burner through guns located on the burner centerline. Core air is injected through the annulus adjacent to the fuel guns to purge the oil atomizer or to promote initial mixing between air and natural gas. Pulverized wood fuel is carried by transport (primary) air in the annulus outside the core-air annulus. Secondary air enters through a variable-swirl block, which imparts a controlled level of swirl. The secondary air flows through the outermost annulus.

The secondary swirl, the cone-like shape of the refractory quarl, and the blockage ratio or bluntness at the burner throat combine to produce the strong internal recirculation zone (IRZ) located along the centerline, a short distance from the burner mouth. The blockage ratio is the ratio of the outer diameter to the inner diameter of the secondary air annulus. This ratio was varied in the trials to separate the effects of secondary air preheat from the effects of secondary-to-primary velocity ratio. The swirl number is a measure of the angular momentum compared with the axial momentum. The swirl numbers tested in the trials ranged from 0 to about 1.6.

The four air nozzles located around the quarl exit provided tertiary air, which is used during staged combustion. Normally, the air that enters through the main burner as core, primary, and secondary air is

sufficient to provide the stoichiometric requirement for complete combustion of the fuel plus a prescribed excess. Staged combustion uses sub-stoichiometric air through the main burner. The remaining air needed for complete combustion is injected through the tertiary ports. This has been a powerful technique for control of NO_x formation with other fuels. Here, it enhances the combustion stability of the coarse, wet wood fuels by minimizing the thermal ballast in the ignition zone and prolonging the residence time in the nearly adiabatic quarl region.

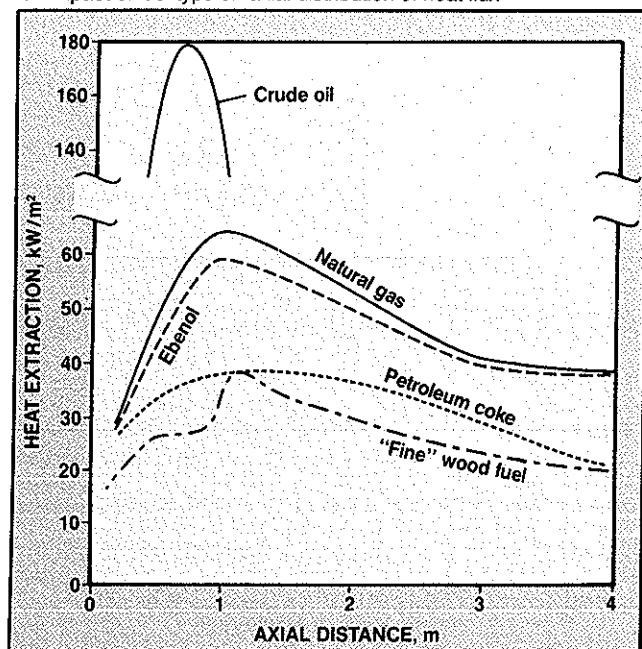
Fuel blending and metering were conducted such that fuel flow fluctuated less than $\pm 1\%$. Input/output data were taken for all flames. These data included fuel specifications, fuel and air input, flue-gas composition, and heat-extraction profile by segments. Many in-flame measurements were taken of the temperature field, fuel-particle concentration and burnout, local gas composition, and aerodynamic flow patterns.

Four fuels were used in these trials. All were obtained in England or Sweden and, except for one, were blends of a coarse and a fine base fuel. Time and cost constraints did not allow separate trials to assess the effect of wood species on burner performance. The fuel specifications are given in Table I. The operating conditions during the trials are listed in Table II.

Test data

Input/output data for the different burner flames provide a direct indication of how well a particular fuel-burner-furnace combination works. However, detailed in-flame measurements are mandatory if the results are to be

4. Impact of fuel type on axial distribution of heat flux



extended to larger furnaces burning different fuels of variable quality.

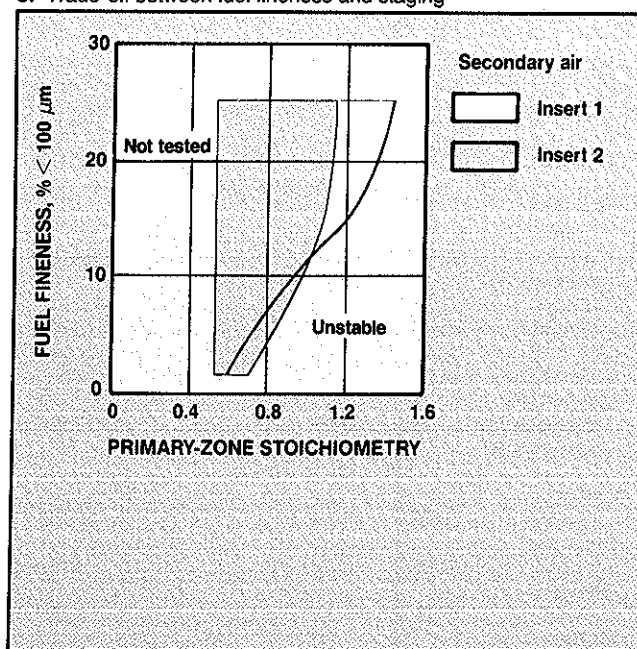
Figure 3 shows six different aspects of a single wood-fines flame. This flame (designated as F-20-2/3) involved a "fines" fuel fired at 2 MW (6.8×10^6 Btu/h) at a secondary swirl level of 0.9, a secondary air preheat of 150°C (302°F), and an overall stoichiometry of 1.2 (i.e., 20% excess air).

This was a staged flame, with the air entering the primary zone providing 75% of the stoichiometric requirement. The remaining portion of the required air (45%) was injected through the tertiary ports. An insert was used in the secondary annulus so that the secondary axial velocity component was 42.5 m/s (140 ft/s). The primary air velocity was 18 m/s (59 ft/s).

Figure 3A shows the aerodynamic flow patterns for flame F-20-2/3. This pattern is typical for a swirl burner used in boiler applications. The strong toroidal recirculation flow at the mouth of the burner contributes to the flame's stability by recirculating hot combustion products from downstream back to the mouth of the burner. This provides the heat to dry and ignite the incoming fuel particles and stabilize the flame. There is a broad, annular, forward-flow region that eventually expands to the furnace walls. Outside the forward-flow region and near the front wall is an external recirculation zone (ERZ), where flow moves back toward the front wall. Along the centerline beyond the IRZ is a region of weak flow that fluctuates in direction.

Figure 3B shows the detailed temperature field for flame F-20-2/3. The incoming fuel and air were at room temperature, and the secondary and tertiary air were 150°C (302°F). Temperatures rise rapidly just outside the quarl to a peak of 1400°C (2551°F) and then fall to a relatively uniform temperature about a meter downstream. The temperature in the ERZ is significantly lower because of heat transfer to the walls. High-temperature gas from the hottest region of the flame is brought back to the mouth of the burner by the IRZ and then is cooled both by dilution with the incoming air and by evaporation of the moisture in the fuel.

5. Trade-off between fuel fineness and staging



Wet fuels are less stable than dry fuels. As higher-moisture particles are dried and heated by the IRZ gases, these gases are cooled, thus slowing down the heat-transfer process. At the same time, the moisture disproportionately extends the time for particle ignition. Particle ignition delayed beyond the IRZ breaks the feedback loop and causes flame instability.

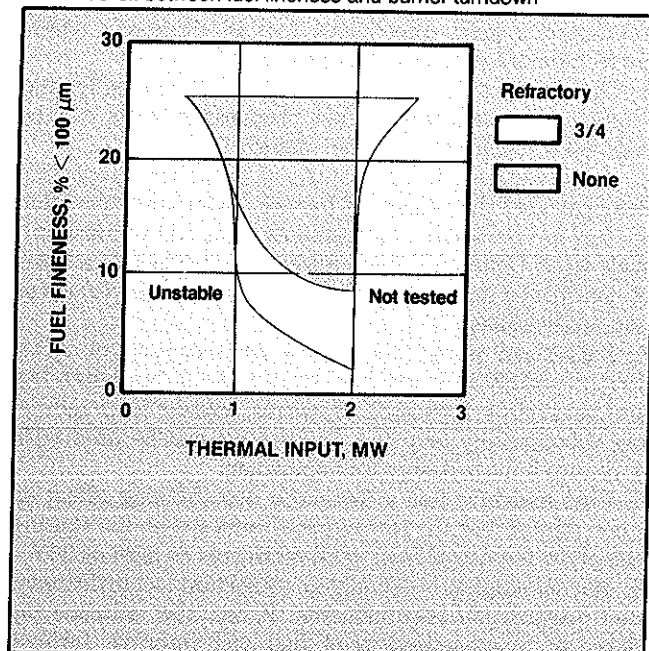
Figure 3C shows the concentration of solid particles in flame F-20-2/3. The location of the primary fuel and air stream can be seen just outside the quarl in the $400\text{-g}/\text{N}\cdot\text{m}^3$ ($0.025\text{ lb}/\text{N}\cdot\text{ft}^3$) region. This annular region of high concentration is slightly larger than the actual primary annulus because the primary stream is entrained in the faster-moving secondary air. The annular area of high concentration is rapidly dispersed by aerodynamic effects and takes on a "candle flame" shape downstream. The particle concentration decreases because of (a) dilution with secondary and tertiary air and (b) combustion of the wood particles.

Figure 3D shows the progress of particle burnout. In the immediate vicinity of the IRZ, only 20% burnout has been achieved; but 90% completion is achieved in a narrow region within 1 m (3.28 ft) of the burner. This is a compact, high-intensity flame.

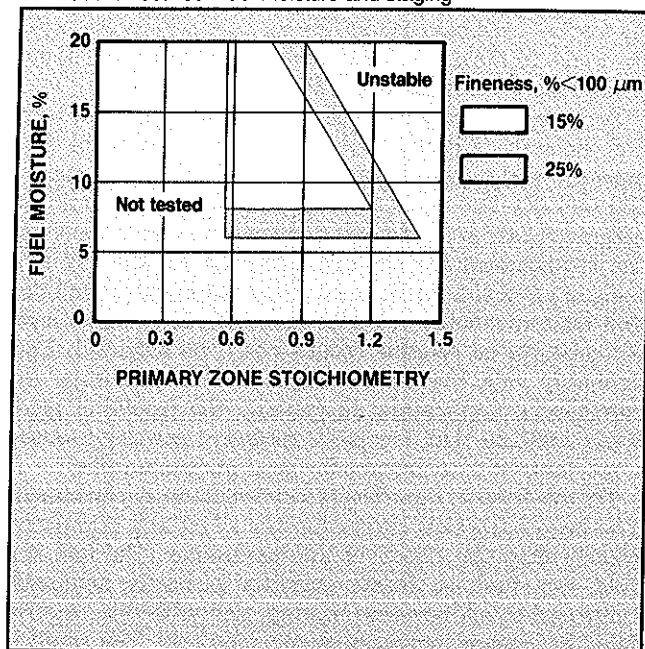
The progress of combustion for this flame can be further detailed with the oxygen (O_2) and carbon monoxide (CO) profiles shown in Figs. 3E and 3F, respectively. The O_2 concentration is high in the region of the tertiary ports and stays relatively high around the outside of the flame. O_2 is rapidly depleted by combustion in the central core of the flame to the ultimate level of the stack-gas O_2 concentration. The CO concentration profile is just the opposite of the O_2 profile, and high levels of CO occur in the IRZ. This is a staged flame, so the primary combustion zone is fuel rich. High CO concentrations would be expected, but these values of 4% and 5% for wood are exceptionally high. The CO concentration rapidly falls as the tertiary air mixes with the primary-zone combustion gases to the ultimate stack concentration.

Figure 3 represents only a small portion of the flame

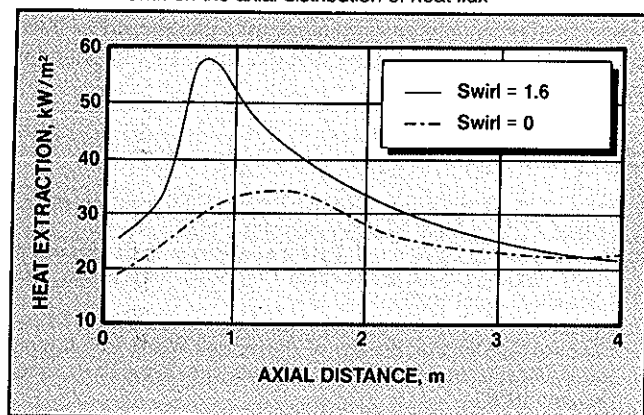
6. Trade-off between fuel fineness and burner turndown



7. Trade-off between fuel moisture and staging



8. Effect of swirl on the axial distribution of heat flux



data taken during the wood-combustion trials. A comparison of the detailed profiles for the various combinations of fuels and operating conditions can reveal the mechanisms for wood combustion and aerodynamic mixing that are important to overall stability and efficiency.

Test results

The flames were measured in great detail in an effort to increase our understanding of the wood-combustion process. This information can then be used to optimize the burner for stable and efficient operation with coarse, wet, pulverized wood.

A more global perspective on pulverized-wood combustion can be obtained by comparing the wood flames with the flames of other fuels. The heat extraction for each of the 17 furnace segments was taken for each of the pulverized-wood flames. Figure 4 compares the axial distribution of the heat extraction for the pulverized-wood flames with those of several other fuels. The data for fuel oil and petroleum coke were taken in the same furnace during previous trials at the IFRF. The natural-gas curve was taken as a baseline for the pulverized-wood trials.

It is clear from these curves that fuel oil is a far more luminous fuel than the others. This would also be true for most pulverized-coal flames. Under similar conditions, pulverized-wood flames are most similar to natural-gas flames. This is not surprising, considering that wood's high hydrogen and oxygen contents limits the soot-forming potential of wood at high heating rates. Petroleum coke has little volatile matter, so its soot-forming potential is also low, resulting in a low luminosity for petroleum-coke flames.

Two of the most important operating parameters for optimizing the use of these fuels in a burner are the swirl level and the degree of staging. More complete data are available in the IFRF report (1), but the trade-offs for fuel and operating parameters can be demonstrated with simple stability plots. These plots designate the regions where the flames operate stably.

Figure 5 shows a stability diagram for fuel fineness and burner staging. Previous studies of wood combustion (2, 3) have shown that only particles smaller than 100 μm contribute to early ignition. Thus, the fuel size distribution has been characterized by its fraction of fines, taken as the mass fraction of fuel particles smaller than 100 μm.

Figure 5 shows that there is a definite trade-off between the required fuel fineness and the degree of staging. With fine fuel having more than 25% fines, stable flames can be achieved without staging. This has been the experience in commercial practice with pulverized wood. Coarser fuels require deeper staging down to a level where only 75% of the stoichiometric air passes through the main burner when the fines content drops to 3%. The fact that stable flames can be achieved with such coarse fuel attests to the utility of this experimental program in optimizing burner design for the minimum (and therefore most economic) fuel preparation for industrial application.

Figure 6 shows the trade-off between burner turndown and fuel fineness for unstaged flames. With 25% fuel fines, good stability is achieved for firing rates between 0.5 MW (1.7×10^6 Btu/h) and 2.5 MW (8.5×10^6 Btu/h). This wide turndown is important when substituting pulverized wood

for gas and oil in boilers where load swings are expected. As the fuel becomes coarser, the turndown decreases until the fuel with fineness of 3% could only be stabilized at one firing rate, the design load 2 MW (6.8×10^6 Btu/h).

Perhaps the most dramatic result of the trials was with fuel moisture. Figure 7 is a stability diagram for fuel moisture and burner staging. With relatively fine ($25\% < 100 \mu\text{m}$) dry fuel at 8% moisture, stable flames could be achieved at all levels of staging. As fuel moisture increased, the requirement for staging increased rapidly. At 20% moisture and similar fineness, deep staging was required and little turndown could be achieved. Above this level of moisture, no reliable results could be achieved. This probably sets the upper limit on fuel moisture for commercial application. In general, the results of these trials indicate that the fuel's moisture content is more important than its fineness for good burner stability.

Figure 8 shows the effect of swirl on flame performance. The heat-extraction curves for low swirl and high swirl clearly show the effects of this parameter. The fuel is a fine, dry fuel, so flame stability is easily achieved. Increased swirl increases mixing, and with this reactive fuel, that means increased combustion rate. The result is a more compact, higher-temperature flame, as seen in Fig. 8.

Summary

The results presented here can be summarized as follows:

1. Wood is a reactive fuel with low CO, NO_x, and SO_x, making it a good alternative fuel in situations where environmental constraints are a factor.
2. The firing of pulverized wood is economically and strategically attractive if fuel preparation costs can be reduced by optimizing burner design.
3. The investigation into the use of pulverized-wood fuel demonstrated the impact of burner design and operation on fuel preparation requirements in a semi-industrial-scale trial. Detailed flame measurements provide a basis of confidence for scaling these results to other furnaces and applications.
4. Pulverized wood fuel with a fines content of $25\% < 100 \mu\text{m}$ and 8% moisture provides excellent flame stability and general performance. However, coarser fuels requiring substantially less fuel preparation can be used with optimum burner design and operation.
5. Fuel moisture has a dramatic destabilizing effect on wood flames, but the technique of combustion-air staging can allow the use of fuels with moistures as high as 20%.
6. Burner staging is not only an important tool to decrease fuel preparation requirements. It can also enhance the flame of a pulverized-wood fuel and improve furnace performance.
7. Pulverized wood flames are most similar to natural gas flames as far as furnace heat transfer is concerned. The heat-transfer characteristics of natural gas should be used as a design basis when retrofitting a fossil-fuel burner for wood fuel.

Literature cited

1. Schmid, C., International Flame Research Foundation report F 091/a/1, Ijmuiden, Netherlands, June 1985.
2. McLean, W. J., Ignition of Pulverized Fuels: A Comparative Study, Western States Sectional Combustion Institute, Salt Lake City, April 1982.
3. Reuther, J. J., Karsner, G. G., and Jack, S. T., Plane Flame Furnace Combustion Studies of Pulverized Wood, Fundamentals of Thermochemical Biomass Conversion, Estes Park, Colo., October 1982.

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