Air jets and mixing in kraft recovery boilers

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Knowledge of furnace air-flow patterns is the first step in designing efficient air systems for recovery boilers.

This paper examines several aspects of single and multiple air-jet systems typical of those used in recovery boilers. We first review the extensive work involving the trajectory and penetration for air jets in crossflow in a wide variety of applications, including combustion furnaces. We next discuss the dominant influence of the interaction of multiple jets. This interaction dramatically changes the determination of jet penetration in a boiler furnace. Flow channeling is seen to be a prominent feature of furnace air flows and is shown to influence mixing, combustion, and char entrainment in recovery-boiler furnaces. Finally, some general guidelines for design of recovery-boiler air systems are presented.

Single-jet penetration in crossflow

The air jets from the nozzle ports of recovery furnaces are large enough and fast enough to be characterized as turbulent jets. Turbulent jets have been extensively tested and are well understood (*1–4*). In a recovery-boiler furnace, the air jets are aimed horizontally but are subjected to the crossflow of the upward-flowing furnace gases. The characteristic trajectory of jets in crossflow has been measured and studied in great detail for a wide range of applications, including combustion systems (*5–10*). The most important result for application to recovery boilers is the determination of a penetration distance. This distance is defined as the horizontal distance that a horizontal jet will penetrate into a vertical crossflow. All the expressions that are used to describe the penetration distance L_p have the same general form, which involves the ratio of the jet velocity to the velocity of the furnace crossflow. One of the simplest and most reliable expressions for jet penetration is (*2*):

$$L_p = k\, D_n\, (T_f/T_n)^{1/2}\, (V_n/V_f) \quad (1)$$

where

L_p = jet penetration distance, ft
k = an empirical dimensionless constant
D_n = nozzle diameter, ft
T_f = temperature of furnace gas, °R
T_n = temperature of nozzle air, °R
V_n = velocity of nozzle air, ft/s
V_f = upward velocity of furnace gas, ft/s
ΔP_n = nozzle pressure drop.

The value of constant k (from various investigators) ranges from 1.5 to 2, so a value of 1.5 is conservative. As an example, using the value of 1.5 for k, the jet penetration can be calculated for a 4-in.-diam. jet operated at fairly typical recovery-boiler conditions.

D_n = 4 in. = 0.33 ft = 0.1 m
T_f = 2000°F = 2460°R = 1367°K
T_n = 280°F = 740°R = 411°K
ΔP_n = 7.4 in. H_2O = 1.8 kPa
V_n = 215 ft/s = 65.4 m/s (based on T_n and ΔP_n)
V_f = 10 ft/s = 3 m/s.

Thus

L_p = 19.6 ft = 6 m.

This penetration, L_p = 19.6 ft, is more than half way across even the largest recovery furnace, despite the relatively small jet size used in this example. Thus, according to the equation, a single jet in an average crossflow typical of recovery boilers should be able to penetrate at least half way across the furnace under even relatively modest jet conditions. This is counter to the intuitive feeling and the limited data concerning jet penetration in these units. However, it is not the penetration equation that is incorrect. Rather, it is the physical description of the process that is inaccurate. The single jet in uniform crossflow is not a good physical model for a recovery furnace. Recovery furnace flows always involve multiple jets that interact strongly, causing nonuniform flow patterns.

Multiple-jet interaction

Each level of the air system for a recovery boiler consists of a set of jets distributed at one horizontal elevation on either four walls or on two opposing walls. **Figure 1** illustrates a layout for one simple secondary-air level. The jets of air issuing from each nozzle are depicted as simple expanding cones proceeding directly into the furnace from the nozzles, except for the corner nozzles, which would interact almost immediately and be somewhat deflected. The pertinent

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feature here is that the entire center is filled with overlapping and colliding jets. The jets from any one wall coalesce and form a broad coherent jet within a fairly short distance from the furnace wall. The jets from opposite walls do not mix or pass through each other but are simply deflected upward, and this is the case regardless of jet size or operating pressure. The maximum penetration in a case like this can only be about 40% of the width of the furnace. This is because the coalesced jets from each wall behave as if they are running into a solid wall in the center of the furnace. This "wall" is created by air flowing out of the jets on the opposite wall.

Figure 2 shows a cross-sectional view of the jet-flow pattern. The jets from each wall curve upward as they approach each other until they are running parallel in a channel located in the middle of the furnace. The region between the channel and the furnace wall is a low-flow zone where slow recirculation takes place. This process of channeling has been studied and observed many times in a variety of flow systems. One particularly effective visualization of the opposing-jet situation shows that the same velocity profile is observed when a wall is placed on the center line of the flow field (*11*).

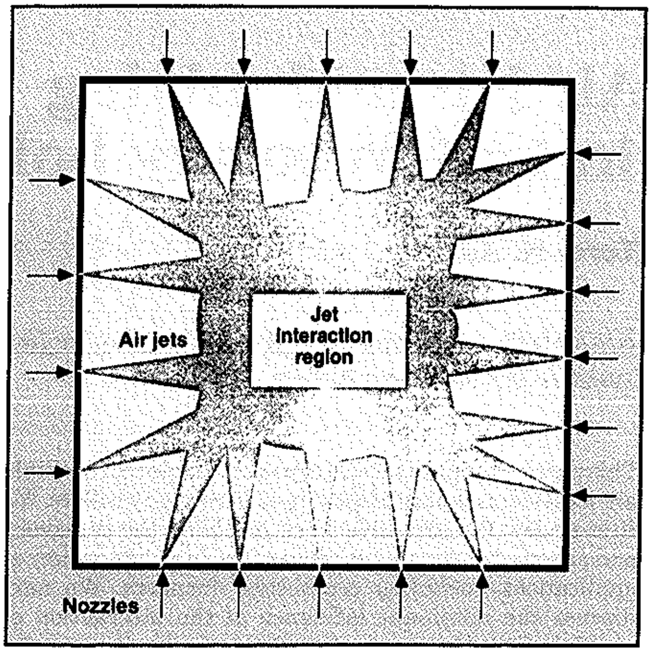
From a more practical point of view, the pattern of channeled flow can be observed in a recovery-boiler furnace using a smelt-bed imaging system (*12*). Though the primary purpose of this imaging system is to monitor the smelt bed for better bed control, it also can be used to view some of the flow patterns in the lower furnace. The sweep of the primary and secondary air jets across the bed can be observed directly with these units. These air jets meet in the middle of the furnace and form a strong upward flow pattern. Entrained particles in the gas space above the bed help show the flow patterns. These particles show a pattern similar to that in Fig. 2, with a downward flow at the walls and a slow upward flow in the region just outside the central column.

An even more practical and convincing test that can easily be carried out is to simply insert a long air-cooled pipe into an unused liquor-gun port of an operating recovery boiler. After just a few seconds, a heavy deposit will be apparent on the top side of the probe, with little on the bottom side. This pattern is the result of the downward portion of the recirculating flow pattern that forms near the wall in the presence of a strongly channeled central flow, as shown in Fig. 2.

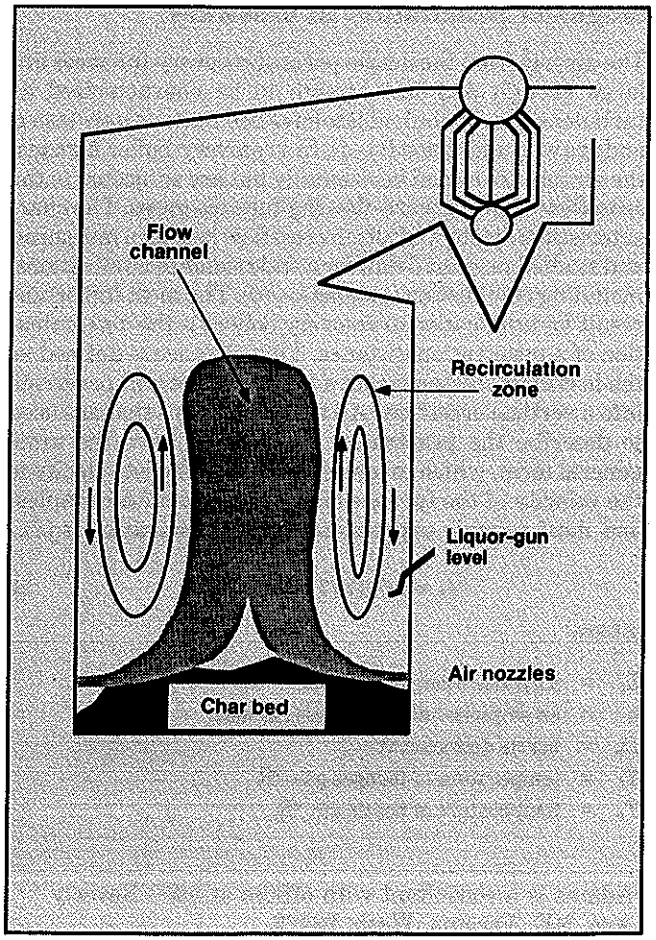
This crude test of observing the deposits on a pipe that has been briefly inserted into a furnace can be used to estimate the size of the channel in the furnace. In a large recovery boiler, approximately 28 ft (8.5 m) on a side, a pipe inserted 8 ft (2.4 m) into the furnace at a gun port will be heavily covered on the topside but have little deposit on the bottom side. An estimate can then be made of the approximate size of the recirculation zone by assuming that it occupies the outer 8 ft (2.4 m) of the furnace cross section. Of the total cross section of 784 ft^2 (72.9 m^2), the recirculation zone occupies approximately 604 ft^2 (56.1 m^2), or 77% of the cross section. The channel occupies only about 23% of the cross section, so that its upward-flow velocity will be approximately four times the calculated bulk average flow velocity for the furnace gas.

It is evident that the single-jet penetration equation does not apply to the real situation that exists in the recovery boiler. The actual flow is nonuniform. The upward crossflow velocity can be several times the bulk average velocity, and

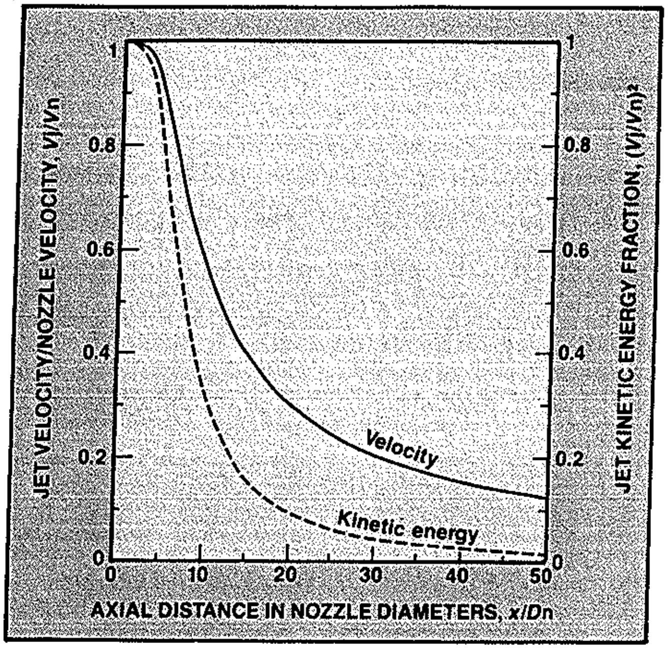
1. Typical secondary-air level showing interaction of multiple air jets. The entire center of the furnace is filled with overlapping and colliding jets.



2. Cross-sectional view of jet-flow pattern in the lower furnace. The jets from each wall curve upward as they approach each other until they are running parallel in a channel located in the middle of the furnace. The region between the channel and the furnace wall is a low-flow recirculation zone, with a downward flow at the wall and a slow upward flow in the region just outside the central flow channel.



3. Axial profile of the jet center-line velocity and the jet kinetic energy as a fraction of the initial kinetic energy.



the geometrical layout of the jets on all four walls limits jet penetration to no more than 40% of the width of the furnace. This dominant flow pattern of channeling in recovery furnaces affects many operational aspects, including particle entrainment, mixing, residence time, and flow patterns in the convective section.

Effects of channeled flow

Particle entrainment

Particle entrainment and carryover are important to recovery-boiler operation because of deposit formation on the tube banks. The carryover particles are largely char, which contains carbon and inorganic smelt constituents. They are entrained in the lower furnace by the upward-flowing furnace gases. For droplets sprayed into the central channel, the upward velocity is several times the bulk average velocity that would be calculated from uniform flow. Very large droplets can be entrained by such a strong flow.

Mixing and combustion

Combustion of volatile organics, CO, and reduced sulfur gases is strongly affected by mixing. Jets of gas mix with their surroundings because of a difference in velocity, which causes shearing. A high-velocity jet will entrain and mix with the surrounding gas at a rate that depends on the turbulence generated at the edge of the jet by these shear forces. All of the initial kinetic energy of the jet due to its initial velocity will eventually be dissipated in turbulence and mixing. The velocity profile for turbulent jets can most easily be characterized for different applications by using the nozzle diameter, D_n, and initial jet velocity, V_n, as scaling parameters. Properly scaled, there is a universal velocity profile for turbulent jets, as seen in **Fig. 3,** where the jet center-line velocity V_j (expressed as a fraction of the initial jet velocity, V_n) is plotted as a function of the axial distance x along the jet. Axial distance x is expressed in nozzle diameters. An approximate measure of the kinetic energy available for mixing at any location along the jet axis can be obtained from the square of the center line velocity. This is also portrayed in Fig. 3, where the fraction of the initial kinetic energy is plotted as a function of the axial distance along the jet.

Figure 3 indicates that for a recovery-boiler air nozzle approximately 4 in. (10 cm) in diameter, the jet velocity will have fallen to only 40% of the initial nozzle velocity at a distance of 5 ft (1.5 m) from the furnace wall. Figure 3 also shows that only about 16% of the original kinetic energy is still available for mixing at the same distance of 15 diameters from the nozzle. This indicates that most of the intense jet mixing occurs near the wall. In the upper furnace, jets that are intended to provide mixing must traverse the recirculation zone in order to reach the central flow channel, but at that distance from the wall, most of the mixing energy in these jets has already been dissipated.

Multiple-jet mixing systems

Optimization of nozzle design and layout to achieve rapid mixing, uniform flow, and limited particle entrainment has been investigated for a wide range of applications. These studies examined mixing applications and chemical reactions (*13–16*), combustion equipment (*5, 6, 17–22*), and other boiler furnaces (*2, 7*). These works are based on models and on experiments. Most of the studies involve initially uniform crossflows in the furnace, with one or several jets issuing from the furnace walls, generally at right angles to the crossflow. Experimental work has also been done on oblique jets and tangential jets.

The simplest scenario for mixing and combustion in a furnace-like environment involves the use of a single overfire-air jet issuing into a uniform crossflow of combustion gas. It is clear from the available data (*13–16*) that an optimum nozzle design creates a jet that is turned by the crossflow and then travels up the center line of the furnace. Either under-penetration or over-penetration would result in poorer mixing.

Single jets are obviously impractical for large boilers, but the same general approach can be applied where multiple jets are used. Each jet should travel up the center line of one segment of the furnace cross section. This approach has been shown to be effective for mixing in combustion equipment (*19–22*) with the use of either directly opposed or staggered jets. Guidelines for nozzle size, spacing, and pressure are available for the case of uniform crossflow. A careful reassessment of earlier data on boiler models (*7*) shows that this approach is most effective even with some nonuniformity.

Application to recovery-boiler air systems

Some practical guidelines for recovery boilers can be drawn from the work on air jets and jet mixing, and areas needing further work can be identified. First, it is clear that the primary function of the air jets located below the liquor guns is to control the smelt bed. Thus the size, spacing, and distribution of these jets will be dictated by this function. In order to control the perimeter of the bed, the air ports on the lowest level must be on all four walls and they must be spaced fairly closely. This is the case for all current boiler designs. Air in the lower furnace must also control the height of the bed. If there is only one level of air below the guns, then there is no crossflow, and these jets can easily penetrate to the center of the furnace before forming an upward-flowing channel. Thus design of the primary air ports basically involves only the quantity of air that must be delivered and the need to control the bed perimeter. Changes in the primary-air port layout, size, and number should only be undertaken when primary-air quantity cannot be obtained with reasonable pressure from the delivery duct. The presence of primary ports on all four walls invariably leads to the formation of a strong central gas flow column in the lower furnace.

Many of these observations also apply to two-level air systems in the lower furnace. In this case, primary air is used solely to shape the bed perimeter. Secondary air is used to control bed height. The need to have the secondary air penetrate to the center of the furnace is only slightly complicated by the crossflow of the primary air from below the secondary-air jets. In fact, for any reasonable port size and pressure, the secondary-air-jet penetration is limited to approximately 40% of the width of the furnace by the opposing secondary-air jets, regardless of the primary flow. Unlike the primary-air jets, there is no stringent requirement for close spacing to obtain perimeter control, so it is possible to use fewer, larger, more widely spaced secondary ports. The only real requirement for the secondary-air jets is that they be capable of providing a sufficient quantity of secondary air within the limits of the forced-draft fan's delivery pressure.

The next level of air above the bed is the first level that could be effectively used to promote mixing and flow uniformity. There are a few systems that use three levels of air below the liquor guns, but such systems are rare. The tertiary-air system is usually located above the guns, and this is usually the only level of air that is expressly intended to provide mixing and flow uniformity. If the flow out of the lower region of the furnace were not channeled but were uniform, there would be readily available design techniques to ensure good mixing. Unfortunately, this is not the case, and the tertiary nozzle design and layout remains an area where additional work is required. The best approach to this design work is flow modeling, along with carefully documented practical installations in the field.

Conclusion

The physical situation of a single jet penetrating a crossflow stream is a building block for understanding the design of recovery-boiler air-jet systems. A great deal of research has been focused on single jets. The jet-penetration distance for a single jet in uniform crossflow can easily be calculated from available equations. Examples show that a single jet would be able to penetrate more than half way across a recovery-boiler furnace under normal conditions. However, the jet systems used in these units always consist of multiple jets, which strongly interact and channel the air flow in the furnace. This interaction and channeling limits the penetration of an individual jet to no more than about 40% of the furnace width, regardless of nozzle size and initial jet velocity. Channeling also causes substantial flow nonuniformity, with localized flow velocities as much as four times the bulk average flow velocity. It can also lead to higher entrainment and poorer mixing. Combustion in recovery boilers could be improved by eliminating channeling. However, the physical necessity of locating air jets on the furnace walls and the process requirement for bed stability will always result in strongly channeled flow in the lower furnace. Improvements in mixing and flow uniformity will have to be achieved through better design of the tertiary-air system.

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