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Air Flow, Mixing, and Modeling for Recovery Boilers

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# AIR FLOW, MIXING, AND MODELING FOR RECOVERY BOILERS

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## ABSTRACT

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The purpose of this paper is to examine the physics of gas mixing as it applies to recovery boiler furnaces. The basic features of recovery boiler furnaces are first reviewed. These features include furnace configuration, air port layout and dimensioning, and liquor gun placement. This information is used to identify the key gas mixing characteristics of recovery boilers. The concepts of both macro- and micro-mixing are then illustrated. Macro-mixing of gases using single and multiple air jets is discussed. A simple mill example of the operation of gas jets is presented to illustrate the key features of jets. Research on two mixing situations analogous to recovery boilers, pipeline mixing and dilution-jet mixing, are then reviewed. Results from these studies lead to a clearer indication of what constitutes macro-mixing in recovery boiler furnaces.

Micro-mixing is the final process that brings fuel and oxygen together for combustion. Micro-mixing is first defined in terms of turbulent intensity, intermittency, and a probability density function. These concepts are then applied to the case of simple jet mixing. This leads to a portrayal of highly non-uniform local gas composition and temperature as characteristic of recovery boiler combustion situations. The impact of micro-mixing physics on gas phase reactions, on in-flight black liquor droplet/particle reactions, and on surface corrosion reactions is discussed. Incomplete mixing will be shown to complicate the direct applicability of laboratory combustion rates to the recovery furnace situation.

## INTRODUCTION

Over the past two decades the internal processes occurring in recovery boilers have received a great deal of attention. Understanding the fundamentals of black liquor combustion is one necessary step in understanding the whole complex process in recovery boiler furnaces. Black liquor chemistry, char bed processes, and furnace gas mixing must also be mastered to make substantial improvements in this mature technology.

The last of these, furnace gas mixing, has been under active examination for the past decade or more. Research has been carried out using small-scale physical models and, more recently, using techniques of computational fluid dynamics (CFD). At the same time, many new or modified recovery boiler air delivery systems have been installed in full-scale mill operations. There is now a wealth of research results and practical experience with recovery boiler air systems. Though many of the new and modified air systems have provided improved recovery boiler performance, this has not always been the case. As well, no fundamental understanding of the basic principles of air injection and recovery boiler gas mixing has emerged. Some of this may come out as CFD application to recovery boilers continues. However, it may help interpretation of the existing information to examine the basic physics of gas mixing. That is the intent of this paper.

In this paper, the fundamental understanding of gas mixing in other situations will be presented and discussed in terms of the recovery boiler application. As well, the physical understanding of turbulent mixing of gases and the means for describing this process will be presented. Several examples of how these concepts of gas mixing can be applied to recovery boiler processes will then be presented.

## RECOVERY BOILER COMBUSTION

Presented in **Figure 1** is a simple schematic of the lower furnace of a recovery boiler. The general layout of a conventional three-level air system is shown along with one of several black liquor guns,

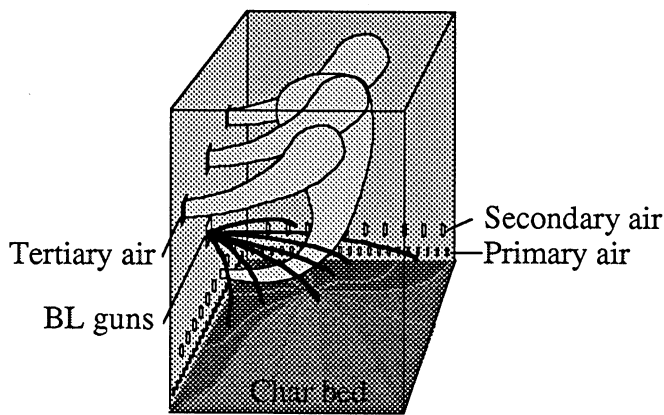


Figure 1—Schematic diagram of a recovery furnace.

and the char bed lying on the floor of the furnace. For illustrative purposes, four air jets are shown issuing from the airports on the same wall as the liquor gun. Of course, air is injected from all the ports, and the pattern of air flow is far more complex than shown here. However, the most important aspects of recovery boiler combustion are clearly portrayed: the air and fuel (black liquor) enter the furnace separately, and mixing of the fuel and air occurs throughout the lower furnace volume.

A scale is not provided in Figure 1, but a typical wall dimension is 10 m. The schematic diagram correctly shows that fuel and air introduction are separated by as much as 5 m. This is very unusual for a combustion device. Combustion can not occur until the fuel and air get together on a molecular scale. In virtually every other combustion device, the fuel and air are introduced through the same opening, or from immediately adjacent openings. They are usually introduced with high relative velocity so that mixing is assured by proximity and by shear between the flows. This clearly is not the case for a recovery boiler. The initial mixing situation in a recovery boiler is very poor. There are other process reasons which have made this the preferred arrangement for recovery boilers, but this arrangement hampers mixing for good combustion.

The issue of gas mixing can be better understood by reference to **Figure 2**. This figure presents a simple diagram of the overall process of gas mixing. The mixing stages are somewhat arbitrarily broken into

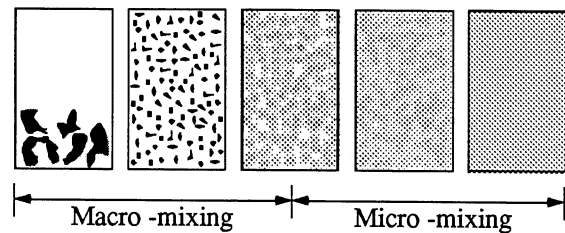


Figure 2—Schematic diagram of macro-mixing and micro-mixing.

“Macro-mixing” and “Micro-mixing.” For fuel and air to react chemically during the combustion process, the individual molecules must bump into each other. This implies mixing on a very fine scale. The job of the air and liquor delivery systems is to first bring the fuel and air generally into the same region by shear and turbulence (macro-mixing) and then to let ordinary diffusion processes bring them together on a molecular level (micro-mixing). Separation of the fuel and air delivery points definitely hampers the first of these. Having the combustion process distributed throughout the furnace volume, and generally away from the high shear air jet regions, hampers the second of these processes. From this perspective, recovery boiler air and fuel systems could not be more disadvantageously arranged for proper combustion. However, the arrangement does work, and the basic processes responsible for the current level of success need to be enhanced to gain improvements in combustion efficiency, stability, and pollutant emissions.

The starting point for understanding the current air system operation is the single air jet. The processes associated with single jets will be discussed below, followed by presentation and discussion of how they are used in other mixing situations.

## CHARACTERISTICS OF A SINGLE GAS JET

Jets of fluid issuing into quiescent surroundings or into other flow situations have been studied for many years. **Figure 3** shows a schematic diagram of a single gas jet along with a representation of two of the most commonly discussed features of these jets: entrainment and velocity/concentration profiles. The figure shows the jet issuing into a quiescent sur-

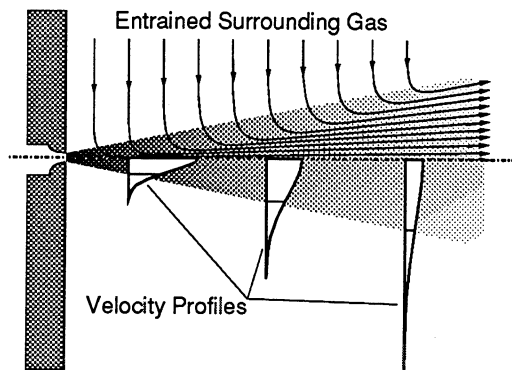
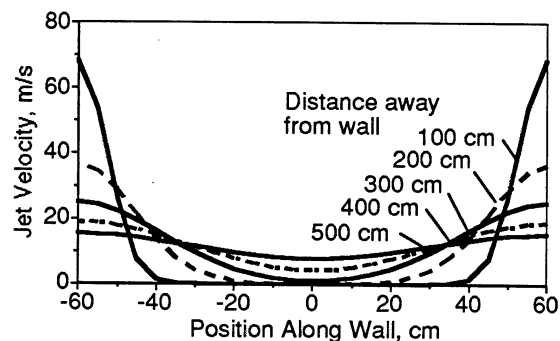


Figure 3—Characteristics of a single jet.

rounding. The gradation in color or gray levels is intended to indicate mixing of the dark jet fluid with the surrounding lighter fluid. Velocity/concentration profiles are shown in the lower half of the schematic at three locations. The bell-shaped profiles are evident, with faster/higher concentration fluid near the centerline, and slower/lower concentration fluid away from the centerline. The peak velocity/concentration decreases and the jet “width” increases with distance away from the nozzle.

The upper half of the jet schematic in Figure 3 shows streamlines for the surrounding gas which has been entrained by the jet flow. Entrainment is the process by which surrounding material is brought into the region of the jet, thus slowing and diluting the jet. In fact, this is the most important point that can be taken from this jet schematic: jets mix by entrainment of surrounding fluid.

One simple result of this view of jet operation that is directly applicable to recovery boiler air system design is the negative impact on mixing of placing the air jets too close together. Reliable equations for jet velocity profiles both as a function of distance away from the nozzle, and away from the jet centerline, are readily available [1]. A simple plot of velocity profile for two adjacent jets is shown in **Figure 4**. Here a specific example applicable to a recovery boiler has been used. Two 25 cm nozzles are placed 120 cm apart on a wall. The gas velocity profiles at five distances from the nozzles are plotted. Up to a distance of 300 cm, or 12 nozzle diameters, the jets act independently,



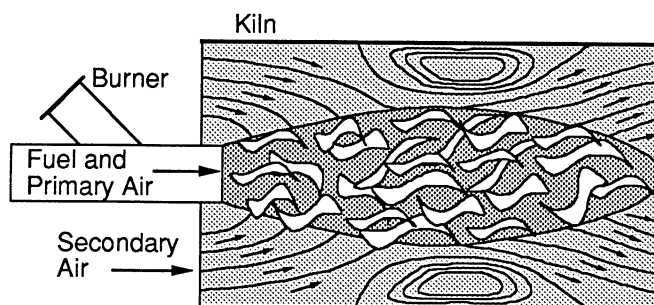
Velocity profiles for two 25 cm diameter nozzles 120 cm apart

Figure 4—Interaction between two adjacent jets.

the jets can interact strongly. At 400 and 500 cm, the two jets are entraining their own jet fluid rather than surrounding gas, at least over a portion of their circumference. As a result, gas mixing between fuel (surrounding gas) and air is hampered and combustion is slowed.

The simple example above places an emphasis on entrainment as the key to good combustion when gas jets are employed. A practical example of this in a kraft pulp mill is the flame in the lime kiln. **Figure 5** shows a schematic of a very simplified front-end of a lime reburning kiln. Primary air is provided along with the fuel (usually natural gas or fuel oil) through the burner. Primary air constitutes between 5% and 25% of the total combustion air. This means that 75% to 95% of the combustion air must be mixed with the burner flow to achieve complete combustion. The jet of burner fluid (fuel plus primary air) *entrains* the induced secondary air to accomplish this end. Typically, the burner flow has more capacity for entrainment than is satisfied by

Figure 5—Mixing in the confined flame of a rotary lime reburning kiln.



the secondary air, so gas recirculation occurs, as shown. This can protect the refractory, and because flame gases are being recirculated, provides flame stability.

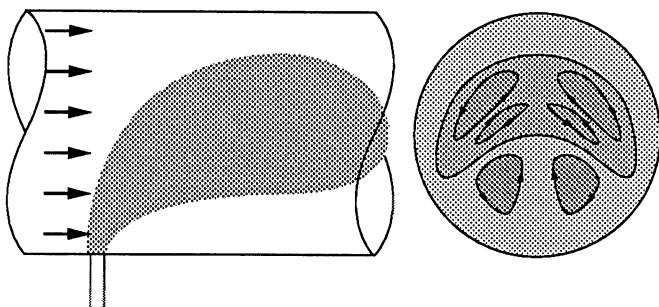
The general schematic of a jet and the specific example of the lime kiln flame both highlight jet entrainment as a key to good mixing. The following two sections present some of the results from two other fluid mixing applications: pipeline mixing and dilution-jet mixing.

## PIPELINE MIXING

Pipeline mixing is generally not a combustion situation. Usually a small quantity of material is to be added to a larger pipeline flow. Chemical reactions may occur, but often just simple material dispersion is involved. Internal elements can be used, but where minimum main flow pressure drop is important, the typical arrangement is for one or more small jets oriented normal to the main pipeline flow. This and other pipeline mixing situations are discussed in reference [2] and [3], which also provide access to the literature in this area.

A schematic diagram of pipeline mixing for the case of a single normal jet of fluid mixing with a main pipeline flow is presented in **Figure 6**. The jet-in-crossflow geometry of this situation has been studied in many other situations including stack plume dispersion. The jet initially moves normal to the main flow, but is gradually turned to flow parallel with the main flow. The end view of this situation is also shown in Figure 6. The well-recognized pattern

*Figure 6—Pipeline mixing schematic.*



of double, counter-rotating vortices is portrayed in this end view.

Many different mixing patterns are possible with this basic geometry. For the same flow of pipeline material and jet material, a larger nozzle would cause the side stream flow to enter with a lower velocity. The “plume” would then not penetrate as far, and would run along the lower portion of the pipe. Mixing is slower for this case. A smaller jet would increase the velocity and send the plume to the upper portion of the pipe, again slowing mixing. In fact, the fundamental result of a great deal of study of pipeline mixing is that whatever the flows, the minimum mixing distance occurs when the plume finishes along the centerline of the pipe.

Initially it would seem logically that the faster the jet the better the mixing. However, this view of jets is basically that their main action is to “push” other fluid around and create turbulence in much the manner of stirring cream into coffee with a spoon. In fact, jets mix by entrainment, so the geometry and operation which enhances entrainment enhances mixing.

In pipeline mixing, having the jet penetrate to a point where it flows along the centerline is the best mixing because it promotes entrainment. With the jet flow centered on the pipeline axis, the physical distances between the two fluid streams is minimized. As well, the double vortices continue to entrain the surrounding pipeline fluid.

The important point to take away from pipeline mixing that is applicable to recovery boilers is not that the jet should be centered on the pipeline flow, but that entrainment is the key to mixing in this situation. Centering the jet provides the best entrainment and, therefore, the best mixing.

## DILUTION JET MIXING

Dilution mixing has been an essential part of gas turbine design since its invention. The issue always has been that the blades of the turbine wheel cannot tolerate the high temperatures associated with the

combustion of most common fuels. As a result, gas turbine combustors are designed to first burn the fuel almost completely using near-stoichiometric quantities of air. This occurs in the first section of the combustor. Thereafter, additional air is mixed with the hot combustion products to ensure complete combustion and reduce the mixed gas temperature to a level turbine blades can tolerate. This latter section of the combustor is the dilution section, and the process is referred to as dilution jet mixing.

Dilution jet mixing has been studied by many researchers. Some of the most comprehensive experimental work has been reported in references [4] and [5] which also give access to the rest of the literature in this field. This work [4,5] dealt with experiments to develop simple design criteria for single-sided and two-sided jet systems, with either opposed or staggered jets in the two-sided arrangement. The dilution jets were oriented normal to the flow in a rectangular main duct. The jet fluid and main fluid were at different temperatures so that thermocouples could be used to map temperature fields downstream from the dilution jets. One important difference compared to that for pipeline mixing, aside from the number of jets, is the relative quantity of dilution jet flow. In pipeline mixing the injected material usually represents only a small fraction of the total flow. With dilution jet mixing, the injected material can be as much or more than the main flow. This is more similar to the recovery boiler situation.

**Figure 7** is a schematic of a two-sided, opposed jet dilution mixing situation. Both the side view and the end view are reminiscent of the pipeline mixing case. **Figure 8** shows a two-sided, staggered jet situation. The pattern shown for both is the optimum dilution jet mixing result. The conclusion from a large series of tests is very similar to the pipeline mixing situation. With multiple jets, the duct is conceptually partitioned into segments. The size and arrangement of the dilution of jets is selected to yield a final jet flow along the centerline of their respective segments of the duct. This is easy to visualize from the schematic in Figure 7. This approach causes the spacing of staggered jets on one side of the duct to be four times that of opposed jets.

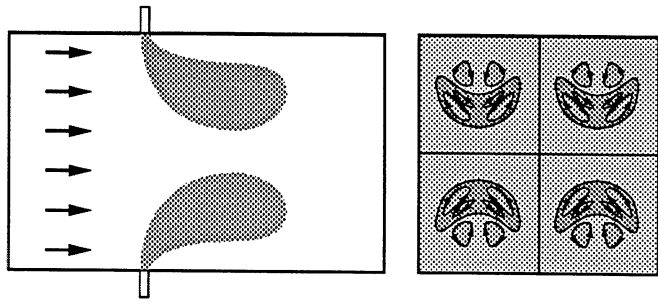


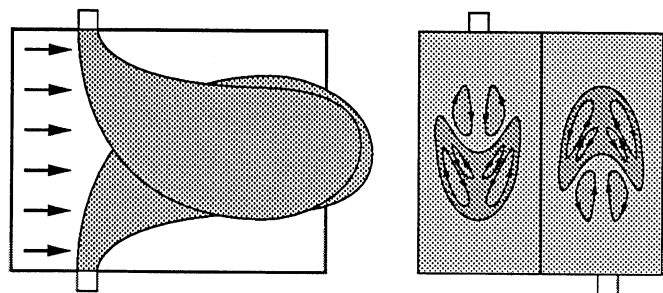
Figure 7—Dilution jet mixing for opposed jets.

The dilution jet mixing results hold some important concepts for recovery boiler air systems. First, even with multiple jets on two walls, the basic physics of mixing remains the same as for pipeline mixing. Entrainment is the key to mixing, so access to the surrounding fluid by the jet is the most important aspect of mixing. Secondly, there is no attempt with the opposed jets to have them penetrate to the center of the furnace. Likewise, the arrangement of the staggered jets avoids shear between adjacent jets from opposite sides. This would only promote jet-jet entrainment, instead of jet-surrounding fluid entrainment.

## MACRO-MIXING WITH JET SYSTEMS

The key element from the foregoing is that jet entrainment is the most important physical process in jet mixing. Most of the emphasis so far has been on macro-mixing which is usually the main focus of pipeline mixing and dilution jet mixing. The simple examples of the interaction of adjacent jets and of

Figure 8—Dilution jet mixing for staggered jets.



dilution jets give a clear indication that size and layout of air nozzles will be the most important aspect of design for maximum entrainment. Jet penetration to or across the centerline of the furnace is probably not a desirable goal of design. As well, breakup of a column or channel created in the lower furnace of a recovery boiler should be by entrainment of the channel into the tertiary jets.

Once the focus of recovery boiler air jet design shifts to entrainment as the key feature, then several design techniques offer significant potential for improved recovery boiler air jet design. The first alternative would be the use of both large, low-pressure air nozzles along with small, high-pressure nozzles. This is not a new idea. Such systems were developed decades ago for stoker-fired coal boilers. In this application to coal boilers, small steam jets operating above two atmospheres pressure were used to enhance mixing and eliminate smoke. A second alternative to improve recovery boiler mixing would be the use of air jet swirl. It is well known from other combustion applications that swirl significantly enhances entrainment and mixing. The third alternative would be the use of rotation. Tangential firing has been used for many years for air introduction above the black liquor guns by one recovery boiler vendor and, more recently, by another vendor below the black liquor guns. Rotation provides relative motion between the jets and surrounding fluid, allowing easier access for entrainment.

The above material is directed at macro-mixing. The following sections treat micro-mixing and present examples of the impact of micro-mixing on some of the other processes occurring in recovery boiler furnaces.

## DESCRIPTION OF TURBULENCE AND MIXING DETAILS

### *Turbulent Eddy Structure and Intermittency*

A schematic of a single jet issuing into a quiescent environment is presented again in **Figure 9**. This time more of the physical nature of the process is portrayed. There is shear between the jet and the surrounding gas. Jet material slowed by the sur-

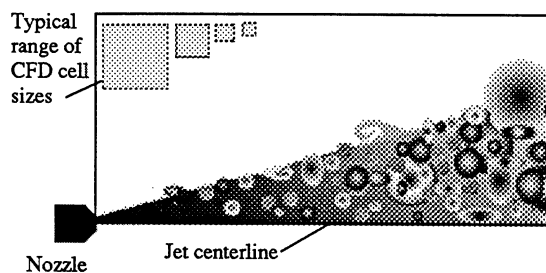


Figure 9—Mixing details for a jet.

rounding gas curls up into a backward-facing swirl, as shown for a couple of examples near the “edge” of the jet. Likewise, surrounding fluid entering the jet curls up into a forward-facing swirl. These swirls become “eddies” of material which have concentrations similar to the region where they originated. The general character of the eddies is approximately portrayed in the figure. The eddies have a characteristic concentration, but it is not uniform across the eddy, nor is there a clear edge to an eddy. As well, the eddies are generated in all sizes up to ones approximately the size of the local jet diameter. Smaller eddies are generated by the jet shear and by shear between the larger eddies. In fact, shear between the larger eddies is the main mechanism for turbulent dissipation. Large eddies interact to form smaller eddies, which interact to form even smaller eddies. This continues until the eddies reach a size where ordinary viscous dissipation brings the fuel and air together for reaction on a molecular level.

For comparison purposes, the approximate sizes of the computational fluid dynamic cells currently used for recovery boiler modeling are shown. The characteristic dimension of the cells ranges from approximately one-half the width of the nozzle to about 8 to 10 times the width of the nozzle. Comparing these cells to the eddies, which can be as large as the jet, gives a physical picture of turbulence which will be difficult to model theoretically or computationally.

**Figure 10** presents concentration profiles for a slice of the jet at one axial location. On the right of the figure is the same concentration profile depicted in **Figure 3**. A smoothly varying concentration from a

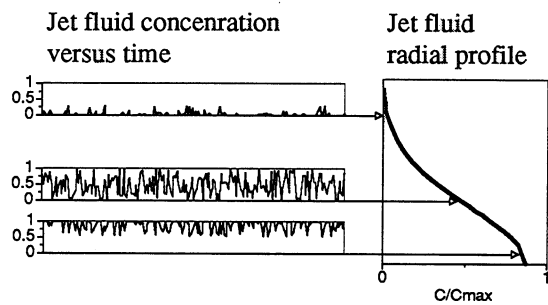
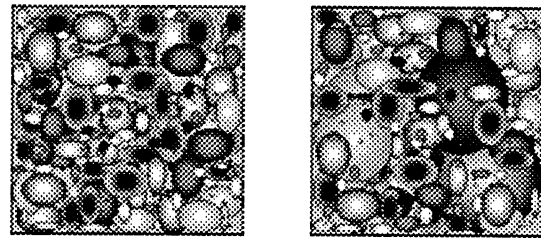


Figure 10—Concentration profiles for a jet versus time and position.

peak of about 0.8 (1.0 is jet fluid) along the jet centerline to nearly zero (indicating surrounding fluid) away from the centerline. The three traces on the left depict the concentration as a function of time at three locations. These traces are similar to the conventional portrayal of turbulence as a fluctuation component about a mean value. One difference in Figure 9 is the characteristic of the traces at the two extreme positions to frequently have values of one (near the jet centerline) or zero (far from the centerline.) The trace that is far from the centerline shows that this location is mostly surrounding fluid, and only *intermittently* has concentrations other than this. The conventional portrayal of random fluctuations about a mean value is not incorrect, but would not give a clear indication of the limitation on chemical reaction. Reaction rate depends on the instantaneous fuel and air concentrations. Intermittency allow first fuel, then air to pass through a region. Clearly, at the instant when the location being measured contains only air or only fuel, no reaction is occurring.

#### Probability Density Function for Stoichiometry

Figure 11 shows a graphic of what the eddy structure might look like in one CFD cell at two instants in time. To be clear, this is only a graphic, not the result of specific test results or data. However, it does capture the basic character of the eddy structure of the flow. The individual eddies have characteristic, but not uniform, concentrations of “fuel” and “air.” Their boundaries are not as clearly defined as in Figure 11. The eddy size range is quite broad, and both the size range and distribution of fuel-rich and air-rich eddies changes from instant to instant.



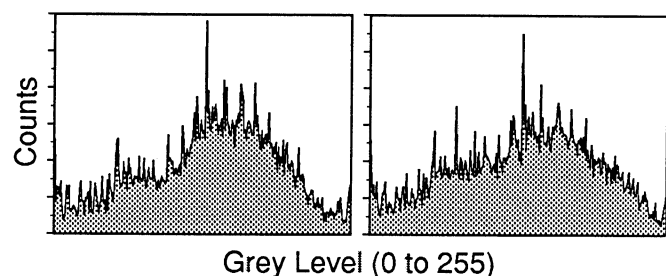
Cell concentration at two instants in time

Figure 11—Concentration non-uniformity in a cell at two instants in time.

Figure 12 is one portrayal of the stoichiometry information in Figure 11. A gray-scale histogram is plotted for each of the two depictions of the cell in Figure 11. A glance at these plots confirms that there is some black areas and some white areas, but most of each graphic consists of various shades of gray distributed throughout the cell. The shades of gray are intended to depict different stoichiometries, or relative concentrations of fuel and air.

Though the two graphics in Figure 11 were drawn separately, their respective histograms in Figure 12 show some important characteristics of actual turbulent mixing. First, the mean value of “stoichiometry” is nearly the same at the two instants in time. Second, despite the substantial difference in the look of the two graphics in Figure 11, the distribution of gray scales, or stoichiometries, is nearly the same. These are characteristics of actual steady turbulent combustion situations.

Figure 12—Concentration histograms for a cell at two instants in time.



The histograms in Figure 12 have some of the general features of a normal distribution of stoichiometries. This similarity is the basis for the Probability Density Function (PDF) approach to reaction rate in a turbulent combustion situation. The kinetic reaction rate depends on the concentration of fuel and oxidizer, as well as temperature. Each of these varies across the cell in a pattern generally like that shown in the Figure 11. Because the PDF's are approximately constant with time, they can be used to first evaluate the kinetic rate expression for each combination of fuel, air, and temperature, then integrated to produce an effective reaction rate. In practice, normal distributions are assumed with the mean values equal to the calculated mean for the cell (from a CFD calculation) and the standard deviation is determined from the turbulent kinetic energy and dissipation rate. As turbulent mixing progresses, the standard deviation decreases until the concentrations throughout the cell approaches the value for the overall mean stoichiometry.

This approach has several advantages. It reasonably portrays the physical situation in turbulent mixing. It allows the chemical reactions to proceed at a rate determined both by chemical kinetics and by mixing. It also allows for incomplete combustion when turbulent mixing is incomplete. For near-stoichiometric conditions, if the standard deviation in concentrations does not go to zero, then there will be regions of the cell which are sub-stoichiometric. Combustion in these regions will be incomplete, and for most fuels including black liquor, there will still be some unburned CO. Other regions of the cell will necessarily have excess air, so O<sub>2</sub> will also exist. Considering that CO oxidation only takes about 20 ms at 1100°C, measurement of CO and O<sub>2</sub> in the same region of space under combustion conditions indicates that mixing is incomplete. This is correctly reflected in the PDF approach when the standard deviation (turbulence scale) is not zero.

### ***The Magnussen Model***

Another approach to modeling combustion in turbulent flows is the Magnussen Model [6]. A graphical depiction of the physical basis for this model is shown in Figure 13. This figure is not an individual

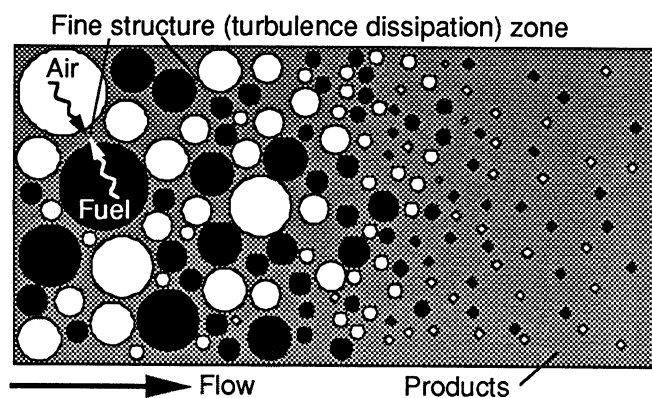


Figure 13—Physical picture for the Magnussen model.

cell, but simply a very idealized flow situation. The turbulent eddies are shown as pure fuel and pure air, though this not necessary for the model. There is a range of sizes of eddies which are initially fairly large. As the flow moves to the right, the eddies break down into smaller eddies, and some of the eddies dissipate into the gray region labeled “products.” This is the general pattern of turbulence, big ones become little ones, and little ones dissipate by vicious forces. In Figure 13, fuel and air are shown to enter the dissipated “products” region from relatively large eddies. This is a convenience for drawing purposes only.

What is correctly portrayed in Figure 13 is that the rate of reaction or formation of products is equal to the rate that fuel and air enter the dissipation region. The rate that fuel enters the products region is just the mean fuel concentration for the cell multiplied by the rate of turbulent dissipation. Likewise for the air. Either the rate of fuel or air entering the dissipation region can limit reaction rate. As described here, only the mixing rate is considered in the reaction rate. In practice, the mixing rate is compared to the chemical kinetic rate to determine which is the rate-limiting step. For most combustion situations it is almost exclusively mixing-rate-limited reaction rate.

A feature of the Magnussen Model which is essential for many combustion circumstances is that the reaction rate can also be limited by the rate that

products enter the dissipation region. The basic idea here is that the fuel and air eddies are not hot enough to react when mixed. The products are hot, so when the three are mixed, then reaction can occur. The chemical kinetic expression would show this if it were evaluated at the fuel and air temperature. However, it is usually the mean cell temperature that is used in the kinetic expression.

The requirement that products must be present for reaction to occur has a physical basis common to a broad spectrum of combustion situations. Recirculating flows are used in a very wide range of burner situations to ensure stable combustion. Recirculation of hot combustion products provides the high temperatures for fuel and air reactions to proceed rapidly. This very practical combustion fundamental is imbedded in the Magnussen Model. With a little foresight and manipulation, it can also be a part of the PDF approach if the PDF for the cell temperature is correctly related to the PDF's for fuel and air.

## SOME IMPLICATIONS OF MIXING FOR RECOVERY BOILERS

The concepts of macro- and micro-mixing presented above are being incorporated into both CFD modeling research and practical recovery boiler application. The purpose of this section is to present examples of how the mixing concepts may affect the view of recovery boiler processes. The three examples are: 1) the fuel-NO<sub>x</sub> mechanism, 2) in-flight char burning, and 3) recovery boiler wall tube corrosion. These are meant to be examples in order to highlight the mixing concepts rather than definitive results and conclusions about the three topics presented.

### *The Fuel-NO<sub>x</sub> Mechanism For Recovery Boilers*

NO<sub>x</sub> emissions from recovery boilers are increasingly coming under stringent permit limitations. Previous research on NO<sub>x</sub> formation mechanisms strongly supports the fuel-NO<sub>x</sub> mechanism over either the Thermal-NO<sub>x</sub> or the Prompt-NO<sub>x</sub> mechanism. Like other fuels, black liquor contains nitrogen as part of its organic content. A portion of this nitrogen is released during pyrolysis and char burning in the form of NH<sub>3</sub> and HCN (and probably also

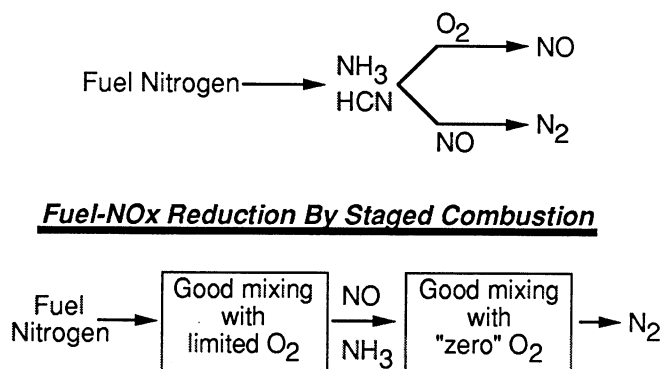
N<sub>2</sub> and NO). Both NH<sub>3</sub> and HCN can be oxidized to NO during combustion and this NO is referred to as fuel-NO<sub>x</sub> because of the origin of the nitrogen.

The actual kinetic mechanism of conversion of NH<sub>3</sub> and HCN is a very complex one involving many individual elementary reaction steps between the original reactants and a wide range of intermediate radical species. It has been convenient, and not inaccurate, to present this process as two parallel paths for the conversion of fuel-nitrogen to NO and N<sub>2</sub>. This global process is shown in **Figure 14** [7], along with one of the practical approaches to reducing fuel-NO<sub>x</sub>, staged combustion.

In general, the upper path in fuel-nitrogen conversion is favored at normal combustion temperatures whenever there is O<sub>2</sub> present. The lower path competes effectively only when temperatures are below about 1000°C or O<sub>2</sub> is nearly completely depleted. Staged combustion takes advantage of this latter situation by supplying insufficient oxygen for complete combustion of the main fuel, then allowing the NO formed to react with the remaining NH<sub>3</sub> (or HCN). This reduces a substantial portion of the fuel-nitrogen specific to N<sub>2</sub> before additional air is introduced to complete combustion of the main fuel.

A key element of the staged-combustion scheme is shown in both boxes of the lower graphic in **Figure 14**, good mixing. For a burner with high relative velocity and swirl, along with fuel and air introduction together, good mixing is relatively easy to achieve. This is not the case for recovery boilers. For

Figure 14—Fuel-NO<sub>x</sub> mechanism.



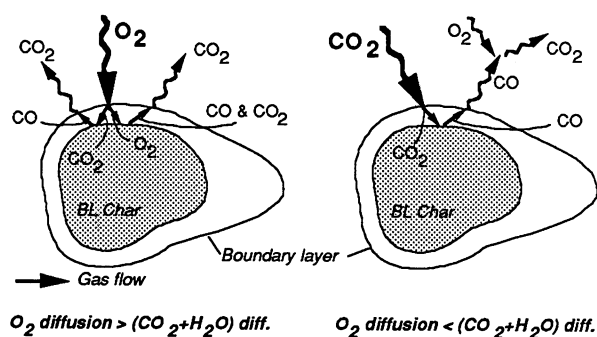
recovery boilers, the initial separation of fuel and air is very large, and the scale of turbulence is huge. Recovery boilers are naturally staged, but good mixing is not a characteristic of recovery boiler flows.

The combination of relatively poor mixing rates along with relatively low values with NO generated should dampen any optimism that the fuel-NOx mechanism portrayed in Figure 14 could be anything more than modestly effective for NOx control in recovery boilers.

### **The Black Liquor Char Combustion Mechanism**

The combustion of black liquor has been extensively studied over the past fifteen years. The basic steps in the mechanism and their rates are now relatively well understood, though liquor-to-liquor variations prevent precise calculation. An important aspect of the char burning stage of black liquor combustion is that char carbon can be consumed either by oxidation or by gasification. A graphic portraying the two processes in char consumption is shown in **Figure 15** for the situation where neither process is kinetically limited by low temperatures. For the oxidation case on the left, O<sub>2</sub> diffuses to the boundary layer where it either reacts with CO or continues to diffuse to the char particle surface. The reaction at the surface can produce either CO or CO<sub>2</sub> depending on temperature. For most combustion conditions the CO released at the surface is oxidized to CO<sub>2</sub> within the boundary layer (depending on temperature and water vapor content) and it is CO<sub>2</sub> which diffuses away from the boundary layer. For gasification only, CO<sub>2</sub> is shown diffusing to the boundary layer for simplicity though H<sub>2</sub>O also participates in gasification. CO<sub>2</sub> reacts at the char surface to form CO which diffuses away through the boundary layer and into the surrounding gas. CO is shown subsequently being oxidized to CO<sub>2</sub>.

The dominant mechanism for char consumption is dictated by the relative concentrations and diffusion rates of O<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O. Because of the required gradients for diffusion of the reactants and products, the processes of oxidation and gasification as depicted here are almost mutually exclusive.



**Figure 15—In-flight black liquor char particle combustion mechanisms.**

**Figure 16** shows a char particle traveling through a furnace against the backdrop of the eddy structure of gas composition within the cell. This depiction places a somewhat different light on the relative dominance of oxidation or gasification. **Figure 17** shows traces for the gray scale (stoichiometry) along the char trajectory of **Figure 16** as it passes through the two cells of **Figure 11**. The gray scale value where oxidation changes over to gasification has arbitrarily been taken as 125 in this figure. Within the normal range of stoichiometries in recovery boiler furnaces, this demarcation must be somewhere near the mean value of stoichiometries (gray scales) for each cell. What is clear from **Figure 17** is that whatever the mean concentration of gases in the cell, a turbulent field is going to ensure that the particle encounters both oxidation and gasification on its flight through the cell. Turbulent eddy range in size from more than a factor of ten larger, to less than a factor of ten smaller than a typical 2 mm black liquor char particle. Both oxidation and gasification could occur simultaneously on different portions of the char surface.

The depiction of char combustion in a turbulent field points to the need for black liquor combustion data under non-uniform conditions. Heat transfer arguments could be used to conclude that the drying and devolatilization processes are less affected by the turbulent flow field (though convection may be enhanced), but char combustion rate may differ significantly from that for steady, uniform gas-phase conditions.

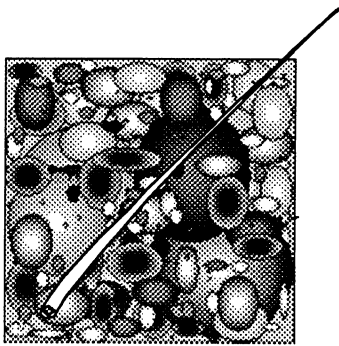


Figure 16—Black liquor char particle flight through a CFD cell.

### Furnace Wall Tube Corrosion

Corrosion of the furnace wall tubes has been a chronic problem in recovery boilers. Corrosion rates are known to be affected by tube wall temperature and by the solid, liquid, or gas-phase composition near the surface. Active research in this area is being pursued. The portrayal of turbulent gas-phase concentrations presented here may bear on the interpretation of corrosion experiments. Shown in **Figure 18** is a cell next to the furnace wall tubes. This cell would be oversized for CFD calculations, but the important point demonstrated is that the wall tubes are subjected not to a constant mean gas composition, but to an intermittent, variable composition. For any corrosion reaction dependent on gas composition, the results in a recovery boiler are not likely to be the same as for a test specimen subjected to the same mean gas composition.

### IMPLICATIONS FOR RECOVERY BOILERS

The physical arrangement for introduction of air and fuel into recovery boilers hinders mixing and rapid,

Figure 17—Gas composition around an in-flight char particle for the two cells of Figure 11.

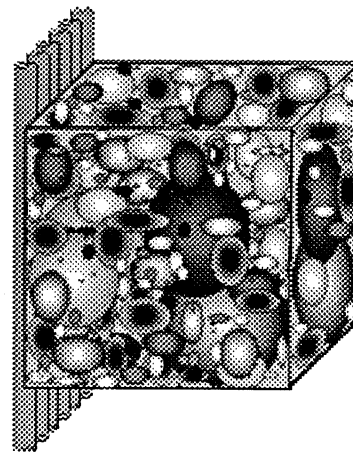
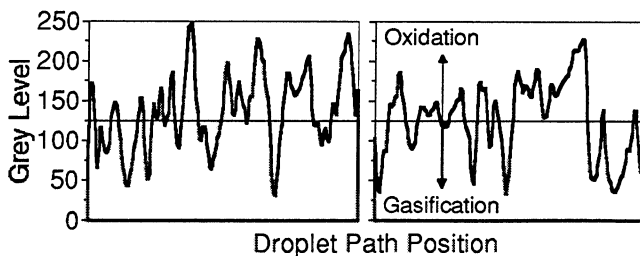


Figure 18—Gas composition near the wall tubes of a recovery furnace.

complete combustion. The air jets are the key feature of recovery boilers for improving gas mixing, and the main physical mechanism of their operation is entrainment. Improvements in recovery boiler mixing can only be obtained by improvements in air nozzle size, number, and velocity which improve entrainment.

### IMPLICATIONS FOR RECOVERY BOILER MODELING

Turbulent mixing is the physical mechanism for bringing fuel and air together. Three descriptions of turbulence were presented: eddy structure, intermittency, and probability density function. The physical models for each helps visualize the expected impact of turbulence on various recovery boiler processes. Three examples were presented to illustrate the potential effects. From the first example, it seems likely that the normal fuel-NO<sub>x</sub> destruction by staged combustion will not work efficiently in recovery boilers. From the second example, the char combustion rate of in-flight droplets is likely to be quite different from data taken with uniform, steady gas composition. From the third example, the turbulent structure of recovery boiler flows will bring a variable, unsteady gas composition in contact with the wall tubes, which may affect the rate of corrosion.

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