

Section III

Burner Designs

11 High-Velocity Burners

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11.1 INTRODUCTION

The term “high-velocity burner” typically implies a burner with a tile outlet port sized to provide an exit velocity exceeding 300 ft/s to the combustion products passing through it, with nominal values in the 400- to 500-ft/s range for commercial products. A high-velocity burner system is usually configured to allow the momentum of the burner’s exit combustion product stream to entrain fully reacted products of combustion (POCs) from the fired chamber. This promotes POC circulation within the fired chamber with the aim of enhancing temperature uniformity and heat transfer.

High-velocity burners have been extensively used in metallurgical, ceramic, and process applications since the 1960s. For gas burners, both premix and nozzle-mixing configurations have been developed and deployed, while oil burners are only made with nozzle-mixing configurations.

Although high-velocity burners are often thought of as providing more benefits in low-temperature applications where the convective heat transfer component is dominant, they have shown themselves to be equally capable of providing value to high-temperature processes. Fuel efficiency, particularly expressed in terms of specific fuel consumption (BTU/lb), or specific fuel consumption rate (BTU/lb/h), is frequently enhanced over conventionally fired systems. This is especially true where the final exhaust gas temperatures leave the fired chamber closer to the load temperature. In addition, heating is often accomplished more quickly because the time required for the coldest part of the load to reach target temperature is reduced.

Economic drivers for the adoption of high-velocity burners include system capital and maintenance costs in addition to the efficiency, productivity, and quality aspects from improved heat transfer and temperature uniformity. In many cases, fewer strategically placed high-velocity burners can provide equivalent or better performance than conventional low- to medium-velocity burner systems. Given that the costs of the necessary flame supervision and safety controls of a burner system are a significant part of both the capital and ongoing maintenance costs, this potential reduction in the number of burners alone can provide justification for their use.

Modern nozzle mix burners may use excess air to provide a “low-temperature head” jet of combustion products to heat and stir a low-temperature application. With high-velocity burners, less excess air is required than would be needed with low- or medium-velocity burners in such an application, because the high-velocity burner’s jet temperature is diluted faster by entrainment of cooler products of combustion from the furnace. The momentum of the gas stream from a high-velocity burner can be used to drive heat into closely packed loads such as brick hacks or piles of aluminum scrap. It can also be used to advantage to promote jet mixing with surrounding gases in such applications as cupola afterburners and other fume incineration processes.

Transportable high-velocity burner systems are widely used for the on-site dryout and preheat of refractory structures such as glass tanks after reconstruction, and the on-site heat treatment of large, welded steel structures such as high-pressure gas storage tanks, where the steel structure is externally insulated with slab or blanket and the burner fired inside the vessel, essentially turning the workpiece into the furnace.

High-velocity burners present challenges to the burner designer. Designers must consider the characteristics of the required combustion product jet. Many factors influence the design of the burner and the selection of its materials of construction, including the temperature of the outlet stream, the size of the flame envelope in the fired chamber, the jet momentum required to provide the target process heating, and the target emissions level for NO_x, CO, VOCs and HCs for the burner and the resulting fired process. High temperatures and/or pressures within the burner are significant considerations both for the burner construction and the design and configuration of its mounting into the fired structure. Burner tile outlet shapes other than the conventional round port can be used to impart specific characteristics to the jet.

To take advantage of the jet characteristics requires study of the aerodynamics within the fired chamber and also of its thermal characteristics. The aerodynamics will be influenced by the size and shape of the chamber and the load to be heated, the placement of the burners and exhaust ports

leading to the flues, and the control strategy employed. The thermal characteristics will be influenced by the heat capacity and losses of the furnace and the load, their distribution relative to the heat source provided by the burners, the placement and nature of the sensors used to provide the inputs to the control system, and the actions of the outputs of that system. Optimization of the design and operation of a high-velocity burner system requires appropriate synergy between all these elements.

Although capable of effective use with most conventional thermal input and fuel/air ratio control strategies, special systems have been designed to complement the characteristics of the high-velocity burner's jet — generically known as “pulse firing systems.” They are available with many proprietary algorithms to enhance the heating and uniformity of the fired application. Special flow control hardware has been developed to reliably translate the output of these control systems into air and fuel flows fed to the high-velocity burners.

Other high-velocity burner characteristics that may be useful to the user include the high excess air capability of many of the nozzle-mixing designs, which allows their use as self-contained direct fired air heaters, or the “integral combustion chamber” configuration that can provide assured high levels of completion of combustion for sub-stoichiometric firing applications such as those where significant free oxygen in the combustion products has an undesirable reaction with the load.

11.2 TYPES OF HIGH-VELOCITY BURNERS

11.2.1 PREMIX BURNERS

In the early 1900s, gas became widely available, and with that came “aerated burners” for higher input industrial use. Premix (or “air blast”) gas burners were one of the early practical types of high-input, high-stability burners — with 100% of air and fuel intimately mixed before the point of ignition and flame attachment within the burner.

The sealed tile premix burner, often called a “tunnel burner” (Figure 11.1) contains the great majority of the combustion within the tile and thus has a very high outlet temperature for its combustion gases. The high volume resulting from the high-temperature expansion imparts a high velocity to the gas stream. Hence, premix burners may be said to be inherently high-velocity burners. However, they are of limited size, turndown range, and stability and have the disadvantage that the high heat release inside the tile is taxing for the refractory. The size limitation typically leads to the use of large numbers of premix burners in a given application. The risk of flashback into large premix manifolds has made such burner systems unpopular except for applications where their ability to provide predictably reacted combustion product streams has value. One such application is a copper shaft melting furnace, running with a sub-stoichiometric fuel/air ratio, where any significant level of free O_2 in the products of combustion must be avoided.

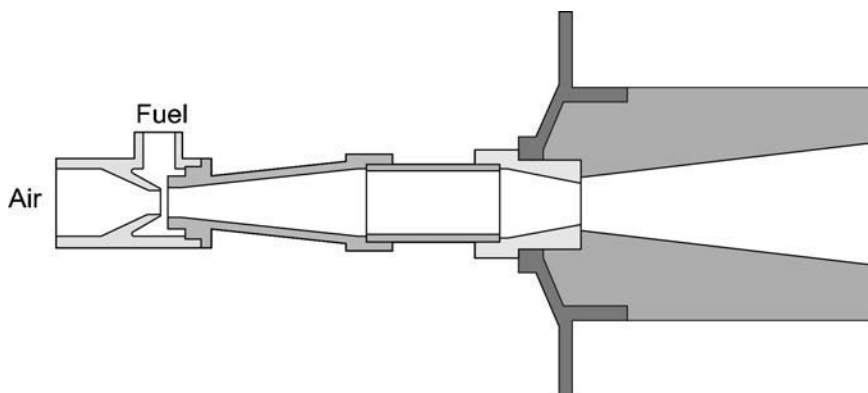


FIGURE 11.1 Premix tunnel burner.

11.2.2 CONVENTIONAL NOZZLE MIX BURNERS

The introduction of nozzle mix burners greatly simplified the control and construction of industrial combustion systems and furnaces over those using premix burners, because they had a much wider operating range and could be safely used at much larger thermal inputs.

All burners must operate within the flammability limits of the fuel they are burning. While true premix burners must operate in a single, narrow flammability window, nozzle mix burners (Figure 11.2) can have many fuel/air ratio regions within the combustion space of their tiles, with only the region at the point of ignition being required to be within the flammability limits. Heat released from regions within flammability limits broadens the limits of adjacent fuel/air regions permitting them to also burn. It can thus appear that a nozzle mix burner is operating outside the normal flammability limits of the supplied fuel based on the total fuel and air supplied to the burner.¹

Because nozzle mix burners can run under significant excess air conditions, the burner's air supply can be set at the maximum setting and the gas flow simply reduced to meet the temperature demand. The burner air and gas may still have to be turned down during times of low heat demand, but adding excess air will provide higher velocity than is possible with an equivalent premix burner at low fire. When fuel was inexpensive, there were few objections to the resulting low efficiency of heating large amounts of excess air to process temperature. Combustion system designers enjoyed the excess air capability of nozzle mix burners, because the extra velocity allowed the use of fewer burners to achieve temperature uniformity, reducing costs for larger furnaces. Combustion system designers also enjoyed the wider stability range of the nozzle mix burners that introduced a cushion to the previously difficult issue of accurately sizing a combustion system within the limited turndown range of the premix burner. Nozzle mix burners also introduced the possibility of firing oil in the same burner structure as gas, resulting in the development of both oil and dual fuel versions.

In the early to mid-1960s, burner manufacturers started to add restrictions to the tile exits of their conventional nozzle mix burners (Figure 11.3) to increase exit velocities.² The higher tile exit velocity increased the POC circulation in the furnace by entrainment, reducing the amount of excess air required to achieve good temperature uniformity over that of the conventional nozzle mix burner. Many nozzle mix burners of this type had very fast fuel/air mixing and provided a clean-burning, well-defined flame. This is a very desirable characteristic for the heating process but puts a great deal of thermal stress on the tile refractory. The conventional way of overcoming this problem is to use an alloy jacket around the tile to contain, support, and seal the refractory against cracks and leakage of hot gases into the surrounding furnace structure.

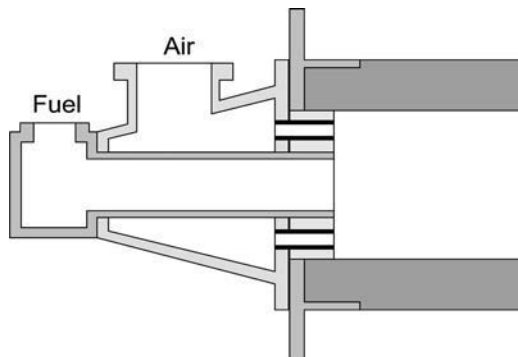


FIGURE 11.2 Nozzle mix jet tube burner.

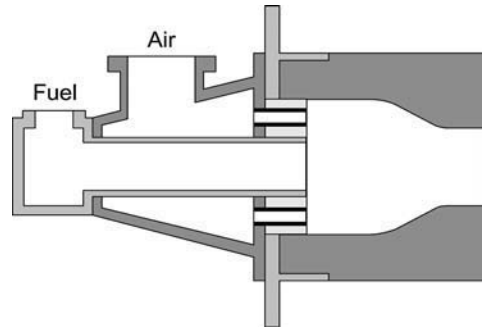


FIGURE 11.3 Nozzle mix burner with restricted tile exit.

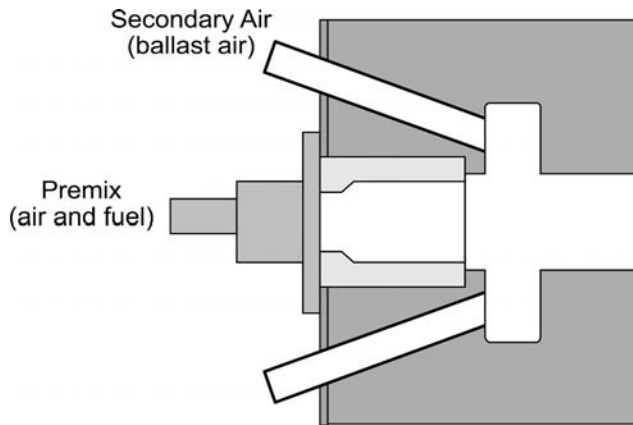


FIGURE 11.4 Iso-Jet (premix core). (Courtesy of Nutec Bickley.³ With permission.)

11.2.3 ISO-JET BURNER

In 1958, the Bickley Iso-Jet® (Nutec Bickley, Philadelphia, PA) burner was introduced as an integral component of Bickley's batch kilns.³ The original Iso-Jet consisted of a premix burner core with secondary air piped through a surrounding tile structure (Figure 11.4) that tempered the hot products of combustion from the premix core during lower-temperature operations. The resulting high-velocity jet provided high convective heating and excellent temperature uniformity with a maximum tile velocity much higher than the nozzle mix burners of the day.

To adjust the furnace temperature, the burner's control system would balance the premix and secondary air flows. Gradually reducing the secondary air flow would increase the chamber temperature. To reach high furnace temperatures, the secondary air was turned completely off, while the premix core continued to operate alone. In this mode, the high-velocity feature was not available, and temperature uniformity was largely dependent on radiation. This made the Iso-Jet best suited for batch furnaces with firing schedules requiring long cycle times at low furnace temperatures. The premix burner core of the Iso-Jet was later replaced with a nozzle mix design to widen its operating capabilities (Figure 11.5).

11.2.4 AIR-STAGED NOZZLE MIX HIGH-VELOCITY BURNER

11.2.4.1 "Jet Can" Burner

In the early 1960s, a significant amount of development of high-velocity air-staged nozzle mix burners was carried out by the gas industry in Britain. A commercial burner arising from this work was the Hotwork High Velocity Burner.⁴ Based on a design concept similar to a gas turbine combustion

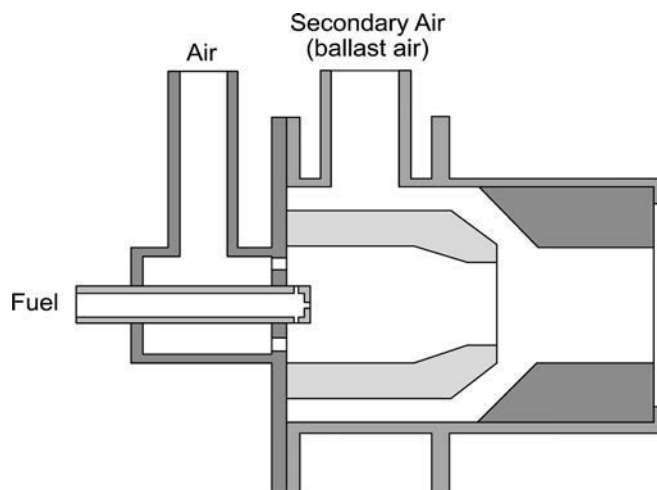


FIGURE 11.5 Iso-Jet III (nozzle mix core). (Courtesy of Nutech Bickley.³ With permission.)

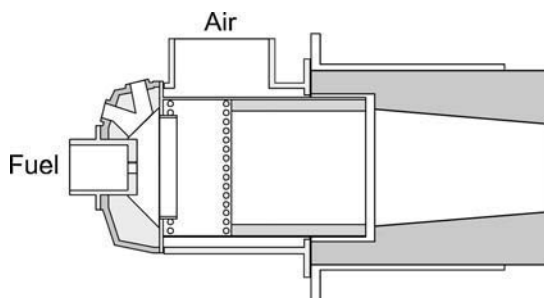


FIGURE 11.6 Jet can burner. (Courtesy of Hotwork Combustion Technology Ltd.⁴ With permission.)

chamber, the burner consists of an air body containing a perforated high-temperature alloy can with a refractory lining followed by a metal-encased high-temperature refractory tile (Figure 11.6). All fuel enters from the rear of the can where it mixes with a portion of the air circulating from the impinging jets formed by the rows of perforations in the metal can. The impinging air jets create a high degree of internal recirculation of the combusting products as they move forward to meet further air introduced to the can. This design is highly stable and operates at a very high combustion intensity. The entire structure is designed to complete approximately 85% of the combustion of a gaseous fuel before the tile exit, and 60% for diesel oil. The hot combustion product stream exits the reduced port tile at a design velocity around 450 ft/s, with significant momentum and a high entrainment capability. This produces high potential recirculation of the gases within the furnace with a relatively small flame envelope. These attributes allowed small numbers of these burners to be used to replace large numbers of then-conventional burners on high-performance furnaces requiring good temperature uniformity. The high excess air capability of the burner also allows it to be used as a high-velocity hot gas generator for drying and preheating applications.

11.2.4.2 “Cup” Burner

In 1969, the authors’ company introduced the Tempest[®] (The North American Manufacturing Company, Ltd.) high-velocity burner. Similar to earlier high-velocity burners, it was a nozzle mix burner with a restricted tile exit, which made it possible to produce good temperature uniformity with less excess air at high fire, but with a number of unique features.

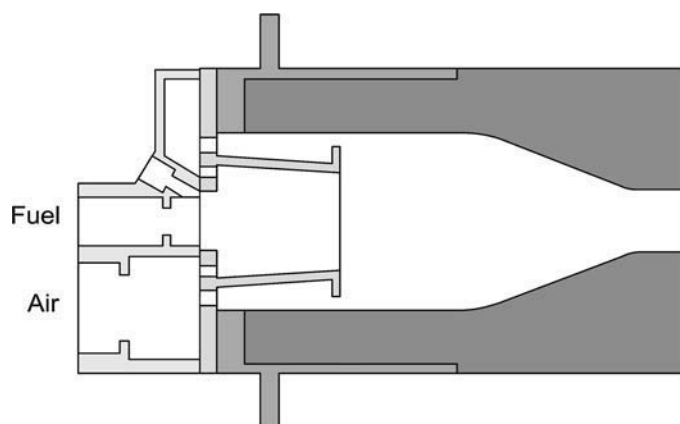


FIGURE 11.7 Nozzle mix cup burner.

The Tempest burner was relatively inexpensive, had a square refractory tile, and integral air and gas flow metering elements to reduce installation costs. The tile was partially jacketed with metal to prevent hot gases from leaking out into the surrounding refractory of the furnace. An internal cup-shaped stabilizer shielded the refractory from the base flame, and staged the air introduction to the fuel inside the tile (Figure 11.7). As the overall fuel/air ratio approached stoichiometric, more of the combustion would take place outside the tile in the furnace, which suppressed internal temperatures and reduced the duty requirement of the tile refractories over those of a design such as the “Jet Can” described above. The excess air limit was also very high, making it possible to hold a furnace temperature below 200°F simply by reducing the fuel rate (thermal turndown) while the air remained at its maximum setting.

During the 1970s, the Tempest burner became very popular for firing tunnel kilns in brick manufacture because the burner’s jet flame could penetrate and release heat deep into a brick hack. This meant wider furnaces and kilns could be built without temperature uniformity sacrifices. Tempests have also been used as auxiliary “stirring” burners while larger, more luminous flame burners provide the majority of the heat input to the furnace. During the 1980s and 1990s, most manufacturers of high-velocity burners embraced the high-velocity cup burner concept and developed similar designs that continue to be popular. New features of updated Tempests and similar burners include self-supporting tiles, metal tiles, shaped tile exits, and dual fuel capability.

11.2.5 “TUBE BURNERS” WITH THIN-WALLED, SELF-SUPPORTING TILES

Ceramic fiber wall construction became an alternative to hard refractory walls in the 1970s. Ceramic fiber is unable to support a conventional refractory burner tile, requiring the use of tile jackets or other similar measures. Advances in ceramic materials and fabrication techniques have made it possible to produce thin-section, self-supporting high-velocity burner tiles. Thin and uniform tile sections are much more resistant to thermal shock than thick nonuniformly walled ceramic structures. The new ceramic materials are denser, stronger, and have lower porosity than traditional refractory, which makes them ideal for containing the hot reacting gases produced inside high-velocity burners. Reaction-bonded silicon carbide and alumina composites are the most often used materials for self-supporting tiles. Heat-resisting metal alloys are also used in low-temperature applications.

The self-supporting tile is also used to reduce the overall size and weight of the extended-length burners required for thick-walled structures such as those typical of tunnel kilns. The geometry of the flame stabilizer in a “tube burner” is best described as a disk centered in the tile with one or

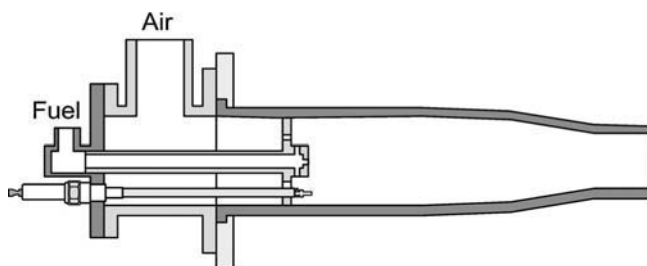


FIGURE 11.8 Nozzle mix tube burner with self-supporting tile.

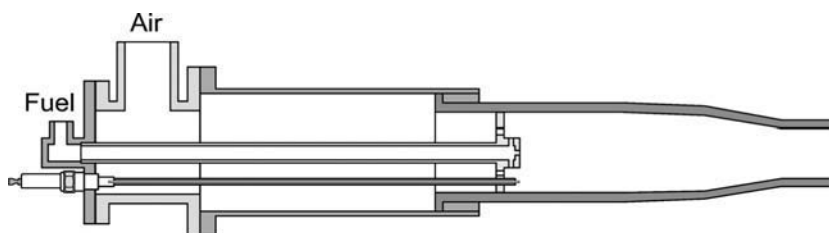


FIGURE 11.9 Nozzle mix tube burner with extended self-supporting tile.

more rows of holes through it and air passages around it. A central fuel nozzle supplies fuel to the burner head. In some respects, these burners' flame stabilizers and resultant flames are similar to those of the early nozzle-mix high-velocity burners previously discussed. They have similar excess air limits and burn a similar proportion of the fuel within their tiles, but their designs are much more refined and they are of much lighter weight (Figure 11.8).

Ignition and flame detection must take place in front of the flame stabilizer disk. For ignition, long, single-electrode spark igniters are fed through from the burner back plate to the front of the stabilizer with the spark gap grounding to the stabilizer or fuel tube. Flame rods for ionization flame detection are common with tube burners and are of similar construction to the spark igniter, but with an electrode typically extending further past the stabilizer air disk.

Most high-velocity burners are designed to fit 9- to 12-inch-thick walls. Extended-length burners are available for mounting in thicker furnace walls. These burners have a design emphasis on small-diameter extension tubes and tiles to simplify installation. Standard insertion lengths vary from 12 to 48 inches, with longer special lengths available. Extended-length tube burners can have an extended metal body, an extended self-supporting tile, or both, to pass through these thick walls (Figure 11.9). To reduce the heated length of the assembly, the burner's stabilizer may be well inside the tile. The length of the tube may be engineered to fit a specific wall thickness, or made with some means of adjusting the length.

Extended-length burners can be retrofitted to existing thick-wall kilns with little or no downtime by normal core-drilling techniques. These eliminate the need for access to the inside of the kiln or furnace for refractory modifications.

11.3 JET THEORY

The foundation of all benefits associated with high-velocity burners is rooted in fluid dynamics and, more specifically, in turbulent jet theory. While it is not within the scope of this text to fully develop the mechanics of free turbulent jet flow, it is important to provide the reader with a fundamental understanding of the fluid behavior. More thorough treatment can be found in reference texts⁵⁻¹⁰ on this subject.

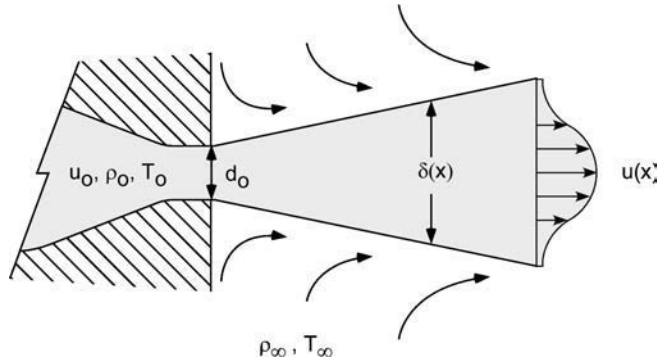


FIGURE 11.10 Diagram of a free turbulent jet.

11.3.1 FREE TURBULENT JETS

To simplify this presentation, certain assumptions must be made regarding the character of the jet flow. Free jets are those that are not acted upon by their surroundings. Other than that through which the jet emanates, there are no walls or surfaces that can constrain the flow field. A typical arrangement for a free turbulent jet is shown in Figure 11.10.

As shown, the emerging jet carries with it some of the surrounding fluid, which was originally at rest, due to the friction developed on its periphery. The turbulent shear created by the two fluids moving at different velocities defines the jet boundary. As the flow progresses in the x -direction, the mass flow within the jet boundary increases due to the turbulent shear. As the same time, the centerline velocity decays with distance. The jet itself is the only source of momentum in the flow field and that momentum must be conserved at each point. Hence, as the jet spreads out, its mass flow increases and its velocity decreases, but the total jet momentum remains constant. For a given application, the most interesting parameters to determine are the centerline velocity $u(x)$, the width of the jet $\delta(x)$, the mass flow $m(x)$, and the entrainment rate $E(x)$.

While the near-field area of a jet can be quite complex, looking at the far-field flow dynamics results in a powerful simplifying assumption. In this case, the density ρ is assumed equal to the entrained fluid density ρ_∞ . The conservation of the source momentum flux J_0 then dictates the other properties as a function of distance from the nozzle. From the cited reference sources,^{5,8,9} we have:

$$u(x) = 7.2 \left(\frac{J_0}{\rho_\infty} \right)^{1/2} x^{-1} \quad (11.1)$$

The flow width is proportional to distance x , and specifically:

$$\delta(x) = 0.44 x \quad (11.2)$$

Also, the decay of the centerline velocity is:

$$\frac{u(x)}{u_0} = 6.5 \left(\frac{x}{d^*} \right)^{-1} \quad \text{where} \quad d^* = \frac{2m_0}{(\pi\rho_\infty J_0)^{1/2}} \quad (11.3)$$

Any arbitrary source produces a far-field flow equivalent to that produced by a circular nozzle of diameter d^* issuing fluid at a uniform velocity u_0 and density ρ . When the jet is circular with a uniform exit velocity profile, the expression for d^* reduces to:

$$d^* = \left(\frac{\rho_0}{\rho_\infty} \right)^{1/2} d_0 \quad (11.4)$$

Also, the resultant mass $m(x)$ and entrainment relationships can be determined:

$$m(x) = 0.282(\rho_\infty J_0)^{1/2} x \quad (11.5)$$

$$E(x) = \frac{m(x+dx) - m(x)}{dx} = \frac{d}{dx} m(x) = 0.282(\rho_\infty J_0)^{1/2} \quad (11.6)$$

An often-surprising result is that the entrainment rate is independent of position downstream of the nozzle.

Finally, by shifting coordinates upstream in the flow field from the plane of the jet exit, a single point source can be defined. This point source is called the virtual origin of the jet. It is located at a position $x = 3.14 d^*$ upstream from the jet exit plane.

One other defined jet parameter that is frequently used is the potential core length. It is essentially the point downstream of the jet exit plane at which the centerline velocity begins to decay. This point is typically five to eight jet diameters downstream of the exit, depending on the geometry of the jet exit. These jet parameters are illustrated in Figure 11.11.

While the formulas and calculations can be daunting, the insights gained from them are powerful. Perhaps the first and simplest involves the jet spread $\delta(x)$. Looking at the inverse tangent of 0.44 (Equation 11.2), the free jet expands at an angle of just over 23° or an 11.5° half angle. This expansion becomes important when looking at burner-to-burner interactions as well as when making quick estimations of impingement locations in confined jet problems.

11.3.2 SOME EXAMPLE CALCULATIONS

Now that the basis for high-velocity burner flow fields is defined, a few specific examples should help quantify the implications of the theory.

For the base case, mass flow and jet exit pressure are representative of conditions found in a 1.0-MMBTU/h high-velocity burner operating with 10% excess air at 60°F with 0.5 psig of upstream nozzle pressure. Case 5 is a simplified example of a partially combusted high-velocity burner, much

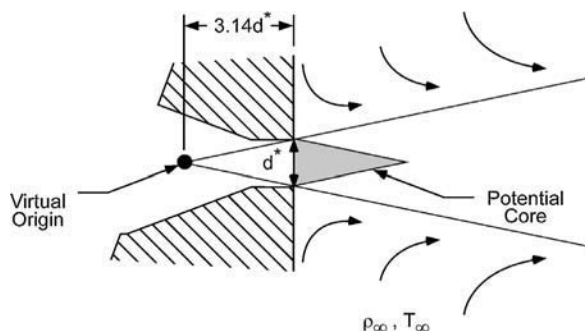


FIGURE 11.11 Virtual origin and potential core of a free jet.

like the cup burner described previously. Likewise, Case 6 represents the “jet can” burner. It is important to note that the continuing chemical reaction alters the rate of entrainment along the burner axis and these changes are not predicted by the cases shown below. They do, however, provide directional insights into burner behavior. Readers are referred to Tachina and Dahm⁹ for a more complete theoretical development of reacting jet flows.

The base parameters for each case are defined in Table 11.1. Making the calculations for mass flow and centerline velocity results in the derived data of Table 11.2. Table units are mass flow, slugs/s; velocity, ft/s; distance, ft; pressure, psig; temperature, °F.

Cases 1 through 3 are all isothermal so $d = d^*$ for each. The jet parameters are self-similar and scale directly with x/d . For each case, the velocity drops by half at $x/d = 9.6$ and the mass flow doubles at $x/d = 3.14$. Case 4 shows the jet change that occurs when a cold jet penetrates a hot environment. The centerline velocity maintains a higher value for a greater distance compared to the base case. Additionally, it takes a much greater distance to achieve the same mass ratio between the jet fluid and the entrained fluid. Compared to the base case, the jet entering an 1800°F environment must travel 2.08 times further to achieve similar effects. This entire change is seen in the scaling translation from d to d^* .

TABLE 11.1
Sample Jet Configurations

Case	Description
1. Base case	1.0 MMBTU/h fuel with 10% excess air, nonreacting, delivered to a nozzle at 60°F and 0.5 psig upstream pressure into a 60°F furnace environment
2. Low velocity	Same as base but with velocity equal to one half of base case exit velocity
3. Increased mass flow	Same as base but with mass increased to represent 4.0 MMBTU/h
4. Hot furnace	Same as base but with an 1800°F furnace environment
5. Low reaction progress	Same as base but with a partially reacted 900°F gas mixture, 17% of stoichiometric fuel combusted at tile exit
6. High reaction progress	Same as base but with a mostly reacted 2600°F gas mixture, 63% of the stoichiometric fuel combusted at tile exit

TABLE 11.2
Mass and Velocity Calculations for Sample Jet Configurations

	1. Base Case	2. Low Velocity	3. Increased Mass Flow	4. Hot Furnace	5. Low Reaction Progress	6. High Reaction Progress
Mass Flow, m_o	0.007212	0.007212	0.028848	0.007212	0.007212	0.007212
Velocity, u_o	200	100	200	200	325	487
Nozzle ID, d_o	0.1416	0.2006	0.2832	0.1416	0.1801	0.2206
Nozzle Pressure	0.5	0.125	0.5	0.5	0.5	0.5
T_o	60	60	60	60	900	2600
T_{inf}	60	60	60	1800	1800	1800
J_o	1.4467	0.7215	5.7869	1.4467	2.3419	3.5128
d^*	0.1416	0.2006	0.2832	0.2952	0.2322	0.1896
Virtual origin	-0.445	-0.630	-0.889	-0.927	-0.729	-0.595
x at $u = u/2$	1.36	1.92	2.72	2.84	2.23	1.82
x at $m = 2^*m_o$	0.446	0.631	0.89	0.929	0.73	0.596
x at $m = 5^*m_o$	1.78	2.52	3.56	3.71	2.92	2.38

Cases 5 and 6 are representations of actual high-velocity burners. Different high-velocity burner designs use different stabilizing techniques that result in widely varying combustion reaction progress, or degree of completion, at the tile exit. In the cup-stabilized burner, only about 15 to 30% of the combustion is complete at the tile exit, whereas a jet can type burner may have over 60% complete. As the reaction progress goes up, the tile exit diameter must also increase. This is due to the initial requirement of a constant upstream pressure; thus, the greater the degree of reaction completeness, the larger the exit diameter. However, at the same time, the exit velocity increases. All these changes are reflected appropriately in d^* ; the greater the degree of reaction completion, the smaller the value of d^* . As shown in the Table 11.2, there is a big difference in performance between these cases and Case 4. At every point downstream, the jet with the higher exit temperature has entrained more mass and maintained a higher centerline velocity.

11.3.3 HIGH-VELOCITY BURNER INSTALLATION AND CHAMBER EFFECTS

While the free turbulent jet analogy provides useful insight, the application of high-velocity burners in operating furnaces creates additional challenges. In many of these applications, temperature uniformity, without product overheating, is the desired objective. In these cases, entrainment of large volumes of furnace gas limit the temperature of the overall flame envelope while providing enhanced convective heat transfer. Optimization of these effects must be considered on a case-by-case basis, but there are some universal approaches to maximizing the benefit.

11.3.3.1 Recessed Burners

In many applications, the distance from the burner outlet to the product being heated is very short. This is typically due to efficient furnace construction and loading where little chamber volume is wasted. In these applications, burners are frequently recessed into the burner wall. This approach effectively moves the virtual origin and exit plane of the burner away from the work and allows for a greater amount of entrainment in the limited space available. This results in a lower overall temperature of the combustion product gas, but with greater mass flow, impacting the load. Based on typical wall thickness, a recess distance of as much as 12 in. can be achieved.

There are several limitations that must be considered with this technique. First, the technique is best used when the jet is free to entrain the furnace atmosphere from all directions. If any lateral confinement of the jet is present near the original jet exit position, it may not be possible to entrain additional products of combustion. Second, the recess cannot be so deep as to permit the jet to fully expand into the space created by the exit relocation. For example, let's look at a 1-in. diameter circular jet, retracted 6 in. into a wall, but with only a 3-in. diameter hole at the wall plane (Figure 11.12a).

Using the rule-of-thumb for jet expansion (23°), such a jet would expand and impinge inside the recess at a position roughly 5 in. from the jet exit. Once this occurs, all of the initial jet mass requirements are fulfilled by the recirculation of the jet itself, not by outside combustion product gases. Additionally, instead of having a high-velocity, 1-in. diameter jet emanating from the wall, we now have a 3-in. diameter, low-velocity jet producing far less bulk fluid motion and resulting in an elevated flame temperature. The condition of jet attachment within the burner recess must be prevented or, not only will the benefits of recessing be lost, but performance will be reduced beyond that of the base case. Figure 11.12b shows a burner properly recessed in the chamber wall. In some cases, a divergent taper in the sides of the recess can be advantageous. Not only does it eliminate jet attachment, but also opens up the area around the exit, allowing more combustion product gases to have access to the base of the burner jet. Finally, when considering a recessed jet, the chamber wall operating temperature capability must be considered. "Pulling the flame back" within the wall to a new position without appropriate adjacent insulating material can cause localized furnace wall and shell material overheating.

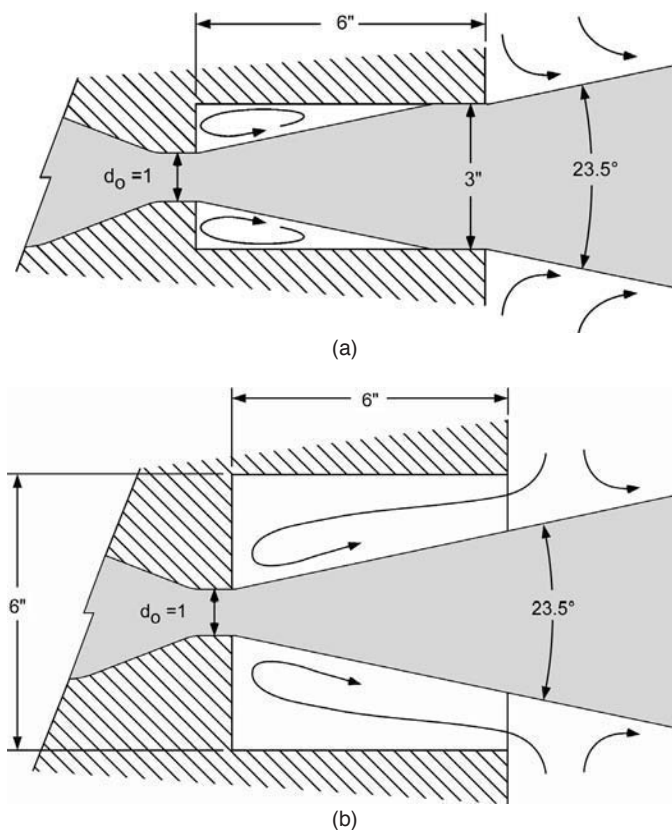


FIGURE 11.12 Schematic of a recessed burner installation.

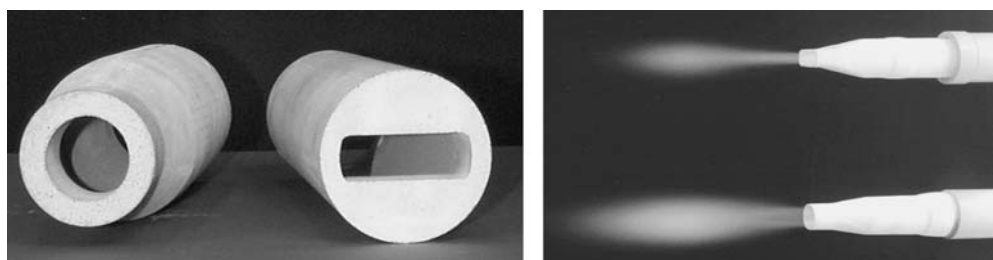


FIGURE 11.13 Round and slotted high-velocity burner tile exits.

A further caution on this technique is the need to consider the possibility of the deposition of material from the furnace gases drawn into the recess in front of the jet. Not only can such accumulation render further recirculation impossible, but it can also cause the concentration of undesirable elements or compounds in a hot environment and lead to corrosion damage of the surrounding materials.

11.3.3.2 Tile Exit Geometry

Local entrainment can be increased by jet exit geometry changes and exit treatments. The most common exit geometry change is from a round burner jet discharge to a slotted shape (Figure 11.13). This change to the exit shape maintains the jet mass and momentum, but redistributes it in another configuration. As higher aspect ratio designs are considered, the ratio of jet perimeter to area increases. Consider

a 1-in. diameter jet exit with an area of .785 sq. in. Creating a slot of the same area with an aspect ratio of 5:1 results in an increase of jet discharge perimeter of over 50% compared to the round exit. This results in quicker dissipation of the potential core and faster jet breakup. The effects of entrainment act more quickly on the long side of the exit while reducing entrainment on the short side.

The slotted exit is ideal for several chamber geometries. If constraints such as walls or supports are present in the chamber, the slot can optimize the product gas entrainment along an axis normal to the direction of confinement. One example is a case where burner-to-burner spacing is too close and jets tend to interfere with one another. If sufficient room is present above and below the burner exit, a slotted tile can be used to draw more product gas from these regions and reduce the burner interference. Another example is a case where the work is arranged in narrow firing lanes and tight temperature uniformity is required. A slotted exit can be used to entrain greater quantities of product gas in the direction of the work, reducing the temperature of the gases in contact with the load. This both promotes uniformity and prevents product overheating. Shaped exits are not as good as round exits for penetrating dense loads and firing wide furnaces.

With the improvements in materials technology during the past few years, new approaches to jet breakup and enhanced entrainment continue to be explored. Many of these techniques use tabs or other small devices to introduce vortices into the jet flow at the burner exit plane. Even small serrations applied to a round exit can have an effect on the core breakup.

11.3.4 EFFECT OF MULTIPLE BURNERS

The full benefits of enhanced convective heat transfer and a high level of temperature uniformity can only be achieved by proper burner placement. Our analysis thus far has been limited to a single free jet. But as we look to apply jet dynamics to our heating system, burner placement and burner-to-burner effects, as well as the geometry of the chamber and properties of the material to be heated, must all be considered. It is important to properly space the burners in both the horizontal and vertical planes of the chamber in order to get as even heating as possible.

11.3.4.1 Centerline Spacing

The first consideration in placing burners on an application is the development of the reacting gas jet. In the sections above, it was demonstrated that a typical free jet expands with $\delta(x) = 0.44x$, or just over a 23° included angle. This parameter is used to set burner-to-burner centerline spacing in high-velocity applications.

Looking first at the effect of burners adjacent to each other, either horizontally or vertically, where the intersection of the jet streams will determine the overall effectiveness of the burner velocities. [Figure 11.14](#) shows the positions of paired burners on three different centerline spacings.

At a burner centerline spacing of 2 ft, the hot gas “cones” meet approximately 4.5 ft from the hot face of the burner tile, assuming a point source. In real jets, the spacing will be reduced by the diameter of the actual jet initial diameter, shortening the intersection distance. As the streams merge, they are unable to entrain additional product gas at the intersection point and temperatures will not diminish as rapidly. This can create hot spots in the load. Further, depending on the location of the load, the two jets may begin to look much more like a single, low-velocity jet. In fact, this is exactly how such an arrangement is treated on a theoretical basis. The two jets merge together as one, with a combined mass flow based on the total mass at the point of intersection and new virtual origin. At burner centerlines of 3 ft and 4 ft, the jet intersection distances are 6.8 ft and 9.1ft, respectively.

It is important to note that the region between burners does not provide for good recirculation and reduction in temperature for either of the two jets. Each jet has its own mass entrainment requirements and the two compete for this particular volume. In satisfying this requirement, the jets will tend to turn toward each other and, in the case of a burner jet, recirculate hot, reacting

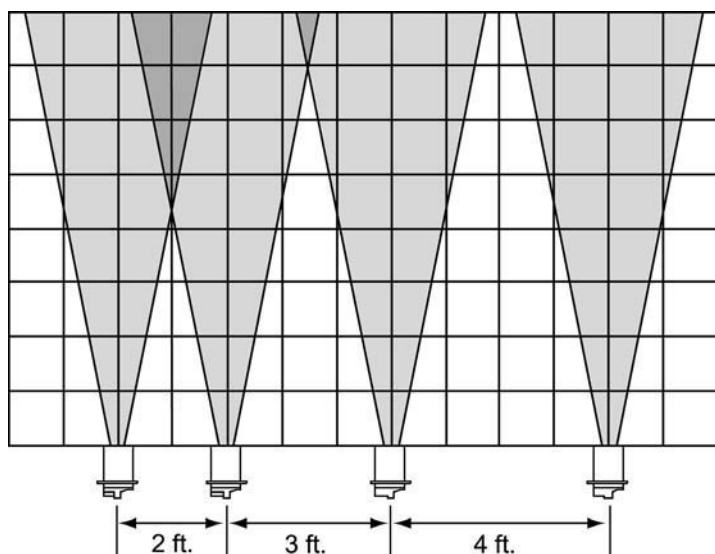


FIGURE 11.14 Effect of burner centerline spacing.

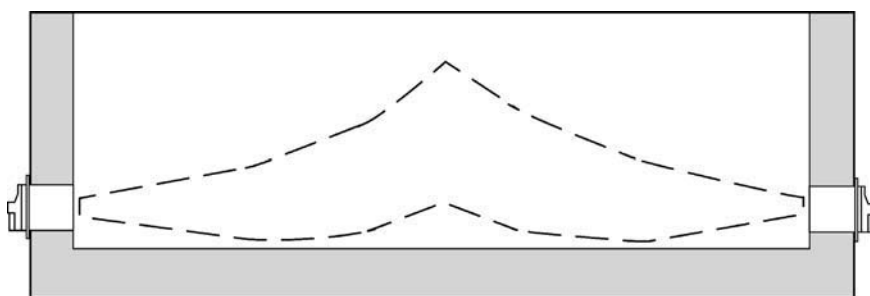


FIGURE 11.15 Typical buoyant jet pattern of an unopposed burner.

gases back into the flame envelope. Experimental studies^{3,5} have shown that if burner nozzles are separated by at least 18 nozzle diameters, no interaction in the flame front will occur. More recent work has shown that this actually depends on the fuel type, and it has also been shown⁷ that at least 26 diameters are required for methane fuel.

11.3.4.2 Opposed vs. Staggered Wall Placement

Under all conditions, the location of burners relative to the load and to each other is important in achieving the most benefit from the investment in high-velocity burners. For many years, one practice had been to oppose high-velocity burners to promote a vertical circulation of the hot gases through the center of the chamber. This works well if the furnace is wide and the burners have been properly sized to allow the gases to turn upward as they meet (Figure 11.15).

However, in a narrow furnace chamber, the gases impact upon each other, resulting in a stagnant flow area at the center of the furnace. The impacting gases are the high-temperature, centerline portion of the combustion jet, resulting in an overheated region of the furnace. For this reason, it is often advantageous to offset or stagger the burner placement to allow the burner gases to sweep the full distance across the chamber and be recirculated for improved temperature distribution.

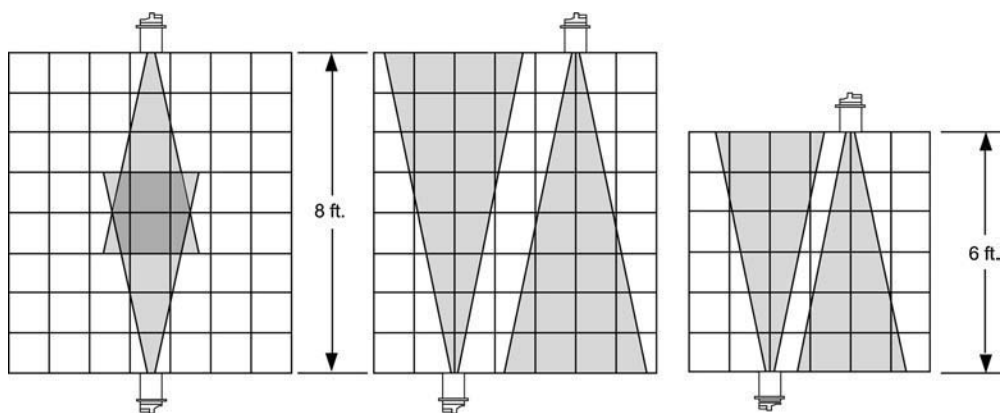


FIGURE 11.16 Effect of centerline spacing on opposed burners.

Figure 11.16 shows this effect on burners located across the chamber from each other, on 3-ft and 4-ft centerlines and at 8-ft and 6-ft chamber widths. It shows the relative positioning that must be considered for the burners to promote good flow across the kiln and load. If the burners are too close together in either of the arrangements, interference from the turbulent interaction of the gas streams can be counterproductive to the goals of high-velocity heating. When firing large open volumes, it is important to remember that staggering the burners will not always provide the best result. Burners on opposite walls still create dead zones, where gases move slowly or are stagnant in the region between staggered expanding jets. In this particular case, locating burners to promote bulk motion of the gases typically provides the best result.

It is also very important to examine the load setting when placing high-velocity burners. Too little space between the wall and the work will not allow for proper recirculation of the product gases. Raising the work off the floor also helps promote good gas recirculation and even heating. Appropriate product spacing is also important to achieving improved product temperature uniformity by enhanced entrainment and gas recirculation.

Proper flue locations are also critical. Essentially, one must consider the “sinks” in the flow field as well as the “sources.” A poor flue location can cause the high-velocity streams to short-circuit the furnace chamber, effectively heating only the flue. High-velocity combustion can offer many benefits, but can only be brought to fruition by a well-designed heating process.

11.4 HIGH-VELOCITY BURNER DESIGN

High-velocity burner design is an exercise in compromise. The most basic difference between the various designs lies in how the high velocity is achieved. All high-velocity burners have some amount of tile restriction after the flame stabilizer arrangement. Making the tile exit smaller increases the exit velocity. The reaction progress inside the tile also affects the exit velocity. As more combustion is completed in the tile, the gas temperature rises and the gas volume expands, which increases velocity. The optimum balance between tile exit size and the amount of combustion allowed to complete in the tile is application and control system specific.

The amount of the fuel combusted within the burner before the tile exit is a function of the design of the mixing and flame stabilizing sections of the burner. While more intense mixing will increase gas outlet temperatures and provide a higher-velocity flame, the internal tile pressure will also rise, requiring higher inlet pressures for air and fuel to maintain the same flow rate. So, as fuel is throttled off, airflow through the burner will increase due to lower pressures in the tile. The differences in firing vs. not-firing airflow rates are greater in burners that have higher percentages of combustion taking place in their tile.

Because of the airflow changes due to the ratio settings, high-velocity burners are typically installed with air and gas flow meters to aid in setting the fuel/air ratio. Orifice meters can be built into the burner, but external meters are normally more accurate because “flow-smoothing” space is not restricted.

11.4.1 DELAYED MIXING/CUP STYLE AIR STAGING DESIGNS

All delayed mixing or cup style high-velocity burners have at least one central stabilizer cup where all of the gas is mixed with a portion of the combustion air. The flame that exits the cup tends to stay fuel-rich in the center of the tile as it meets the remaining air passing around the outside of the cup stabilizer. Most of the individual air and gas jets inside the burner run substantially parallel to each other, slowing the fuel/air mixing. The amount of burning that takes place in the tile depends on the tile volume and the geometry of the stabilizer. The reacted products and the remaining fuel and air exit the tile and entrain furnace atmosphere while the balance of the combustion takes place in the furnace.

The stabilizer cup allows the burner to achieve very high excess air rates by initially shielding the gas from most of the air. Even with the airflow at a high rate, the fuel can be reduced to a rate where the flame will shift completely into the base of the cup and remain stable. The air outside the cup and the hot gases from inside the cup are mixed in the tile before exiting. Excess air capabilities for delayed mixing burners are typically in the range of 3000 to 5000% excess air (equivalence ratio = 0.03–0.02).

Allowing combustion to complete in the furnace has a number of advantages. Because the delayed mixing design is less dependent on expanding combustion products, the tile exit velocity will not fall off markedly when running at high excess air rates. The tile and the burner’s internal parts are also less thermally stressed as the air passing around the outside of the cup cools the cup and shields the inside surface of the tile from the centrally concentrated flame. Combustion is completed in an environment containing entrained products of combustion from the furnace chamber resulting in inherently low NO_x emissions.

Designing for significant combustion outside a high-velocity burner has the potential disadvantage that the combustion reaction may be quenched when the fired chamber is cold, resulting in incomplete combustion of the fuel, with the presence of fuel fragments, CO, and aldehydes in the combustion product gases.

11.4.2 FAST MIXING DESIGNS

Fast mixing high-velocity burners are designed to burn as much of their fuel in the tile as possible. This may be achieved with either the “jet can” style burner or with a disk-shaped stabilizer, combined with an appropriate internal volume. The fast mixing designs require a high-integrity tile structure of low porosity and high resistance to thermal shock. Self-supporting, reaction-bonded silicon carbide tiles are often used because they meet these requirements and have a high thermal conductivity. A cast refractory tile for this duty will typically be contained in a heat-resisting alloy jacket to maintain the refractory under compression and minimize the potential for the escape of the very hot internal gases into the surrounding structure through cracks.

The disk stabilizer style has fewer stabilizing zones than the “can type” stabilizer, leading to more limited excess air capabilities typically in the 500 to 1000% air range (equivalence ratio = 0.17–0.09). Burners of this style can be controlled by pulse firing or time-proportioned control systems that do not rely on high excess air capability for the complete combustion system to provide a high level of turndown.

Allowing more of the fuel and air to mix and combust within the burner has the advantage of a higher tile exit velocity for a given exit diameter. It also suppresses the potential for CO, aldehyde, and other unburned hydrocarbon emissions when run with an excess of air, although NO_x emissions can increase as a result of the higher internal tile temperatures and the lack of dilution from cooled

combustion products. The fast mixing style is the burner of choice for sub-stoichiometric firing applications where the burner is required to operate as a reactor and provide a hot, low-oxygen combustion product stream to the fired process.

11.4.3 IGNITION: DIRECT SPARK, PREMIX PILOTS

High-velocity burners require an ignition source inside the burner to ignite the fuel/air mixture. The high velocity at the restriction of the tile exit typically prevents an external flame from propagating back through the tile port to the burner's intended stabilization zone. Hot furnaces, externally applied torches, (and flaming oily rags) will not reliably light high-velocity burners. Attempting torch lighting through a shutter at the back of the burner is not recommended, because the high internal tile pressure inside a high-velocity burner may cause a “stinger” — a direct flame risk to the operator.

The most common methods of lighting high-velocity burners are direct spark igniters and premix pilots. Direct spark ignition is the most popular for gas burners. It has the advantages of simplicity and lower cost over premix pilot systems, but the location of the spark gap inside the burner is critical to achieving reliable lighting. As the best location may be in an area of continuous combustion, the igniter design for long life can be challenging.

Premix pilot burners deliver much more energy than spark igniters and have a much larger zone of influence. Being burners in their own right, they project a flame into the combustion space of the high-velocity burner, and may be located external to the main combustion space and thus less subject to thermal deterioration. Accordingly, they are chosen for larger-capacity gas burners and most oil burners. The fuel supplying a premix pilot must be turned off once the main burner is ignited (an “interrupted pilot”) for safe operation of any burner system with flame supervision. Doing so also allows the pilot combustion air to cool the pilot tip.

There are many different styles of direct spark igniters, most specific to the burner in which they are being used. They range from simple industrial spark plugs (Figure 11.17) to extended versions that perform as flame rod flame detectors when the burner is lit (Figure 11.18).

11.4.4 FLAME SUPERVISION

Note: This section is not intended to act as a specific guide to the use of flame supervision systems for high-velocity (or any other) burners. The reader is referred to the applicable international, national, local, and insurance industry codes, standards, requirements, etc. for appropriate information on this subject.

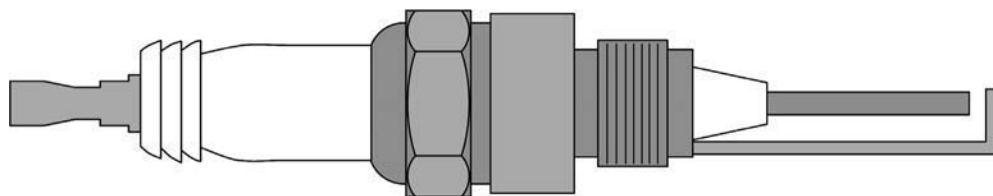


FIGURE 11.17 Industrial spark plug.



FIGURE 11.18 Combination flame rod igniter.

A reliable flame supervision system will reduce the incidence of combustion-related accidents. At the most basic level, well-sighted observation ports will allow operating personnel to confirm ignition and the establishment of combustion. The geometry of the burner will dictate how good the observation will be, shorter burners typically having better observation capability than the long tube-style burners. Care should be taken during burner installation to ensure that the operator's view down a burner observation port is not restricted by piping or other obstructions.

The most common methods of electronic flame supervision are the use of ultraviolet (UV) scanners and flame rods. Some high-velocity burners are designed to have the capability to use either, leaving the choice to the system designer. Other designs can use only one.

UV scanners have the advantage that they mount externally to the burner and need only a UV source in their line of sight. Their disadvantages are higher initial system costs and their potential for failure into an unsafe "flame detected" condition. Codes and standards typically require that "self-checking" UV scanners be used for continuously operating burners, or mandate a frequent safety check of "non-self-checking scanners" to reduce the risk of undetected failure. A UV scanner's "eye" must be kept clear of obstruction (such as dirt and water vapor) to prevent nuisance shutdowns. It should also be recognized that water vapor, CO₂, and many gaseous fuels absorb UV light. UV scanners will not reliably detect flame through long columns of these gases, making them unsuitable for use with burner designs where this condition might arise.

Flame rods cost less than UV cells and fail a "no flame detected mode." Most burners must be specifically designed to permit the use of a flame rod, normally require the use of a flame rod specific to the burner, and incorporate an appropriate electrical grounding path for the flame. Many tube-style, high-velocity burners have "twin igniter/flame rods" where the igniter and flame rod are identical electrode structures and are thus interchangeable. Some electronic flame ignition/detection systems allow a single rod to be used as the igniter and the flame rod with an appropriately designed burner.

11.4.5 TILES

The tile serves as the interface between the burner flame holder and the furnace. The restricted exit is the most obvious common feature in all high-velocity burners.

A tile of high integrity is a prime requirement for a high-velocity burner to prevent the high-temperature, high-pressure combusting gases within the tile from reaching the surrounding furnace structure. High thermal shock resistance is required to minimize reliance on the conduction of the surroundings to reduce the material stress effects of sudden tile material temperature changes.

There are many tile material choices available for high-velocity burner applications, each having advantages in different situations. They include molded refractory, cast refractory concrete, high-performance ceramics (for self-supporting tiles), and cast or fabricated heat-resisting metal.

Molded refractory and cast refractory concrete tiles are relatively inexpensive and can be made with simple tooling. Properly designed and manufactured, they can withstand very high temperatures and have some resistance to mechanical stress and abuse. Refractory material is very dense and somewhat subject to stress cracking. For these reasons, refractory tiles typically rely on external support for integrity. There are a number of ways to reduce the chance of hot combusting gases leaking out through cracks in the tile. Simply making the tile walls thicker will help, but the tile will become heavier and take up more space. Adding a metal jacket to the outside of the tile is very effective at stopping leaks by keeping the refractory under compression and providing support. However, the jacket may be subject to rapid degradation from the furnace environment by conduction through the walls or direct exposure to products of combustion from gaps in the insulation structure. In most cases, jackets are designed to stop short of the hot face of the furnace wall, leaving some portion of the refractory concrete tile unprotected.

Round refractory tiles with their uniform wall thickness are not as prone to stress cracking as square tiles of the same material. However, square refractory tiles have been a popular choice for

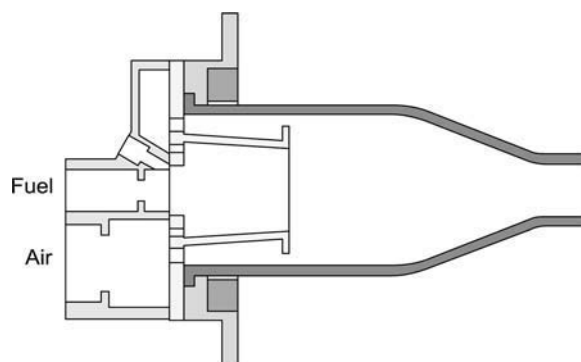


FIGURE 11.19 High-performance self-supporting ceramic tile.

smaller-capacity, high-velocity burners, especially for installation in furnaces built from brick where special cutting is reduced. In both cases, these tiles are typically made from very dense refractory concrete cast directly into a metal mounting plate or box, or from a preformed tile cemented into a mounting.

High-performance self-supporting ceramic tiles ([Figure 11.19](#)) are light in weight with relatively thin, uniform wall thickness. No external support is required for these materials other than that of the fixing of the burner mounting plate to the furnace wall. They are well suited for use in ceramic fiber-lined furnaces.

Such tiles are typically produced from reaction-bonded silicon carbide or other ceramic composites that resist high-temperature oxidation and thermal shock. The reaction-bonded silicon carbide tiles have very low porosity and high thermal shock resistance — ideal for containing the high-temperature products of combustion in high-velocity burner tiles. They also permit stabilizer designs that allow more combustion inside the tile without risk of damage to it. They are more expensive than refractory tiles and are more susceptible to mechanical damage. Silicon carbide tiles may require an air gap between the tile and furnace wall to prevent overheating the tile material.

Rolled heat-resistant stainless steel, heat-resistant cast iron, or investment cast alloys can be used for high-velocity tiles in lower-temperature applications. Metal tiles have the advantage of high resistance to mechanical damage and do not have porosity or thermal shock issues. Not only are they self-supporting, but they can be designed to support the entire weight of the burner. High-velocity burners with cup-style stabilizers are well suited for metal tiles, because they release less heat inside the tile, and the same air that keeps the cup cool also helps control the temperature of the tile. Some designs are fabricated with double skins with forced air-cooling between them. Metal tiles need to be chosen carefully, depending on the intended application temperature. They are not generally thought suitable for “clean” applications where metal oxide shed from the surface would spoil the product being heated.

11.4.6 LIGHT OIL, HIGH-VELOCITY BURNERS

Although most high-velocity burners are gas fired, oil-fired high-velocity burners are available. Most of them are “dual-fuel” versions with the ability to fire with diesel oil or gas ([Figure 11.20](#)). Air atomization is used to provide suitably fine oil droplets to the combustion process to reduce the potential for carbon formation in the reduced port tiles. Both compressed air and low-pressure air at pressures around 1.5 psig are commonly used for this atomization.

When compared with gas-fired high-velocity burners, their oil-fired versions have less turndown capability, are very difficult to light reliably with direct spark ignition, have significantly less excess air capability, and are prone to carbon formation in the tile if the appropriate fuel/air ratios are not

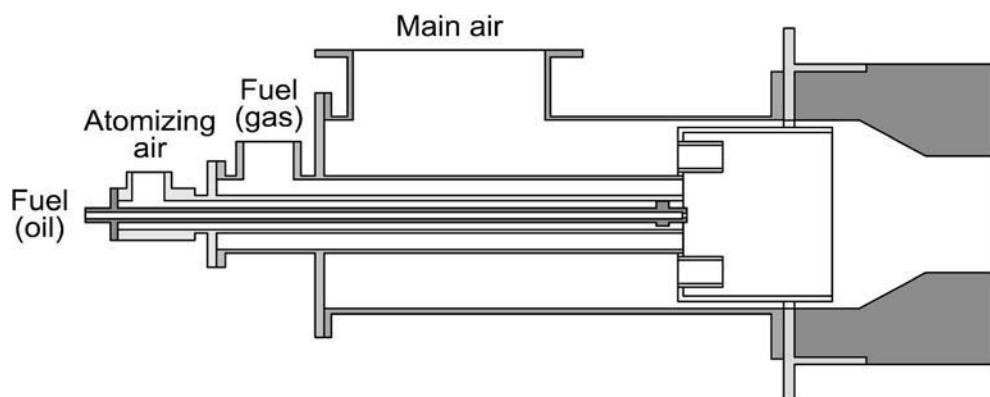


FIGURE 11.20 High-velocity dual-fuel burner.

maintained. Low atomizing air pressure and oil of much greater viscosity than diesel can also lead to carbon formation in the tile.

11.5 HEAT TRANSFER

Most of the impetus for applying high-velocity burners revolves around increased convective heat transfer. Increasing convection results in better temperature uniformity in the fired chamber, localized uniformity improvements in the heated work, and can result in improvement in product quality and reduced cost of production. The purpose of this section is to provide the framework to achieve these benefits for various heating applications.

11.5.1 BURNER SELECTION AND SIZING

Earlier sections indicated the importance of relative burner placement for optimum performance in a given application. The selection of the number of burners and their individual heat input requirement is inevitably linked to the final system performance by those considerations. The total number of burners used in a furnace is determined by factoring the furnace input capability and the input of the particular burner sized for optimum firing of the product. A larger burner will tend to throw heat a greater distance while a smaller burner will have the centerline velocity dissipate more quickly. To choose the optimum burner size, the length of the fired path on the burner axis must be considered. These choices, in conjunction with the reaction progress at tile exit and associated exit velocity, determine the heat flux profile from the burner.

Selection of an oversized burner can create significant problems in the heating application. One area of particular concern is the opposite (or target) wall across the furnace from the burner. Excessive centerline velocity and temperature will create hot spots on the refractory surfaces opposite the burner. This can result in refractory damage as well as localized overheating of the product due to re-radiation. Additionally, furnace seals can be over-pressured, potentially directing hot gases into undesirable areas, such as between the wall plates and refractories or into areas where structural members are located. Over time, this might lead to a catastrophic failure of the furnace.

With oversized burners, it is not simply a matter of turning down the burner firing rate. At turndown, the velocity of the burners is reduced, resulting in reduced entrainment of furnace gases with a connected loss of convective heat transfer capability. Oversized burners can also degrade product quality, counteracting one of the primary benefits of high-velocity firing.

If burners are undersized based on the width of the chamber, although they have sufficient total input among them, the area of optimal heat release may not be located in the proper part of the

load. For example, the burners may dissipate most of their heat in the near field, leaving the hard-to-heat areas cold, such as the bottom center of a brick hack.

11.5.2 MATERIAL HEATING APPROACHES WITH HIGH-VELOCITY BURNERS

11.5.2.1 Solid and Large-Shape Heating

High-velocity combustion is often utilized to heat large shapes to uniform temperatures. One example is the heating of steel ingots prior to forging. In demanding aerospace applications, the temperature uniformity requirement may be as tight as $\pm 15^{\circ}\text{F}$ throughout the entire chamber volume. These applications can use high-velocity burners to stir the products of combustion and produce very uniform temperatures. Although most of the heating at the target temperatures occurs by radiation, high-velocity burners bring all the radiating refractory and metal surfaces to a uniform temperature.

When heating solids, the best strategy is often large-scale (“bulk”) furnace gas movement. A row of high-velocity burners mounted on one furnace wall at a high level above the work can create the desired recirculation. If the work can be elevated on piers or other furniture above the hearth, a second row of smaller high-velocity burners can be added at hearth level on the wall opposite the other burners (Figure 11.21). Careful consideration should be given to the position of the flue exit ports from the furnace. Wherever possible, the flue ports should be located low in the furnace wall. This will ensure that good furnace pressure is maintained and that the furnace exhausts the coolest gases for best fuel efficiency. This approach eliminates the infiltration of ambient air, which affects temperature uniformity and fuel economy. It also helps overcome any buoyancy effects of hotter gases that exist, despite the stirring of the high-velocity burners. This combination will reinforce the bulk recirculation pattern and aid in increasing the convective heat transfer to the piece and creating the most uniform refractory temperature possible. Although much of this heating may occur at relatively high temperatures, some variation in excess air level can still be utilized to create even greater temperature uniformity, where the value of the load and elimination of rejects may far outweigh the fuel cost associated with increased excess air.

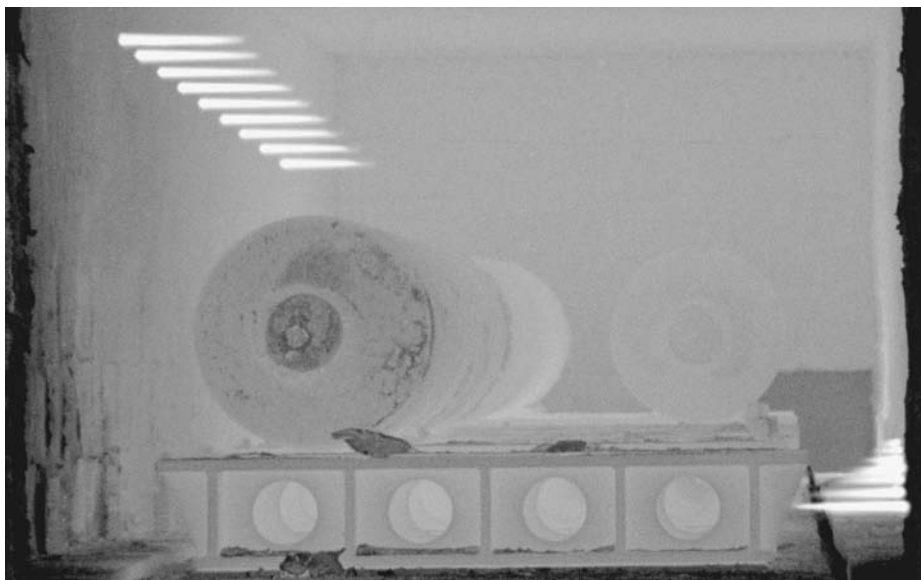


FIGURE 11.21 High-temperature heating of a large shape.



FIGURE 11.22 Typical tunnel kiln for brick production.

11.5.2.2 Densely Packed Loads

Another common application for high-velocity burners is the firing of densely packed loads, such as brick hacks. The heating of brick must follow a very specific time and temperature profile to achieve organic material burnout and proper ceramic bonding. A single brick can be fired to the desired properties in a very short time in a laboratory test furnace — typically less than 2 hours. However, production at industrial levels requires the firing of large hacks of formed and dried bricks in tight stacking arrangements. Every brick within these hacks must follow the same prescribed time and temperature profile. This creates significant difficulty as exterior bricks are heated more quickly than those in the interior of the hack. The time to successfully fire a brick hack increases substantially over the laboratory cycle, often to 40 to 60 hours, dependent on the actual time to heat the coldest brick in the hack.

Because they drive hot combustion products to the innermost bricks of a hack, high-velocity burners have become the burner of choice for firing brick tunnel kilns (Figure 11.22). Without the velocity from the burners, interior bricks would essentially be heated only by conduction, a very slow and inefficient means. The majority of the burners in the firing zones of a tunnel kiln are typically mounted low in the sidewalls, with a combination of staggered and opposed arrangements. The opposed burners provide heat release in the center of the load while the staggered burners sweep across the hacks, distributing heat across the setting. The intent is to get the heat to penetrate the load evenly, especially to the normally cold bottom of the hack. This is difficult to impossible with conventional low- or medium-velocity burners, regardless of the position of burners or type of control system.

A smaller quantity of high-velocity burners placed at intervals in the upper sidewall can also help in breaking up “crown drift” in tunnel kilns. This phenomenon occurs when hot products of combustion migrate to the low-flow-resistance area at the roofline of the kiln above the hacks and travel toward the exhaust at the cold end of the kiln, thus “bypassing” the area of the kiln cross section occupied by the hacks. It reduces the overall efficiency of the heating process and can affect the optimum control of the kiln. High-velocity burners placed high in the side walls, firing above the hacks, will entrain these stratified products of combustion and push them downward at the opposite wall to be entrained by the lower burners and allow their heat content to be put to useful work within the hacks. High-velocity burners firing vertically downward from the roof can also be

used for a similar purpose, particularly in wide kilns where side-mounted burners do not have the drive to create significant recirculation across the full width of the kiln.

High-velocity burners are also very effective in the low-temperature preheat zone at the entry end of a tunnel kiln.¹¹ These burners are typically fired at elevated excess air rates to achieve the lowest possible temperature difference between the resulting entrained gases and the bricks, while providing the required heat input to match the curve. This approach ensures that the bricks will be uniformly heated in an oxidizing environment conducive to the controlled burnout of any organic material in the clay. The entire hack can then pass into a more highly fired zone without risk of affecting product quality and yield of saleable product from the kiln. Adding high velocity burners to tunnel kiln zones, which previously relied on recirculating fans, can significantly increase the production capability of a brick kiln. By maintaining better temperature uniformity throughout the brick hacks in the preheat zones, less time is required to heat the interior bricks in the high temperature heating zones. Therefore, if the burners in the early part of kiln properly condition the load, the hot zone burners need only to maintain the temperatures required for the final material properties to develop.

11.5.2.3 Well-Spaced Loads or Open Settings

Firing of ceramics such as dinnerware, cookware, sanitary ware, and technical materials typically falls into the category of heating a well-spaced load. In these instances, the individual pieces are spaced on support structures without piece-to-piece contact. This minimizes imperfections in the fired part and allows for the high degree of temperature uniformity desired in these applications. Because nearly all of the surface area of the load is swept by combustion product gases, uniformity as close as $\pm 10^{\circ}\text{F}$ can be achieved. High-velocity burners, often running with excess air, move large volumes of products of combustion between and across the pieces of the load. Because the support structures form part of the load to be heated, the quantity of supports and the spacing between the parts must be minimized for best economic use of the kiln interior space and fuel utilization (Figure 11.23).

These applications frequently arrange the material into lanes, several pieces high. When firing such an arrangement, it is important to understand the spread of the high-velocity burner jet and its rate of entrainment of surrounding gases in order to reduce hot spots on the load. The combustion envelope must not overheat pieces sitting close to the burner wall. The combination of excess air,



FIGURE 11.23 Typical china setting.

distance to the part, jet spread, and spaces between the parts affects the temperature of the products of combustion as they sweep across the fired piece. High-velocity burners with slotted tile exits may offer distinct advantages in firing narrow lanes in such circumstances. Its elevated rate of near-field entrainment and preferential vertical entrainment can aid in the movement of gases through the kiln while minimizing the temperature gradients at the work.

11.5.2.4 The Fired Chamber as the Load

The high excess air capability and high-velocity combustion product jets of lightweight, air-cooled tile, high-velocity burners are the accepted method of dryout and preheat of large refractory structures and are also applied to the on-site heat treatment of large welded structures. The equipment and technology for such applications is generally provided by refractory dryout/heat treatment specialist companies as a contract service.

Using temporarily mounted lightweight 10 million BTU/hr burners of the jet-can type with double-skinned air cooled outlets, jets of dilute POC from 200°F to 2500°F are projected into the structure to be heated, the jet temperature being controlled according to the required program for the particular treatment. The number of burners to be used is evaluated based on the heat requirement of the cycle determined by the temperature curve to be followed, the size and shape of the space being heated, and the amount of water vapor to be removed in case of a dryout. The temporary burners are configured to produce a POC circulation pattern conducive to achieving the best temperature uniformity in the volume of the fired space. As the burners' access points to the interior of the structure are frequently not in "ideal" locations, the art and ingenuity of the contractor's experience is an important element in the configuration exercise. A means of controlling the exhaust rate from the space is installed so that the volume can be pressurized relative to atmospheric pressure to prevent the ingress of ambient air in the interests of control of uniformity and elimination of waste of the fired fuel.

For a refractory dryout, large volumes of water can be removed at low temperature differences with the refractory surface, thus allowing a closely controllable rate of temperature increase to eliminate explosive spalling caused by trapped steam.

In the heatup of sensitive materials such as the silica bricks and fused-cast refractories used in glass tank construction, close control of temperature uniformity is required to prevent damage to the structure from differential thermal expansion and/or spalling. The convective heating provided by the high-velocity burner jets and their entrainment of circulating products of combustion gives operators the ability to control the rate of change of temperature to a few degrees per hour with single-digit temperature differentials at the materials' transition points.

Large, fabricated structures such as gas storage tanks, chemical process equipment, and pressure vessels frequently require stress relieving *in situ*. The use of high-velocity burners offers an alternative to the highly labor-intensive and expensive electrical method of strapping resistance heaters to the exterior surface. The subject structure is temporarily externally insulated, and one or more burners installed to fire into the internal space. In some extreme cases of thin-walled vessels and high-temperature treatments, the internal pressure created by the combustion process has been consciously employed to prevent collapse of the vessel.

Figure 11.24 shows the use of a single burner on an aluminum melter heatup, and Figure 11.25 shows multiple burners in use on the heatup of a steel plant coke oven battery.¹²

11.6 CONTROL OF HIGH-VELOCITY COMBUSTION SYSTEMS

Burner control techniques have evolved along with furnaces and high-velocity burners. To best utilize the high-velocity burner's jet properties, the heat input and fuel/air ratio control system should generally be chosen to operate the burner(s) at the maximum input rate for the longest possible time in any heating cycle. The particular application will dictate the best choice for a given furnace, considering the type of product being heated, the type of furnace, the degree of temperature

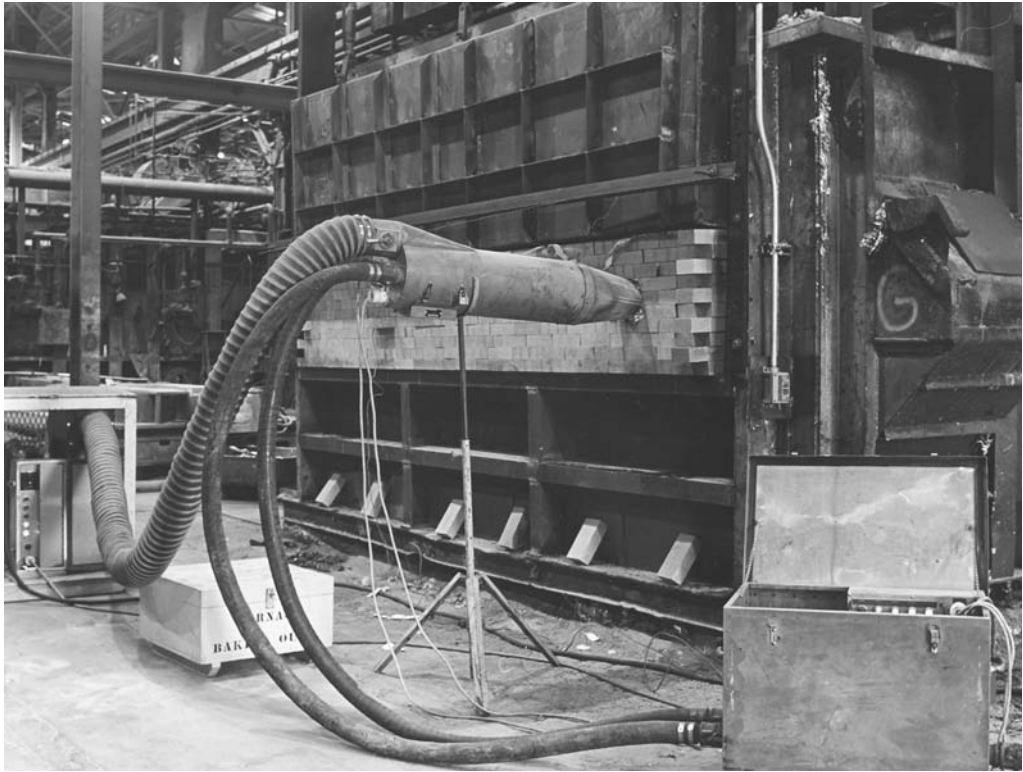


FIGURE 11.24 A single temporary burner on an aluminum melter heatup. (Courtesy of Hotwork—Division of Fosbel, Inc. With permission.)

uniformity required, the desired atmospheres, and the prevailing economics (usually an evaluation of product value and quality vs. the cost of the energy to produce it).

Most modern furnaces have multiple control zones, each monitored by a temperature-measuring element such as a thermocouple or infrared scanner. Each zone may have multiple burners controlled as a group to meet the demands of the zone controller. The fuel input to the burners is varied, either by continuous modulation or pulse-width modulation, to maintain a desired furnace temperature.

All burners have some capability to operate at lower fuel rates than their design maximum. The amount a burner can turn down is often referred to as its “turndown ratio,” defined as the maximum firing rate divided by the minimum firing rate. With continuous modulation, the higher the turndown ratio, the greater the range of temperatures that can be maintained in the furnace. For pulse-width modulation, the burners are typically operated at a fixed rate, and the firing time at that rate is adjusted to change the heat input. Differences in the control methods affect the means by which the output of a group of burners is reduced within a control zone.

All of the piping examples shown in this section are intended to illustrate control concepts only. They do not show flow meters, manual or electrical shutoff valves, and other components needed for normal operation or to meet applicable safety codes. Valves must be “approved” for fuel shutoff service as required by the regulatory authority having jurisdiction.

11.6.1 FUEL/AIR RATIO CONTROL

Each control zone or individual burner must have a means of fuel/air ratio control for efficient operation. While electronic controls are available for this purpose, the most prevalent method of fuel/air ratio control is the cross-connected ratio regulator.

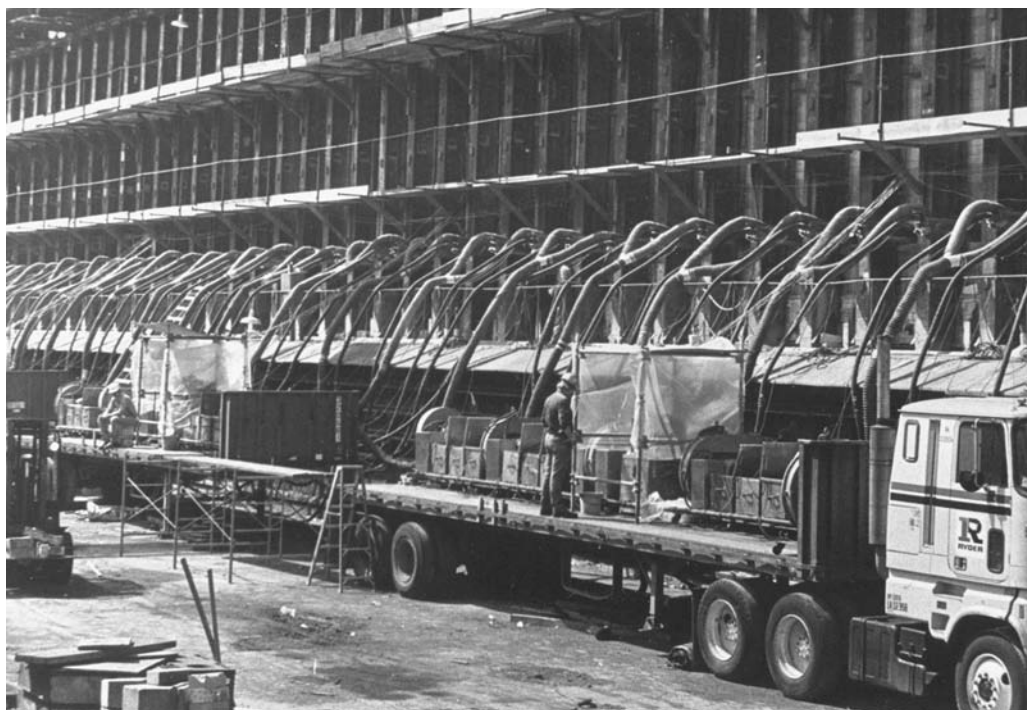


FIGURE 11.25 Multiple temporary burners in use on the heatup of a steel plant coke oven battery. (Courtesy of Hotwork—Division of Fosbel, Inc. With permission.)

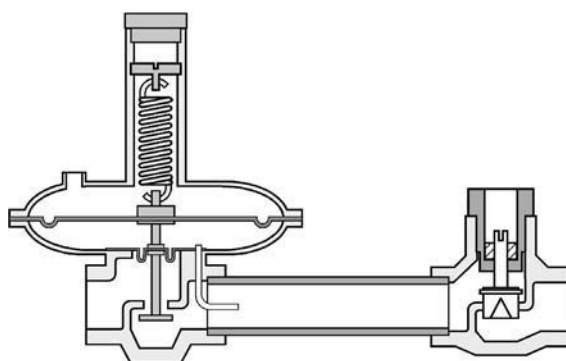


FIGURE 11.26 Cross-connected ratio regulator with limiting orifice valve.

The function of a cross-connected ratio regulator system is based on the principle that the internal air and gas orifices of a burner are fixed resistances to flow, such that the flow and pressure are related by the “square root law:”¹³

$$\frac{Q_1}{Q_2} = \sqrt{\frac{\Delta P_1}{\Delta P_2}} \quad (11.7)$$

The cross-connected ratio regulator (Figure 11.26) is designed to maintain a fuel outlet pressure that matches the combustion air pressure to the burners. A pressure sensing line is run from the burner combustion air line to the regulator’s main diaphragm case to provide an opening force to the regulator’s gas valve. An internal gas outlet pressure sensing port applies that gas pressure to

the other side of the main diaphragm as an opposing, closing force. A plug valve attached to the diaphragm adjusts the gas pressure exiting the regulator to maintain a pressure balance. As the regulator only controls pressure directly — not the actual flow — a downstream variable resistance, such as a limiting orifice valve, is required in the gas line to adjust the actual flow at the high fire rate.

A biasing spring in the regulator is used to set the low-fire fuel/air ratio. A negative bias can be applied to the ratio regulator by tensioning the diaphragm spring. This makes the fuel/air ratio “leaner” at low fire without significantly affecting the high-fire setting.

Some high-velocity burners have gas pressure requirements that are higher than their air pressure requirements. The simple cross-connected regulator described above, supplying fuel at the same pressure as the air, will not be able to supply sufficient gas pressure to operate the burner near the stoichiometric conditions. There are a number of options for ratio control in these cases. Multiplying regulators that provide gas pressure at a multiple of the air pressure, or electronic fuel/air ratio systems, can be used. If there is sufficient air pressure available, an orifice can be put in the burner air supply to raise the air pressure to the point where it is at least 25% greater than the required fuel pressure, allowing a simple cross-connected regulator to function properly.

It is common to use a single cross-connected regulator to control the gas flow for an entire zone of premix or conventional nozzle mix burners. However, the restricted tile outlets and tile back pressures of high-velocity burners will accentuate any pressure variations occurring in the tile as a result of combustion. These are manifested as variations in air and fuel flows to the burner, and, when high-velocity burners are on a common control manifold, a pressure disturbance in one burner can affect the others. This may initiate additional sympathetic pressure variations to the degree that the entire group of burners will display erratic behavior. The effect of feedback of tile pressure fluctuations can be minimized by using an individual ratio regulator for each high-velocity burner, and by placing the limiting orifice valve as close as possible to the burner gas inlet and taking the highest possible pressure drops allowed by the system across it and the burner air valve.

11.6.2 FIXED FUEL/AIR RATIO TURNDOWN (ON RATIO TURNDOWN)

Fixed fuel/air ratio control using cross-connected regulators is the most prevalent control system style for high-velocity burners. This is the only control method available for the early premix systems that required the fuel/air ratio to be set near stoichiometric at all firing rates and is often called “on ratio turndown.” In this control scheme (Figure 11.27), the zone temperature controller positions a motorized air valve to vary the airflow into the burner. The ratio regulator delivers fuel to maintain the appropriate fuel/air ratio at any airflow rate. The air valve can be continuously modulated or operated in a high/low mode.

Fixed fuel/air ratio systems optimize fuel efficiency but do not maximize the potential of the high-velocity burner. Velocity decreases as the burner turns down and the entrainment capability of the jet is reduced. A common way to maximize the time at high fire is the use of “high/low”

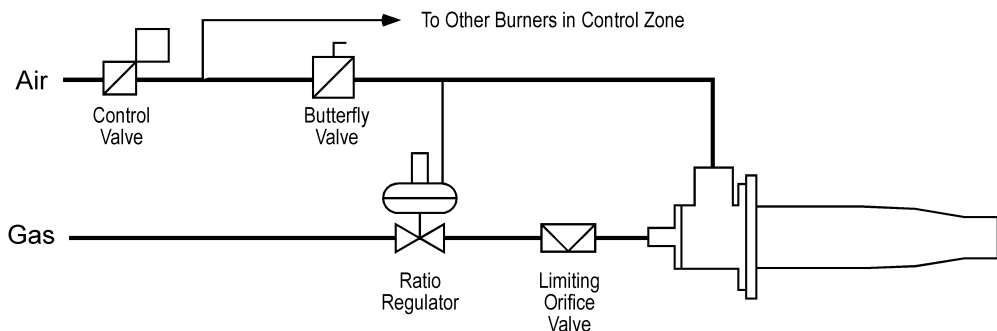


FIGURE 11.27 Fixed fuel/air ratio control schematic.

control, where the motorized air control valve is either at the maximum setting or the minimum. This method of control maximizes the time the burners are at high fire, which maximizes the entrainment and recirculation benefits, but may create difficulties for furnace pressure control, as all the burners in a control zone cycle firing rates simultaneously.

11.6.3 VARIABLE RATIO OR “THERMAL” TURNDOWN

Nozzle mix high-velocity burners have a wide fuel/air ratio capability that can be used to advantage in ratio control systems. To maintain burner nozzle velocity with reducing input requirement, the fuel flow can be reduced faster than the airflow, the increase in the excess air rate resulting in a lower temperature flame. If there is enough burner capacity available, the high fire ratio can be made “leaner” to force the burner to spend more time at high fire where the velocity is highest. This concept taken to its extreme is known as thermal turndown.

In the extreme thermal turndown system, the airflow remains fixed at the maximum setting while only the fuel flow is reduced when temperature demand drops. This method of control maintains the highest velocity for any firing rate and is useful for applications that require the ultimate temperature uniformity. At intermediate firing rates, the hot-mix temperature exiting the burner may only be a few degrees higher than the furnace setpoint, which provides for very even heating. Furnace pressure control is simplified because the amount of air introduced into the furnace remains relatively constant at all firing rates. The disadvantage of thermal turndown systems is the loss in fuel efficiency resulting from heating the excess air to the furnace temperature.

To use a thermal turndown control system, the burner must be capable of running at high enough excess air rates that the minimum temperature requirement for the furnace can be maintained without overshooting. The Bickley Iso-Jet burner described previously is an exception in that it has a premix or nozzle mix core (depending on the vintage) that runs close to stoichiometric ratio while additional air is added around the primary burner to temper the resulting hot mixture to the desired temperature.

There are a number of ways to set up a zone of burners with thermal turndown control. One popular method is to pipe the burners in the same manner as for on ratio control but to control temperature with a motorized control valve that bleeds off some of the impulse pressure feeding the cross-connected regulator instead of a motor that reduces main air flow (Figure 11.28). Note that a main air control valve may still be required to meet an enforced low-fire start requirement of a safety code.

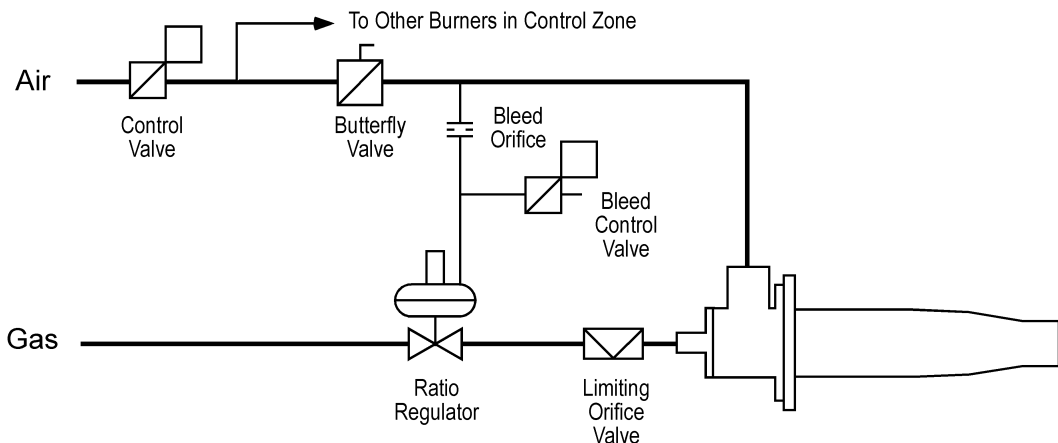


FIGURE 11.28 A typical method of thermal turndown control schematic.

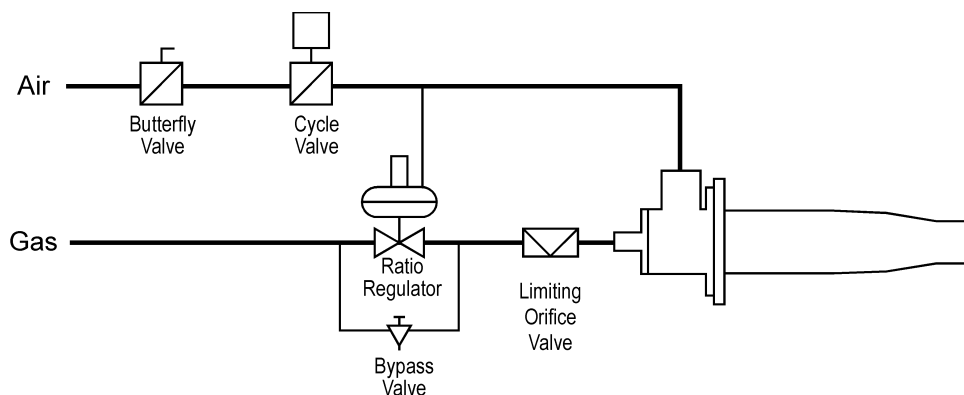


FIGURE 11.29 Typical pulse firing control schematic.

11.6.4 PULSE-FIRING INPUT CONTROL

As earlier stated, high-velocity burners are most effective when operated at high fire where the velocity and mass flow are the highest. A pulse-firing system reduces input in a zone by selectively turning down individual burners in the zone to low fire while the other burners remain at their maximum firing rate. As the required input decreases, more burners are turned off and fewer are left on. One such example would be that at 50% firing rate, half the burners will be at their full firing rate and the other half at low fire. The selection of high and low firing burners is continuously changed by the pulse-firing system logic in order to step the required heat input around the total number of burners and create temperature uniformity in the fired chamber.

Pulse-firing has the advantages of better potential temperature uniformity and more consistent furnace pressure control than modulated or high/low fixed fuel/air ratio control systems, and has better fuel efficiency than thermal turndown systems.

Pulse-fired systems use fast operating air cycle valves to switch from high fire to low fire. A small amount of air is allowed to pass through or around the closed valve position to provide the low fire air. Fuel is commonly controlled with a conventional cross-connected regulator having its spring set for a negative bias to close the valve seat at low fire, with a low-capacity bypass to set the low-fire gas rate (Figure 11.29). This arrangement typically provides more consistent minimum flow conditions than does relying on the regulator to accurately position for very low flows. Cross-connected ratio regulators are designed to constantly adjust gas flow, so they are well-suited for use as cycle valves in applications that do not require a gas-tight seal in the closed position. This may eliminate the use of a dedicated electrical or pneumatic valve where individual automatic gas valves have not been used to interrupt the gas flow for the pulse-firing system.

11.6.5 HIGH-VELOCITY OIL BURNER CONTROL

While high-velocity oil burners can be controlled by methods similar to those described above, oil burners do not typically have turndown capabilities as high as gas burners.¹⁴ Their low-fire input cannot be turned down as far using fixed fuel/air ratio control, nor do they have wide excess air capability, thereby limiting the degree to which thermal turndown can be employed. It may be necessary to use a high/low/off control with oil burners if high turndown is required. Spark-ignited gas pilots are often used for improved reliability over direct-spark ignition.

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