Premix Burners -

Technology Advancement & Engineering Challenge

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Introduction

In recent times premix burners have been applied to gas appliances, primarily in response to regulations restricting combustion emissions. Emission of oxides of nitrogen (NOx), in particular, can be reduced substantially when conventional burner systems are replaced with premix. There is also a secondary possibility - appliance efficiency can sometimes be increased because premix burners are capable of operating at excess air levels lower than those typical of conventional burners.

It has become evident that appliance engineers, standards writers and regulators have not anticipated or fully understood some basic characteristics of premix burner systems that can make their application problematic. An unappreciated advantage of the older technologies, it turns out, is that they typically have broad tolerance for real-life conditions in the field and inherent ability to meet onerous requirements in approval standards. The purpose of this paper is to outline some of the phenomena that come to bear in the application of premix burner technology.

Premix Burner Performance

Figure 1 illustrates the variation of premix burner performance with excess air, or air/fuel ratio. As with any combustion system, thermal efficiency is very good when operated at low excess air because of high flame temperature. Except at extremely low excess air, carbon monoxide emission is very low, allowing such application. NOx emission is very good at excess air levels typical of conventional burner systems and is extremely low at high excess air levels. NOx emission increases steeply as excess air is reduced to very low levels. Thus, achieving both low emission and high efficiency is subject to some fundamental limitations.

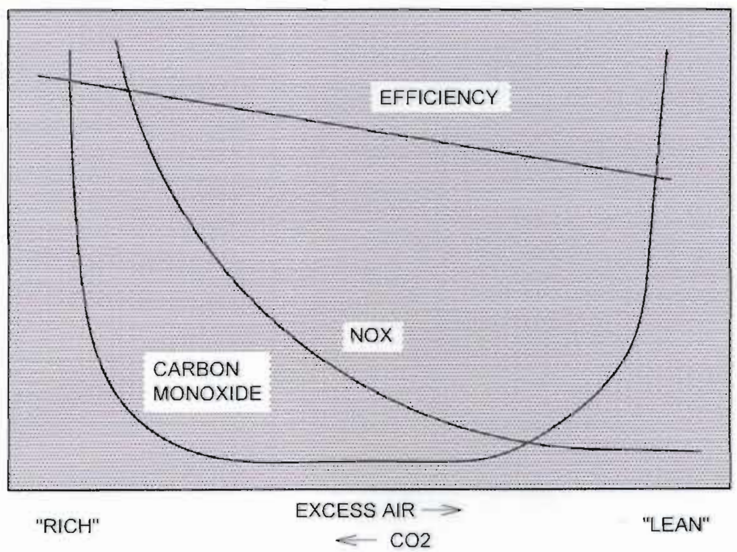

Figure 1. Performance Characteristics – Premix Burner System

Partially-Aerated and Premix Burner Systems

Most current-design gas appliances employ partially-aerated burners, the essentials of which are illustrated in Figure 2.

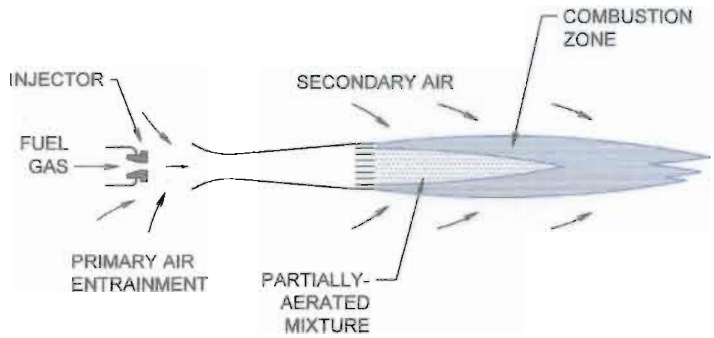

Figure 2. Partially-Aerated Burner

In such burners only a portion of the stoichiometric air quantity (i.e. that amount necessary for complete combustion of the fuel gas) is mixed with the fuel gas prior to combustion. This air is called primary air. Additional air, referred to as secondary air, enters the flame after ignition to complete the process. The "Bunsen" burners used in chemistry laboratories are partially-aerated burners.

Typically, primary aeration is in the range of 25 to 50 percent of stoichiometric. With that degree of aeration complete combustion is not possible, but upon addition of very little secondary air, the mixture becomes *combustible*, which is a highly significant point. Burning takes place at an interface where mixture velocity, burning speed and turbulent flame-holding phenomena balance. Secondary air continues to enter downstream of that point by diffusion and turbulence. The flame is usually quite long. The total of primary and secondary aeration is substantially greater than stoichiometric – broadly in the range of 140 to 180 percent of the latter, alternatively stated as 40 to 80% excess air. Operation with less than 40 percent excess air is not unusual, but as the stoichiometric condition is approached, the combustion process deteriorates and emission of carbon monoxide goes to high levels.

In premix systems all of the combustion air is mixed with the fuel gas prior to ignition. The actual combustion process is quick and compact relative to partially-aerated systems. Operation at very low excess air is possible without significant carbon monoxide emission and designs at 20-40% are not uncommon. NOx emission is generally low but climbs rapidly as excess air is reduced. Unlike partially-aerated systems, wherein flow of combustion air can be motivated by flame buoyancy and the momentum of the fuel gas jet, most premix systems are fan-assisted. A fan or blower is required to push or pull fuel gas and combustion air through the burners because of the pressure drop associated with the high flow volume. A forced-draft premix burner is illustrated in Figure 3.

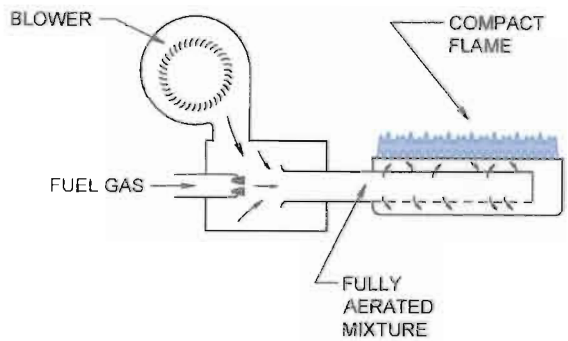

Figure 3. Premix Burner

Premix burners can be applied as "radiant" or "blue flame" burners, surface loading being the primary factor that separates the two regimes. – Compared to blue flame burners, radiant burners operate at low input per unit of burner surface area.

Basic Characteristics of Premix Burners

Compared to conventional (partially-aerated) burners, premix burners are much more sensitive to changes in excess air level. Reducing excess air, whether by actually decreasing combustion air or by increasing firing rate without commensurate combustion air increase, causes premix flames to burn hotter and concentrate near the burner surface. Increasing excess air, by actual increase of combustion air or by reducing firing rate without combustion air reduction, causes premix flames to become longer and cooler and generally less stable.

The key to understanding premix burner application is to be aware of and control the air/fuel ratio – i.e. maintain it not too "rich" and not too "lean". A rich or lean condition can be reached by changing either firing rate or aeration, as illustrated in Figure 4.

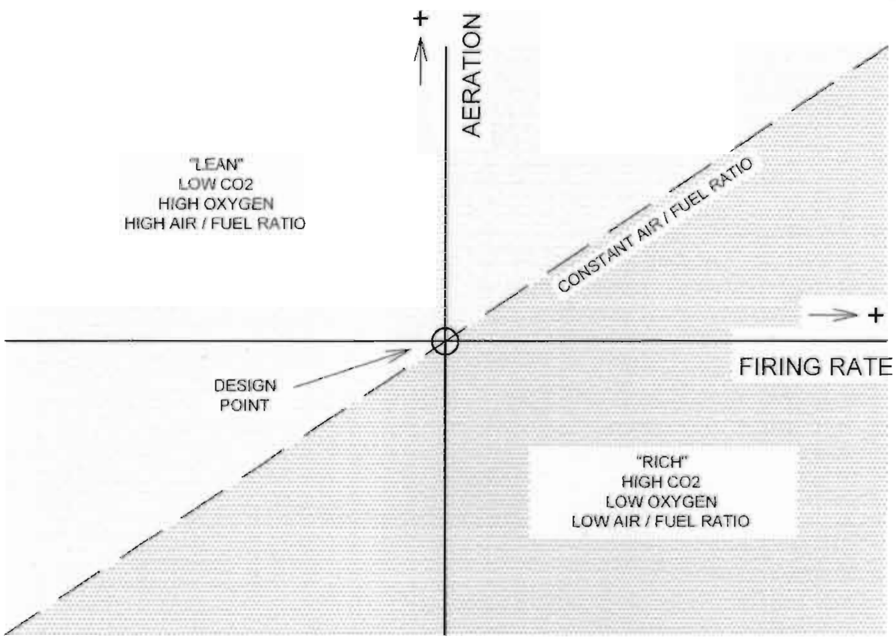

Figure 4. "Rich" & "Lean"

In radiant ("red") burner applications, a hot flame, concentrated at the burner surface, is exactly what is needed, and a relatively rich condition tends to be acceptable. In a blue flame application burners are typically designed for "cool" operation and an overly rich condition can lead to failure of the burner itself or of other combustion chamber components. There is also a tendency for highly objectionable combustion oscillation noise at the rich condition, when flames are short[(2)]. Efficiency is generally very good because of high flame temperature. Combustion quality can also be very good (low carbon monoxide emission), even at very low excess air. Emission of oxides of nitrogen (NO_X), which is generally very good, tends to increase steeply as excess air goes to low levels.

While partially-aerated burners can be operated at extremely lean condition without problem, premix burners cannot. As excess air increases, flames become longer and unstable. Ignition can be problematic and the appliance may be shut down by its flame proving controls, resulting in "no heat" complaints. Noise of a fluttering nature, which can be quite severe, is possible. Efficiency drops off and as excess air becomes high, carbon monoxide emission can increase. Generally, NO_X emission is very low.

Fuel Gas Combustibility

In the lean regime, instability and ignition difficulties reflect approach to the lower limit of combustibility. The primary component of natural gas, methane, will not burn if the percentage of gas in an air/fuel mixture is less than 5 or more than 15 percent[3]. At the lower limit it takes too much energy to bring the mixture to ignition temperature and maintain a flame because there is so much air to be heated. If a mixture just above the lower limit is burned, the combustion products would contain about 99% excess air. In more familiar terms, the carbon dioxide content of a dry combustion sample would be about 5.6%. Partially-aerated burners can easily operate with that degree of total aeration because the most of the air enters downstream of the ignition point. The premix burner has no such advantage and the result is reluctant or impossible ignition or major flame instability. Also, as illustrated in Figure 1, carbon monoxide emission becomes very high for operation near the combustibility limit.

An analysis for propane gas leads to essentially the same result as for methane.

The Operating Neighborhood

Given these characteristics, the "operating neighborhood" for a premix burner application can be illustrated as in Figure 5.

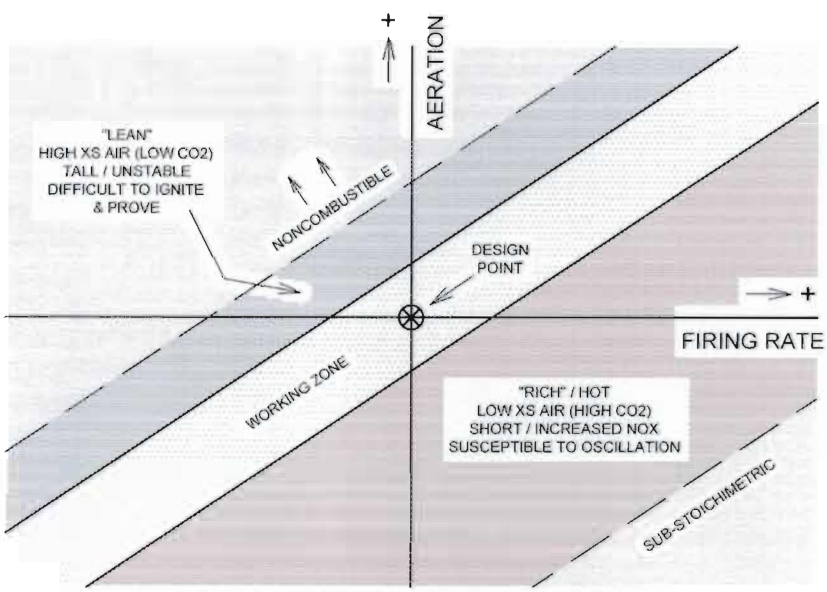

Figure 5. Operating Neighborhood for Premix Burner Application

In this illustration a design operating point is identified in the center of the grid. Horizontal movement on the grid is an increase or decrease in firing rate. Vertical movement is a change in aeration. The "working zone" diagonal on the plot represents comfortable operation for the burner. Aeration or firing rate can be changed with acceptable results as long as air/fuel ratio is maintained within a reasonable range around the design value. If firing rate is reduced excessively or aeration increased excessively, operation slips into the "lean" zone, where flame length gets larger, instability is noted and ignition and flame proving become marginal. At the extreme, operation ceases because the mixture becomes noncombustible.

Movement in the other direction, i.e. increased firing rate relative to aeration or decreased aeration relative to firing rate, results in operation in the rich zone, where flames become short and intense and susceptible to oscillation. At the extreme, movement in the rich direction results in deficient air – i.e. a sub-stoichiometric condition. That extreme is seldom reached, however, because development engineers monitor carbon monoxide and NO_X emission levels, which become unacceptably high before the sub-stoichiometric condition is reached.

Rich & Lean Operation - Consequences

Operation outside of the "working zone" has undesirable consequences – relatively minor ones for small departures, but substantial ones for operation in strongly "rich" or "lean" zones relative to the design point.

Rich operation leads to:

- Increased efficiency (no complaint, of course!).
- Increased NOx emission.
- Carbon monoxide emission – usually quite low initially, but increasing to very high levels as aeration becomes inadequate.
- Good ignition.
- Short, intense very hot flame. Burners and combustion chamber components become highly stressed and can fail.
- Highly obnoxious combustion-driven oscillations can be encountered as flames become shorter and more prone to same.

Lean operation is accompanied by a different set of issues:

- Reduced efficiency.
- Reduced NOx emission.
- Very low carbon monoxide emission if slightly lean, increasing to high levels as the aeration becomes extremely high.
- Difficult ignition as excess air increases.
- Unstable flame with large scale turbulence – sometimes with highly objectionable low frequency oscillation or appliance vibration.
- At the extreme, no combustion at all.

Successful premix burner application requires that these rich and lean conditions be avoided at both in design point and in the anticipated realm of operation in the field.

Controlling Rich vs. Lean Operation – Firing Rate and Aeration

As indicated in Figure 5, the key to successful application is control of firing rate and aeration – and controlling them *relative to each other*. Operation can move out of the working zone by an uncoordinated change of either. Firing rate can change due to several factors:

- Fuel gas properties
- Gas orifice diameter tolerance
- Pressure regulator tolerance
- Backpressure at the gas orifice
- Supply pressure
- Design-specific issues

Aeration can change due to other factors:

- Fan-assisted combustion system type – forced or induced draft
- Combustion blower strength – operating speed, voltage, deterioration, etc.
- Flow resistance within the appliance, combustion air supply or venting – i.e. contamination, debris, soot, etc
- Change in air density due to temperature or pressure
- Design-specific issues

Firing Rate Change – Wobbe Index

The flow of gas through an orifice is governed by the Bernoulli Equation, which can be reduced to:

$$Q = K(HHV)D_O^2\sqrt{\frac{\Delta p}{SG}} \qquad (1)$$

Where Q is the firing rate, HHV is the gas heating value, D_O is the gas orifice diameter, Δp is the differential pressure across the orifice, SG is the specific gravity, and K is a catch-all constant, in this case including the discharge coefficient and conversion of measurement units as appropriate.

If a fuel gas is substituted and no other adjustments are made, only the heating value and the specific gravity differ. In a ratio of the new and original firing rates, orifice diameter, the orifice differential pressure and the constant cancel, leaving the following, where the subscripts 1 and 2 identify the original and new condition:

$$\frac{Q_2}{Q_1} = \frac{HHV_2 / \sqrt{SG_2}}{HHV_1 / \sqrt{SG_1}} \qquad (2)$$

The Wobbe (W) index has been defined as the ratio of the heating value to the square root of the specific gravity. It has the dimensions of the heating value, i.e. Btu/ft^3 in North American units. Using the Wobbe index, the new firing rate is given by:

$$Q_2 = Q_1 \frac{W_2}{W_1} \qquad (3)$$

The new and original firing rates are thus proportional to the Wobbe indices of the new and original fuel gases respectively.

Firing Rate Change – Variability of Fuel Gas

The variation of natural gas properties in North America has largely been ignored because the vast majority of appliances have utilized partially-aerated burners, which on the whole, are flexible and capable of operation over a range of firing rates without special adjustment. Since premix burners are less accommodating, fuel property variation becomes an important consideration.

Per the preceding, the Wobbe index indicates the firing rate change when a new gas is substituted in an appliance with no other changes. Typical North American natural gas has a Wobbe index of about 1345 Btu/ft^3. – i.e. a heating value of about 1040 Btu/ft^3 and a specific gravity of about 0.6 yields an index of 1343 Btu/ft^3.

Figure 6 shows the variation of natural gas Wobbe indices for a number of U.S. locations, according to a recent survey by the Gas Industry[4].

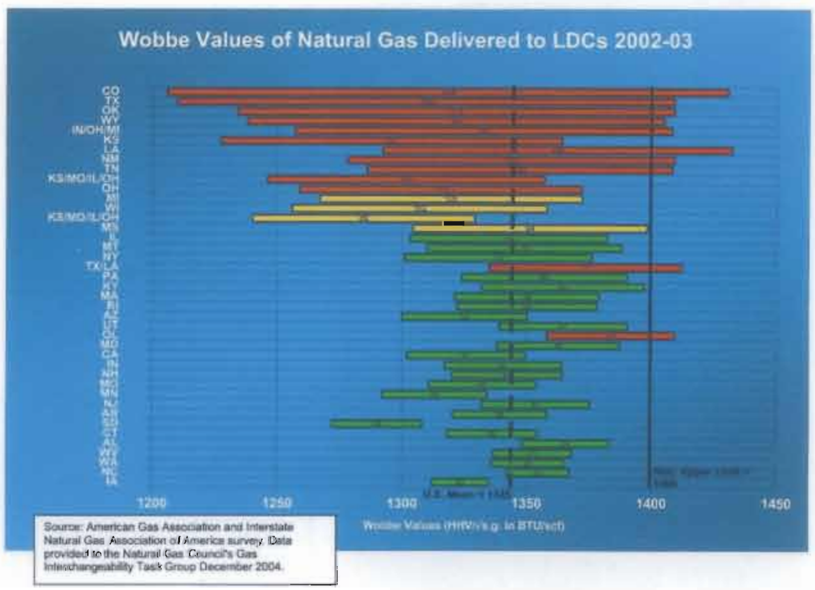

Figure 6. Wobbe Index Data for United States Locations

Note that values range from around 1200 to over 1400 Btu/ft^3. An appliance set up for operation with the "average" gas would fire at less than 90% of its normal rate if operated with the gas having Wobbe index near 1200 Btu/ft^3. Likewise, it would operate at about 106% of rate using the gas having an index of 1430 Btu/ft^3. An appliance adjusted for operation with one of the gases at either extreme would be further off the mark when operated with fuel at the other end of the range.

Firing Rate Change – Controls & Tolerances

Even if fuel gas is unchanged, other variables of can affect firing rate. Per Equation 1, input varies as the square of the orifice diameter and as the square root of the pressure differential across the orifice. A variation of 2% in orifice diameter results in a 4% change in firing rate and a 5% variation results in 10% change in rate. Obviously, production tolerance on orifice diameter is especially important.

Differential pressure across the orifice would appear to be of less concern, but gas pressure regulator tolerances can be significant. A common natural gas manifold pressure specification is 3.5" WC. With that basis, a misadjustment of 0.3" WC, which is not completely unrealistic, results in a 4-5% change in firing rate.

Firing Rate Change – Modulation or Stage-Firing

Modulation or stage-firing systems are used to match loads or transient conditions that require substantially less heat than the full rating. For the most part, systems with partially-aerated burners can readily operate at reduced input, even without reduction of aeration. In premix systems, however proportionate reduction of aeration is mandatory because failure to do so results in the highly unstable or noncombustible condition. There is a compensating effect, however - proportionate reduction of aeration maintains high flame temperature while heat exchanger loading is reduced. Efficiency increases.

Firing Rate Change – Design and Production Choices

Gas control manufacturers offer a wide range of products to meet special requirements of appliance designers. One of them is a slow-opening characteristic, which can provide a desirable "soft" ignition in conventional appliances. In the premix scenario the slow-opening characteristic results in a lean mixture during ignition, especially if the appliance has fan-assisted combustion. Initially the mixture may even be noncombustible. When the mixture finally reaches combustibility, considerable fuel is present and ignition can be anything but "soft".

"Factory de-rate" has been a common practice historically and has provided desirable margin versus production and field variations that might otherwise result in overfiring. In a premix system, de-rating reduces field reliability. The air/fuel mixture is prejudiced in the lean direction and any field conditions that further reduce input can lead to ignition or flame stability problems or a noncombustible condition.

Firing Rate Change – Gas Supply Pressure

Obviously reduced gas supply pressure can reduce firing rate. Most appliances are designed with substantial margin, however, and can operate properly at pressures substantially below the "nominal" natural gas supply pressure of 7.0" WC. Manifold pressures are typically much lower than the supply pressure and only severely deficient pressure or grossly undersized gas piping reduces firing rate. Even when firing rate is reduced, the appliance owner is seldom troubled because typically, the appliance was oversized at installation. Partially-aerated burners have been the norm, and they usually operate without problem even when input is severely reduced.

With premix systems, low supply pressure can result in lean operation, especially in appliances with fan-assisted systems – i.e. in most premix appliances. Severe pressure deficiency results in a noncombustible air/fuel ratio.

ANSI/CSA standards[5,6] require that natural gas appliances operate at the seemingly unreasonable supply pressure of 3.5" WC. Obviously, an appliance designed for operation with 3.5" WC manifold pressure will operate at substantially reduced firing rate when subjected to that test, and it may not operate at all. Given that certification is dependent on meeting the requirement, the only choice is to reduce the design manifold pressure. That introduces a new issue – increased sensitivity to tolerance or misadjustment of the pressure regulator. Earlier it was noted that with 3.5" WC manifold pressure, a 0.3" WC change affects firing rate by 4-5%. As the design manifold pressure is reduced, the same degree of misadjustment has an increasingly detrimental effect. So the reduced supply pressure test hits twice – first to force a lower manifold pressure and second to make the appliance more susceptible to operational problems.

The aggravation is more pointed in a forced-draft premix system, as illustrated in Figure 7. In the forced draft system, flow resistance of the burner, heat exchanger and venting system create a backpressure at the gas orifice. The pressure differential across the gas orifice is thus reduced by the amount of pressure drop through those downstream components. The manifold pressure, on the other hand, is constrained by the supply pressure test requirement in the standards. As the resulting differential is squeezed to a low value it is increasingly vulnerable to miss-adjustment. Changes in downstream flow resistance can also affect the firing rate in ways that vary with the specific appliance design or field conditions. These factors work together to present the appliance designer with a very narrow operating range.

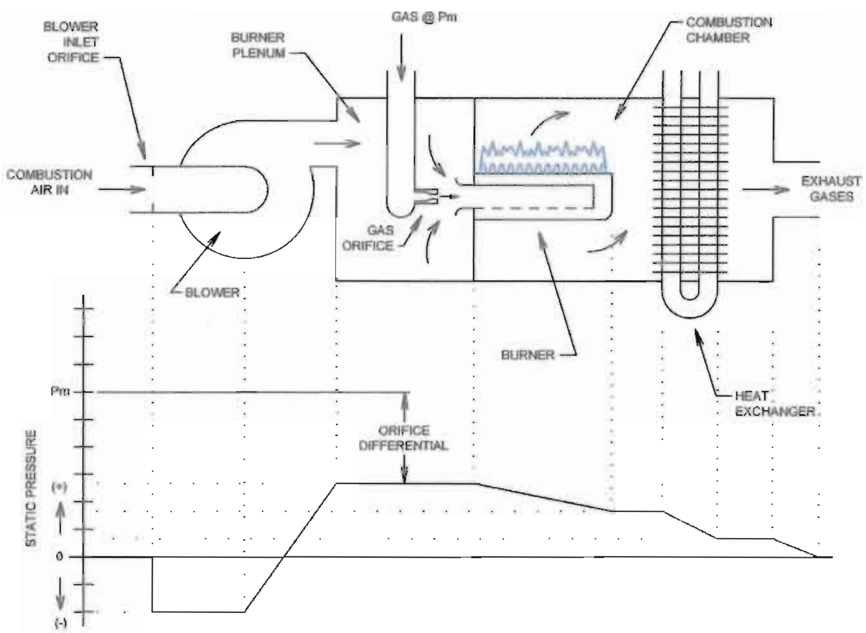

Figure 7 – Pressure Diagram for Forced-Draft System

Aeration Change – Fan-Assisted Systems

Most premix systems are fan-assisted, as stated previously. An attractive approach, for a number of reasons, is to utilize an induced-draft design, in which a blower at the appliance outlet pulls combustion products through the system. An induced-draft system is illustrated in Figure 8.

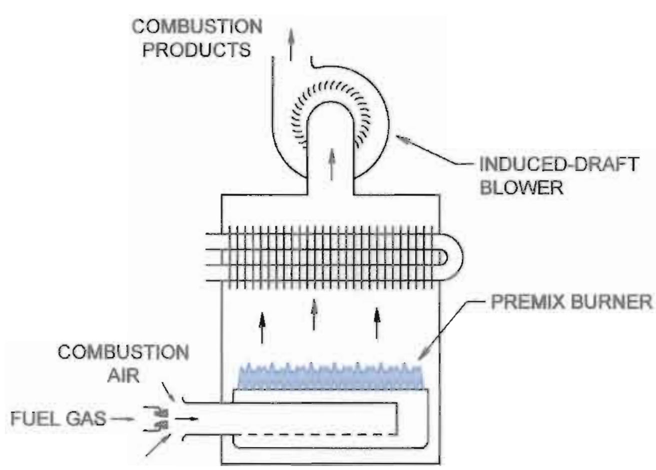

Figure 8. Induced-Draft Premix System

Induced-draft systems, whether or not they have premix burners, undergo a very large change in aeration during the transition from ignition to a steady state (hot) condition. If the induced-draft blower operates with essentially constant speed during that period, the actual mass flow through the system changes drastically because of the density change associated with the temperature of products handled by the blower.[a] A non-condensing appliance operating at 81 or 82% efficiency, for example, would produce combustion products at 350-400°F. At startup, however, an induced-draft blower would handle ambient air at about 70F. Ignoring secondary phenomena, the density of gases handled by the blower changes essentially per the perfect gas law, which states that it is inversely proportional to the absolute temperature. Using the typical numbers:

$$\rho \propto \frac{1}{T} \tag{4}$$

$$\frac{m_{Cold}}{m_{Hot}} = \frac{\rho_{Cold}}{\rho_{Hot}} = T_{Hot}/T_{Cold} \tag{5}$$

Where ρ is density, m is mass and T is the absolute temperature. The "cold" or ambient temperature is 70°F or 530°R. The "Hot" or steady state temperature is 380°F or 840°R. The ratio of the startup aeration to the steady state aeration is then the inverse ratio of these temperatures:

$$\frac{m_{Cold}}{m_{Hot}} = T_{Hot}/T_{Cold} = \frac{840}{530} \tag{6}$$

$$\frac{m_{Cold}}{m_{Hot}} = 1.58 \tag{7}$$

So aeration at startup is nominally about 60% higher than at steady state. In a premix system this makes ignition impossible. Successful operation is possible only if the appliance control strategy provides a reduction in aeration during startup.

Aeration Change – High Elevation Operation

When fan-assisted systems are operated at high elevation, aeration is reduced in proportion to the barometric pressure. Of course, fuel gas density is also reduced, but in conventional systems, they do not remain in proportion. Assuming the forced or induced-draft blower operates at essentially constant speed, the volumetric flow through the system is approximately the same at any elevation per the so-called fan laws.[b] Aeration mass flow will therefore change in proportion to the air density, or barometric pressure, which decreases at about 3.3% per 1000 feet increase.

The firing rate, on the other hand, is governed by the aforementioned gas orifice equation, which can be restated slightly as:

$$Q = K'\rho_G (HHV) D_O^2 \sqrt{\frac{\Delta p}{\rho_G}} \tag{8}$$

The new constant K' accommodates extraction of gas density (ρ_G) from the former constant K. The significant thing is that density appears both in the numerator and under the radical in the denominator. The net result is that the firing rate is proportional to the square root of the density, and therefore to the square root of the barometric pressure. Accordingly, the firing rate de-rates "naturally" at about 1.7% per

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[a]A motor driven fan or blower increases speed when density is reduced because less power is required. The increase is typically quite small, especially if the motor is conservatively sized.

[b]In addition to slightly increased blower speed due to low air density, heat transfer is changed somewhat, and undoubtedly the flow system resistance is changed, contrary to the fan-law assumption. Nonetheless, these assumptions provide first-level insight to behavior of the combustion system.

1000 feet of elevation increase. Since aeration is reduced at a greater rate, the conventional fan-assisted unit tends to richer operation as elevation increases – assuming the fuel gas Wobbe index is constant. A de-rate may be necessary to prevent problems associated with rich operation. A deep de-rate, however, may push the system too far in the lean direction, depending on how it was originally set up for sea-level operation. Assuming there are no other issues, a reasonable approach to de-rating of premix systems is to de-rate to the extent necessary to maintain the air/fuel ratio at its sea level value.

An additional factor must be noted. At many places in the Rocky Mountain Range gas of very low Wobbe index is delivered – Colorado for example, as illustrated in Figure 6. This must be considered in analysis of high elevation operation and any de-rating recommendation.

Tracking Combustion System – Air/Fuel Proportioning

The term "tracking combustion system" is applied to various fan-assisted systems in which air and fuel gas flow are interconnected such that they change together in accordance with the Bernoulli equation. The specific approach may involve a "zero regulator", a "zero governor", a "negative pressure regulator" or an "amplified positive pressure control", all of which deliver fuel gas in proportion to air flow. One form of the tracking system is illustrated in figure 9.

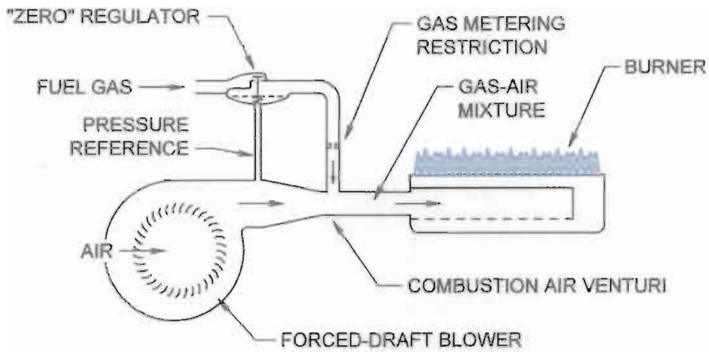

Figure 9. Tracking Combustion System

Since a gas orifice or equivalent metering device is used, the aforementioned gas orifice equation applies and Wobbe index change affects the system just as it does in conventional systems. For constant Wobbe index, however, the air/fuel ratio remains constant both for air flow change and for barometric pressure change. Modulation of firing rate can be done by simply changing blower speed or otherwise changing air flow.

Tracking Combustion System – High Elevation Operation

For the constant-Wobbe case, a tracking system accommodates elevation change very nicely. Barometric pressure decrease affects both air and gas density in the same way and the air/fuel ratio remains unchanged. For constant air volume flow (e.g. constant-speed blower), the result is a de-rate of about 3.3% per 1000 feet of elevation increase – i.e. the same as the barometric pressure change. Modulation can be superimposed at constant air/fuel by changing blower speed.

In actual practice the scenario isn't quite that clean, however. It turns out that in much of the Rocky Mountain area, gas of very low Wobbe index is distributed, Colorado being a prime example, as illustrated in Figure 6. This has led to operating problems with tracking premix systems because the full impact of the lower Wobbe index is brought to bear. (Recall that there is a compensating effect in conventional systems, which tend to go rich with increased elevation.) An unexpected result is that the correct adjustment for a tracking system appliance installed at certain high elevation locations may be to *increase* the orifice size.

Summary

Hopefully the point has been made that specifying and controlling the air/fuel ratio or the "rich" vs. "lean" operation of a premix burner system is the key to successful design. The behavior of the burner with change of air/fuel ratio should be defined by test, and once determined, the variables in design, production and field application must be evaluated and handled appropriately. A broad list would include:

- Fuel gas properties, primarily Wobbe index.
- Component tolerances, notably gas orifices, pressure regulators & combustion blower hardware.
- Production setup, such as de-rating practice.
- Anticipated field misapplication such as undersize gas piping.
- Design-specific features or phenomena such as cold start issues with induced-draft systems or backpressure in forced-draft systems.

It is possible to design tests to evaluate most of these factors by estimating the range of expected conditions and imposing those values on the system, noting that there is low probability that all would exist at their extreme values simultaneously. The best way to evaluate Wobbe index effect is to substitute an appropriate gas orifice size with no other changes to the appliance.

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