PDHonline Course M367 (8 PDH)

Design of Atmospheric Gas Burners

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DESIGN OF ATMOSPHERIC GAS BURNERS

INTRODUCTION:

Gas burners are used in a wide variety of consumer and industrial products. Practically all domestic and commercial gas burner applications and many industrial gas applications employ atmospheric gas burners. There are basically four overall classifications for gas-fired burners; 1.) Atmospheric 2.) Power 3.) Forced and Induced Draft 4.) Premix and Pressure Power. These are distinguished from each other solely by design. Atmospheric gas burners use primary air, at **atmospheric pressure**, to combine with delivered gas, resulting in a homogenous mixture of gas and air ready for combustion. The other dominant burner type, **power burner**, is generally dependent upon a blower in order to provide the necessary **primary air** for combustion. An optimal ratio of gas and air is achieved with a power burner to control the mixture ratio injected into the combustion chamber for eventual ignition. Figure 1 below will show the basic design of a power burner assembly.

Figure 1—Power Burner

As you might suspect, forced and induced draft burners, premix and pressure burners and power burners are generally used for a commercial or industrial application and, by virtue of design, would not be suited to many applications where size is a real issue; i.e. ranges, gas lamps, gas grills, etc. Their size alone makes them prohibitive for many uses. One great advantage power burners have over the other atmospheric types is the ability to reach very high input rates. I recently had a project that required my involvement with a truly exceptional gas test lab. While there, I witnessed the testing of a gas-fired furnace with an input of 3 million Btus/Hr. This furnace used one (1) power burner to generate that tremendous input. I do know of another furnace by the same manufacturer that fires 15 million Btus/Hr with only one power burner. The technology is very well defined, remarkably reliable and very safe. The other burner types are versions of the power burner design and will not be shown or discussed in this text.

This course addresses atmospheric gas burners not of the power burner type. These are much more prevalent in the consumer market and cover a wide range of very basic applications. Some of these applications are as follows:

- Ranges for use in kitchens, both domestic and commercial
- Commercial bakeries for bread, cookies, pies, cakes, etc.
- Warming ovens to keep food hot and sanitary after cooking
- Autoclaves
- Gas lamps for outdoor lighting
- Gas logs for fireplaces
- Gas grills
- Room or zone heaters used to heat shop floors, loading docks and other work areas
- Heating liquids contained in storage tanks for cleaning, degreasing, coating, paving, etc.
- Bunsen burners used in laboratories
- Industrial "heat tunnels" used for drying adhesives, coatings, evaporating surface moisture prior to other processes, baking ceramic graphics to control panels to insure durability.
- Domestic and commercial clothes dryers
- HVAC systems

These represent just a few applications but demonstrate uses that are common in today's marketplace.

BENEFITS:

There are definite reasons for the use of atmospheric gas burners. The most important are as follows:

- Great possibilities for variation to meet requirements for port loading, number of ports, length of mixing tube, height of burner head, air shutter design, etc.
- Simplicity of design
- Easy to troubleshoot when difficulties arise
- Flexibility when using a variety of gasses; i.e. natural, LP (propane or butane), manufactured, mixed, etc.
- Suitable for a range of inlet gas pressures
- Inlet pressures are typically low so that safe use of products is insured
- Can remain operational at a fairly low supply pressure
- Gas represents a low cost fuel for heating and lighting purposes
- Gas is an abundant fuel found in significant quantities in most countries
- Controls available today are more than adequate to insure proper operation and safety of gas burners and gas distribution system.
- Considerably smaller in size relative to power burners , thereby allowing for more application possibilities.
- Cost of operation is typically lower than electricity for the same equivalent input.

This course explores the **design** of atmospheric gas burners and those rules governing their proper operation. By proper operation, we mean several "general" characteristics **absolutely necessary** for the very best use of the equipment. These are stated as follows:

RULES GOVERNING USE:

1. Controllability over a wide range of turn-down pressures without danger of flash-back or burner outage. Even for thermostatically controlled operations where the burner is either full-on or off, this characteristic is very desirable. Flashback occurs when the flame "flashes back" from the burner head to the burner orifice. This results with actual burning of the gas / air mixture at the orifice and no discharge through the burner ports. (Please see Definition of Terms in the Appendix to this text.)
2. Uniform distribution of heat, including uniform flame height and good flame distribution over the area being heated.
3. Combustion must be complete. Neither carbon nor carbon monoxide should escape from the flames. The American Gas Association (now the Canadian Gas Association) says that a maximum of 800 parts per million (PPM) for CO (carbon monoxide) must not be exceeded for safe operation.
4. The flames must not lift away from the burner ports. This is termed "blowing" or "lifting" and is caused when the velocity of the air/gas mixture, at the ports, exceeds the velocity of the flame front for the particular gas in use. The speed of the flame front is determined by the specific fuel gas being used. That speed will vary between natural, LP, mixed and manufactured gases.
5. The flames must not "float" from the burner ports. This is an indication of less than adequate primary air.
6. Ignition should take place rapidly. The flame should travel from port to port over the entire burner rapidly and without difficulty. The American Gas Association says that ignition must occur within four (4) seconds and the carryover from port to port must be rapid.
7. The burner should operate quietly on ignition, during burning, and on extinction. Significant noise is an indication of lifting and possible irregularities in the burner fabrication itself; i.e, burrs, improper casting, misalignment, etc.
8. Substantial and durable construction is essential to withstand severe heating and cooling while remaining operational for the life of the appliance in which it is used. Significant care must be taken when selecting burner materials to preclude issues with overheating and sagging of burner parts.

These requirements **must be met** for a wide range of actual service conditions including differing gasses.

AIR AVAILABLE FOR COMBUSTION:

Before we go further, let us discuss the differences between primary air, secondary air and excess air. Understanding these terms is critical to understanding gas burner design and we will use them throughout this text. I would like to mention again that integral to this course is a complete glossary of terms common to the industry. It is all-inclusive. Some of those definitions may not apply to our text for burner design but, but I think it is informative and will aid your efforts at understanding gas-fired products in general. Please take a look if you have not done so already.

PRIMARY AIR:

Air which is mixed with gas **before** that gas/air mixture is ejected and ignited at the ports is called primary air. A definite minimum amount of primary air is required for complete combustion no matter what gas type is being used. That minimum percentage of primary will vary depending upon the type of gas, its specific gravity and its heating value.

SECONDARY AIR:

All other air supplied to the burner is called secondary air. In an ideal case, primary air and secondary air should be 100% of the air needed for complete combustion. All air supplied is called **total air**.

Ideally, 10 cubic feet of air is needed for 1 cubic foot of **natural gas** if complete combustion is to be accomplished. Suppose that 15 cubic feet of air is supplied to a burner for each cubic foot of gas. The total air is 150% (15/10 X 100%). Excess air is 50% (150%-100%). Now suppose that 5% of the air supplied from that 15% is primary air. The remaining 10 cubic feet would be secondary air and excess air.

Approximately 20 cubic feet of air is needed for 1 cubic foot of **propane** and 30 cubic feet of air is needed for **butane**. Please note that this is a volumetric measurement with the respective flow rates being in FT^3/ Hr. It is proper to consider $Ft.^3$/Hr of fuel gas combined with $Ft.^3$/Hr of primary air for complete combustion. This mass flow rate would be the total mass flow rate for the mixture of gas and air entering the mixing tube.

Figure 2 below is a photograph of an actual range maintop using a five burner arrangement. It demonstrates an ideal flame appearance hoped for when using atmospheric gas burners. Most gas cooktops employ a four or five burner arrangement with the placement of these burners within a thirty inch, thirty-six inch or forty inch width. This picture was taken with the lights out to emphasize the flame pattern and flame color. Burners that are operating properly will exhibit the appearance shown below with the following characteristics:

IDEAL BURNER CHARACTERISTICS:

1. Blue flame with possibly some yellow tips when using propane or butane as the fuel. **(NOTE: These burners are firing natural gas with a heating value of approximately 1075 Btu/Ft^3)**
2. Distinct individual flame pattern. You can count the number of ports by counting the number of individual flames emanating from those ports.
3. No blowing or lifting of flames; i.e., separation of the flame from the burner port.
4. No lazy flames. (This is an indication of too little primary or secondary air.)
5. No flash-back of burner flames.
6. No offensive noise during ignition, operation or extinction.

7. No offensive odors emanating from the combustion process.
8. Flame heights are uniform around the burner periphery**. (NOTE: In looking at the simmer burners below (smaller burners), you will notice that the flame heights are not equal. This is by design and involves the configuration of the burner grates mounted above the burners themselves.**)

Figure 2-Gas Burner Operation

As mentioned above, these burners are firing natural gas and have various inputs depending upon burner placement. The largest burner, right front as you look from left to right, has an input of approximately 12,000 Btu/ Hr. Burners of this type can fire up to 20,000 Btu/Hr when the design is proper. The smallest burner, or simmer burner, right rear, is firing 5,000 Btu/Hr. Again, please note that the flames are very uniform in height, blue with no trace of yellow or yellow tipping and have a very distinctive individual pattern or form. These burners are examples of a **sealed burner** configuration in which all of the primary air is entrained from the bottom of the burner box. All secondary air is **ambient** air available around the burner ports themselves. A sealed burner is an excellent choice for a range top due to the very tight, liquid-proof, conditions required between the burner head and the maintop. There are no "crud cracks" through which spillage can occur. Here again, a well designed burner will be capable of burning natural gas, liquefied petroleum gas (propane and butane), manufactured gas and mixed gas with pressures ranging from 3.5 inches water column (W.C.) to 11.0 inches W.C. Burners cannot be expected to transition between natural gas and other gas types without an orifice change and a change to the regulator to compensate for pressure differences. This is done quite easily and with a minimal amount of time. The burners in Figure 2 have a turn-down-ratio of approximately 10 to 1 and can go from a maximum input to simmer without producing excessive carbon monoxide or flame extinction. A 5,000 Btu/Hr burner should be expected to operate properly at 500 Btu/Hr in the simmer mode. Please note that the higher the maximum burner input the higher the simmer rate **if** a single orifice is used. Some "dual ring burners" have a main burner orifice and a simmer orifice. The purpose for this design is to achieve a much lower simmer rate but with a very high main burner rate. Figure 8 illustrates a dual ring burner. The simmer section is seen in the center with the main input being around the outer periphery or the outside ring. The total burner input is the main burner ring plus simmer.

OVERALL CONSTRUCTION:

The following photograph will show a gas-fired slide-in range demonstrating the positioning of component parts relative to the maintop itself.

Figure 3 Gas-Fired Slide-In Maintop

As you can see, there are two sealed burners positioned on the right side of the maintop. The high input burner is the right front burner with the simmer burner located at the right rear. In this case, the burner fires at 15,000 Btu / Hr. The simmer burner fires 5,000 Btu / Hr. The diameter of the high input burner is approximately 5.00 inches and the diameter of the simmer burner is 3.75 inches. Both burners are mounted on a glass surface with minimal clearance between the glass and the burner base. This is truly a sealed burner configuration. Cast iron grates are positioned over the burners for location of the cooking utensils. I show this to merely demonstrate the fact that sometimes flame impingement can occur when a burner tyne is directly above a burner flame. This can cause sooting or carboning and is definitely a condition to avoid. The center grate, painted black, covers the exhaust manifold from the oven cavity and also provides a resting place for utensils. An individual burner, mounted to the maintop is shown by Figure 4 **(NOTE: The burner cap is removed to show the mounting details and the placement of the electronic spark ignition device.)** As you can see, the spark igniter is at the 8:00 o'clock position. The raised area in the center of the burner is the throat. We will discuss the purpose of the throat at a later time.

Figure 4 Burner Base without Burner Cap.

Let’s now take a look at a “modern day” in-shot burner. This burner type can generate very high input rates and deliver those rates from a fairly small burner package. The following digital photographs will show the configurations in use for a great number of residential heating systems.

Figure 5—In-shot Burner

We are going to consider the various burner parts later on in the course, but please notice the ring to the very left of the component. This is where the orifice is located. The gas stream is directed into a converging/diverging nozzle and then into the mixing tube. The orifice is installed into a burner manifold supplying the gas to the system. The port location is in the opening to the far right and looks as follows:

Figure 6—Burner Ports

These are fairly typical ports for an in-shot burner. If you could see the resulting flame, you would see that it looks very much like the exhaust of a jet engine with the inner cone being very sharp-pointed and coincident with the center line of the burner mixing tube. It is not uncommon for this type of burner to be mounted side by side on a common frame. This arrangement is frequently used in commercial and residential furnaces and HVAC systems.

BURNER CLASSIFICATIONS:

Atmospheric burners are further classified by port type. These types are as follows:

- Drilled port
- Slotted port (See Figure 9)
- Ribbon port
- Single or monoport
- Infrared
- Jet or inshot (See Figures 5 and 6)
- Impingement
- Target
- Pilot

As you might suspect from looking at the previous figures, the designs vary considerably but the basic theories of combustion remain the same. Our course will consider the basics and examine the operation of one "classic design".

POOR BURNER OPERATION:

Now, I would like to show you a picture of a burner system that is **NOT** firing properly. Sometimes it is easier to discuss proper operation by looking at a burner behaving badly. This design, shown in Figure 7 below, breaks **ALL** of the rules given above. This is a gas grill basically used for "tail-gate" cooking. The propane tank and grill are integral parts of the trailer. The trailer is attached to the car with a bumper hitch, then towed to the game behind the vehicle. I was asked to "pass judgment" on the design and indicate to the designer what corrective actions I would recommend. It did take some time.

Figure 7 Burners Firing Improperly

Here is what we know:

- Yellow flames; an indication of inadequate primary air and incomplete combustion. This condition will produce sooting (or carboning) and will generate an intolerable amount of carbon monoxide. If this product were used in an enclosed space, there would be definite issues with the accumulation of carbon monoxide. We can expect some yellow tipping because the fuel gas is propane. Typically, propane and butane produce yellow burner tips but this is much too much and represents a condition that must be rectified.
- Flame height is very irregular which tells me there are real issues with primary air injection, burner alignment and issues with the burners being level relative to the mounting system. The orifice size metering gas to the burners is very suspect and, as I discovered, much too large relative to the design capability of the burners for propane.
- Very probable that there is an issue with delivery pressure. A "lazy" flame indicates the pressure needs to be checked and corrected if inadequate. A system firing on propane should have 11.00 inches water column (W.C.) **downstream** of the regulator and available at the burner orifice(s). It is difficult to see from the picture, but the gas delivery system to the orifices was almost serpentine in configuration; tubing every where! The tubing was 0.25 inch in diameter with each of the four burners orificed to fire 50,000 Btu/Hr. This was truly a "master blaster" but with a gas delivery system very suspect relative to pressure losses. Please remember—pressure losses in a gas delivery system are the **enemy** and are to be avoided at all costs.
- In looking at the "superstructure" of the burner system, there is a real issue with misalignment of the burners during movement of the trailer. The burners can become displaced thereby creating a hazardous condition. This definitely needs to be corrected to provide additional stability of the entire system.
- This last point is somewhat academic, but the designer did not consult any design standard prior to initiating the project. It was all "off-the cuff". Cut and try. If it works fine, if not fix it. No real attempt at obtaining the ANSI standard for gas-fired grills or gas-fired products and following that standard.

Believe it or not, there were corrections made to the design and much better performance did result. That product is now is in the "field test" phase and will be introduced in late summer—ready for kickoff.

BASIC CONFIGURATION:

Now let us examine the basic operation of an atmospheric gas burner. We do so by looking at two typical burner designs. Our course will examine the design criteria for each burner part so the following figures can be referred to throughout the text. We will progress from left to right with the introduction of gas to the burner orifice and the introduction of the air through the air shutter. Please take a look at Figures 8 and 9.

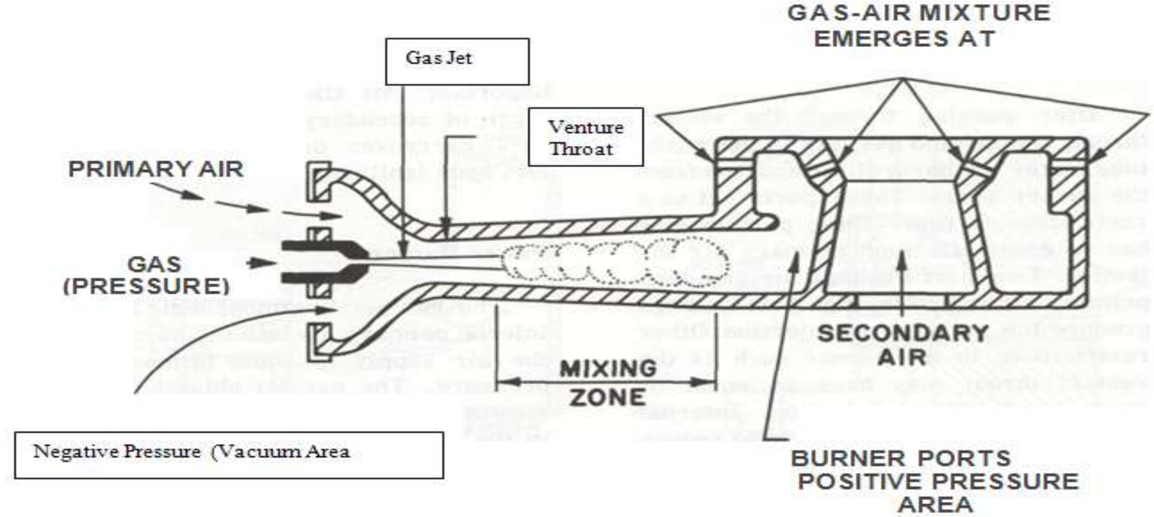


Figure 8 Basic Components of an Atmospheric Gas Burner.

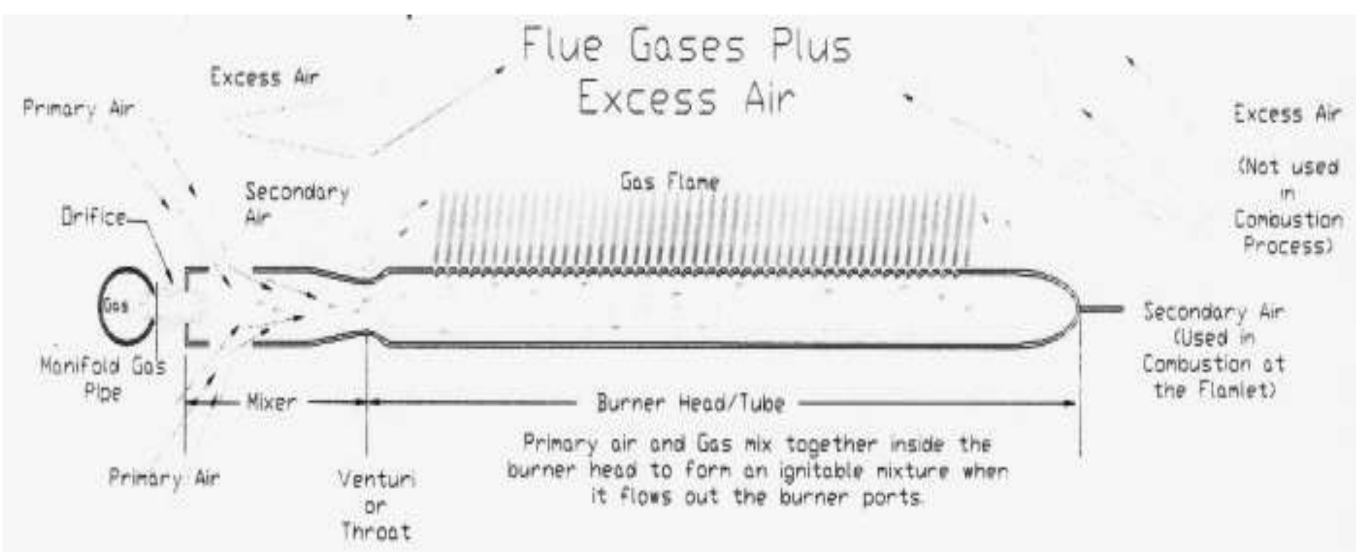


Figure 9 Basic Components of an Atmospheric Gas Burner—Ribbon Type

As you can see, both burners have the same components but the design and resulting configurations are very different. Figure 8 represents a burner that is typically made from cast material while Figure 9 represents a burner that is typically made from steel. To lessen the effects of corrosion, this type of burner is generally made of aluminumized steel or stainless steel. The ports are not cast into the burner head but slotted or ribbon type cut into the body of the burner itself. Both burners, as well as the burner shown in Figure 5, represent design flexibility that exists to the engineer during the concept phase.

These burners do not show an ignition source but one is definitely necessary for proper and timely ignition of the gas / air mixture. With today's technology, that ignition source would be a "spark igniter" positioned closely to one of the burner ports. A spark module, generally mounted within the structure, discharges up to 15,000 VDC (but with less than 0.50 amp) to the igniter. The spark then "jumps" from the igniter electrode to the burner to provide the temperature necessary for ignition. One port is lit and carryover occurs to the adjacent ports until there is a continuous flame. There are still some burners that use a "standing pilot" as the ignition source. A standing pilot generally fires between 500 and 1,000 Btu / Hr and contributes very little to the overall total input. There are also configurations in which a spark igniter lights a pilot burner and the pilot burner lights the main burner. This configuration is just about non-existent due to advancements in technology. Let me mention that countries "do their own thing" and technologies differ. We are considering designs prevalent in the US, Canada, Mexico and Western Europe. I have discovered that technologies in the middle-east and some parts of Asia and Africa can vary greatly.

If the burner ports are inline; i.e. ribbon ports, slotted ports, etc. the carryover occurs in the very same manner except more than one ignition port may be needed to insure that carryover. One thing critical to ribbon or slotted port burners, the ignition ports must remain free of lint or any other obstruction to insure the necessary four second ignition.

Figure 10 below will show a typical igniter and the relative placement of that igniter to the burner ports. The placement of the igniter; i.e. left, right, top, bottom etc can be critical to the operation of the burner itself and may affect testing for fabric ignition. Fabric ignition failures may necessitate moving the igniter to another location around the circumference of the burner base.

Figure 10—Position of Spark Igniter

Now let us take a look at the actual operation of the burner itself. Please keep in mind the references for operation are depicted in Figures 8 and 9.

BASIC BURENR OPERATION:

Gas is supplied to the burner orifice by virtue of pressure from the distribution system or the gas bottle; i.e; propane or butane. For natural gas, that pressure is generally delivered between 9.00 and 12.00 inches water column. The gas is then regulated to a delivery pressure between 3.5 and 4.00 inches W.C for natural gas. If the gas is propane or butane, the delivery pressure will be between 10.5 and 11.00 inches W.C. A regulator is located on the gas bottle so adjustments may be made to achieve the proper delivery pressure. It is not uncommon to have an additional regulator mounted on the gas-fired device. All regulators have "pressure ports" from which the gas pressure may be measured so if there is any doubt about delivery pressure, please check. A simple "U" tube manometer is completely adequate for this measurement. Simply measure the difference between the heights of the columns. This difference is the pressure relative to atmospheric.

As mentioned earlier, the air for combustion is called **primary air** and is provided at atmospheric pressures from outside the appliance. Gas is metered by virtue of the **burner orifice.** Primary air is drawn through the air shutter as the gas is "streamed" from the orifice opening. The injection of the gas creates a negative pressure relative to the ambient pressure so atmospheric air is entrained through the air shutter and the mixing face. The orifice diameter controls the gas flow rate, generally measured in Ft^3/ min or Ft^3/Hr. The combination of gas and air occurs in the mixing zone or burner tube. It is very important that the internal design and length of the mixing tube allow for proper combination so a homogeneous gas /air mixture can result and be delivered to the burner head prior to ejection through the burner ports. The venturi "throat" serves as a converging / diverging nozzle to increase the velocity of the gas/air mixture prior to entering the mixing tube. The mixture is then swept into the burner head and distributed to the individual burner ports for ignition. The ports act as a restriction to flow; thus, port loading has a great effect on primary air injection. (I would again direct your attention to the glossary in the appendix for the definition of port loading.) It is also important to note that internal burner roughness has an effect on the injection of primary air through friction losses. It is definitely possible to increase primary air by enlarging the burner ports ,thereby reducing individual port loading. When this occurs, care must be taken to make sure that no flashback results. Flashback occurs when the velocity of the ejected gas/air mixture is less than the velocity of the flame front through the individual ports. When this occurs, burning may actually "flash back" to the burner orifice. This condition is prohibited by ANSI (The American National Standards Institute). Ignition takes place at one port with carryover to the remaining ports. Again, ignition time should be at or less than four (4) seconds to preclude an accumulation of uncombusted gas. This time is also prescribed by ANSI. Continued ignition takes place around or along the burner ports until gas is no longer supplied to the burner. This control is generally accomplished by virtue of a thermostat that senses temperature or closure of a gas valve done manually by the user.

BURNER TYPES:

As mentioned earlier, there are several types of atmospheric burners; i.e. 1.) Drilled port burners, 2.) Slotted port burners, 3.) Ribbon port burners, 4.) Single port or monoport burners, 5.) Infrared radiant burners, 6.) Jet burners, 7.) Impingement target burners and 8.) Pilot burners. **ALL** atmospheric burners, regardless of design, have the same basic components and the very same method of operation. For this reason, we can use the example given by Figures 8 and 9 for all descriptive information in this text.

BURNER COMPONENTS:

I would like now to take each burner component and describe its design and function relative to the overall assembly of parts. We are going to begin with the air shutter and progress from left to right as we basically disassemble the burner. Again, please refer to Figure 8 and 9 when reading the text. We will be discussing the following:

1. Air shutter
2. Burner face
3. Burner orifice
4. Burner throat
5. Burner venture
6. Mixing tube
7. Burner head
8. Burner ports

Please, one note; in writing the formulas for this text, I have chosen to use the "^" symbol to represent a factor raised to a power. In other words, (pD)^0.25 , represents the fourth root of the sum of gas pressure and specific gravity. All powers are represented in this fashion. I feel this method accomplishes clarity that the typical √ does not give.

Air Shutter:

Some atmospheric gas burners are designed with fixed primary air openings; consequently no air shutters are necessary. **These designs are generally used with one specific gas at one specific gas pressure and one predetermined orifice diameter.** When burners are designed for numerous gasses, an adjustable air shutter is generally required. If the burner under consideration is to be utilized for natural and mixed as well as manufactured gasses, it must have air injecting ability for the lowest product of pressure and density. The formula that describes this relationship is as follows:

$$(pD)^{0.25}/(H)^{0.50} = \text{air injecting ability of burner}$$

Formula 1 Air Injecting Ability of a Burner

Where p = gas pressure in inches water column (W.C.)
D = specific gravity of gas
H = heating value of gas in Btu / Ft^3

(Please see "Gas Facts" in the appendix for heating values and specific gravity values for various combustible gases.)

The above equation simply indicates that the air injecting ability of an atmospheric burner varies as the fourth root of the mass velocity divided by the square root of the heating value per cubic foot of the gas. It is important to note that the air injecting ability of the burner must be sufficient to insure satisfactory combustion and flame characteristics at the desired input with **any** gas it is designed to burn. This also tells me that the air injecting ability will differ somewhat when using different gases with differing characteristics.

The American National Standards Institute (ANSI) states that **'air shutters shall be substantially made, shall resist rusting and shall be designed so that they can be held firmly in any set position'.** It is very critical to note that, once set for a specific gas and gas pressure, the air shutter open area must not change due to vibration, gravity, shipment, installation, etc. Also, ANSI indicates that the air shutter openings must not be susceptible to blockage by lint and dust. The purpose of an air shutter is to **regulate and control** the amount of **primary air** available for combination with the gas in use. In order to properly control the flow, all of the air should pass through the adjustable opening and not around the air shutter and the burner face. For this reason, there must be a good fit between those two components. The total area through which the primary air is drawn should be between 1.25 and 2.25 times the **total port area**. A larger area is more desirable when the total burner input rates are higher. In other words, a burner firing 5,000 Btu / Hr is going to require less primary air than a burner firing 15,000 Btu/Hr. 1.25 to 2.25 is a "rule of thumb" but it's a good one and a good starting place when designing the burner head and the burner ports. Air shutters are generally made from sheet metal and are attached to the burner head using a set screw or sheet metal screw.

Burner Orifice:

The primary purpose of the gas burner orifice, regardless of type, is the maintenance of a **predetermined** input rate to the burner. As mentioned earlier, the flow rate issuing from the burner orifice is measured in Ft.³ / Hour or Ft³ / Minute. The volume of gas flowing through an orifice depends upon its specific gravity, pressure and the area of the opening and the resulting "coefficient of discharge" of that opening. The coefficient of discharge or "K" value is dependent upon the inner configuration of the orifice itself. Please keep in mind that the gas is mixed with atmospheric air to provide a combined flow rate of the gas/air mixture into the burner head. The flow rate is, ideally, divided equally between the burner ports so that individual port loading is uniform. This condition is assumed throughout this course. If a burner exhibits uneven flame heights, this will probably indicate uneven port loading. There are several reasons for unequal port loading. These are as follows:

- Imperfections in port fabrication; i.e. slag in port casting, unequal port diameters, etc.
- Issues with burners being level relative to superstructure
- Centerline of orifice not collinear with centerline of burner throat or mixing tube
- Improper design of burner head.

There are three general orifice types as follows:

- **Fixed Orifice**—This is the most common and consists of a drilled opening in a suitable plug. As mentioned above, the inner configuration of the orifice may vary; consequently, there must be a factor noting and accounting for that variation. This is the "K" factor. Fixed orifices are shown in Figure 12.
- **Adjustable Orifice**—Generally there is one moving part and one stationary part to this orifice type. A tapered needle is used to vary the gap between the two parts so that when they are brought close together the orifice area is decreased. The tapered needle may be located on the stationary or the movable part. Oven cavity burners for domestic ranges typically use orifices of this type. Examples are represented by Figure 11.

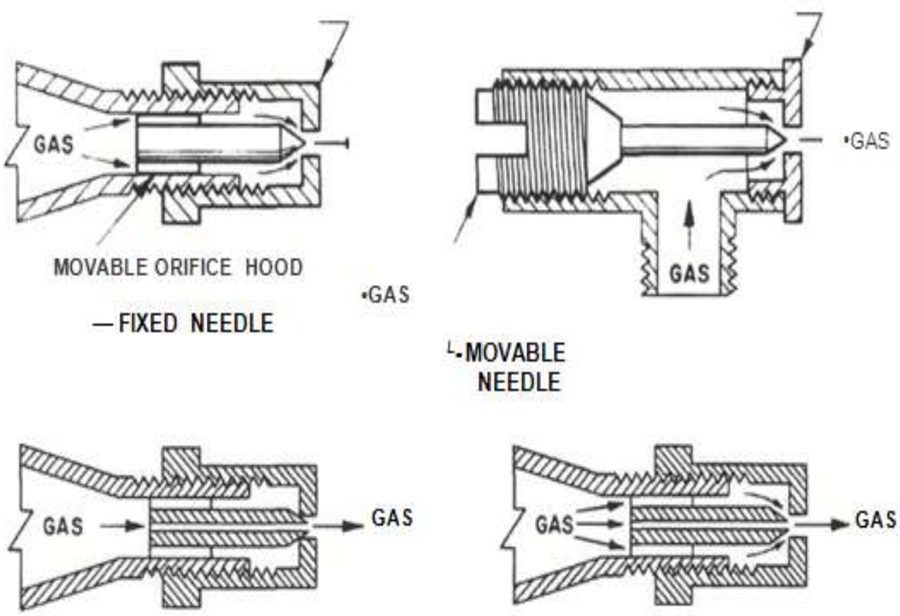


Figure 11—Adjustable Orifices

- **Pressure Reduction Orifice**—This orifice type is primarily used for controlling butane-air gas mixtures and is not shown here.

Since the fixed orifice is by far the most common type, we are going to direct all of our discussion around this configuration.

Figure 12 below will show the various fixed orifice designs and their internal configurations.

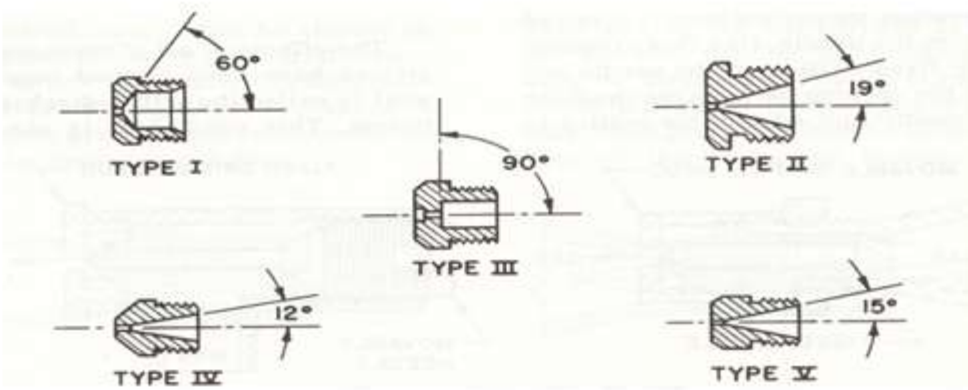


Figure 12—Fixed Orifices

The "angle of approach" varies from 12 to 90 degrees, depending upon orifice type. This variation produces the greatest contribution to the differing "K" factors. The internal configuration, of course, contributes to the "K" factor also but to a lesser amount. The resulting "K" factor for each orifice type is given in Table 1 below.

ORIFICE TYPE	ORIFICE DISCHARGE COEFFICIENT
I	0.80
II	0.82
III	0.65
IV	0.83
V	0.83

Table 1—"K" Factors for Orifice Types I II, III, IV

The quantity of gas that will issue from an orifice may be calculated from the following formula:

$$q = 1658.5\ KA \sqrt{H/d} \text{ where}$$

q = gas discharge in Ft^3 / hr
K = coefficient of discharge (This is dependent upon orifice design and is given in the following table.)
A = area of orifice in in^2
H = gas pressure in W.C.
d = specific gravity of gas

Formula 2—Flow of Gas Through an Orifice

As you can see, the "K" factor is an important consideration relative to the flow of gas through an orifice. Please note, the "K" factor does not vary that much for angles of approach up to 60°. The real variation occurs when the angle of approach exceeds 60 °. This formula is "good" for calculating the flow rate through all three orifice types.

I would like to show now input tables that will represent **flow rates** relative to orifice diameter. We begin with Table 2 below. The gas type, the specific gravity of the gas, the "K" factor and the gas pressure are very critical to the flow rate and must be factored into the overall equation. Table 2 portrays the input in **cubic feet per hour** relative to sea level. We can calculate the input in Btu/Hr by multiplying the values in Table 2 by the heating value of the gas; i.e. Btu/Ft^3 x Ft^3/Hr = Btu/Hr. This is a "handy" way to convert flow rate into Btu/Hr. and is used throughout the industry.

Example:

For an orifice number of drill size 50 and a pressure of 4.00 inches W.C., we have a flow rate of 14.94 $Ft.^3$/Hr with a gas having a heating value of 1,000 Btu/Ft^3. With this in mind, our calculation would be (14.94 $Ft.^3$/Hr x 1,000 Btu/Hr or 14,940 Btu/Hr.)

Table 3 shows the actual input in Btu/Hr for various orifice sizes depending upon orifice inlet pressures. The orifice sizes are given in the left column with gas inlet pressures above the table. This table is constructed for natural gas but similar tables exist for other gases. Please keep in mind that Formula 2 is "good" to calculate the flow rate of any gas through any of the orifices shown above. This formula was used to do just that for the tables that follow. The calculations were generated for equipment at **sea level and altitudes up to 2,000 feet.** This is very important to note since ANSI prescribes a down-rating of burner inputs for increasing altitudes due to a decreasing availability of atmospheric air. This is customary for all domestic burners.

Example:

From Table 3, an orifice size of 50 with a gas pressure of 7.00 inches W.C., will produce an input of 13,850 Btu/Hr.

UTILITY GASES
(Cubic Feet Per Hour at Sea Level)

Specific Gravity = 0.60
Orifice Coefficient = 0.9
For utility gases of another specific gravity, select factor from Table 5,
For altitudes above 2,000 feet, first select the equivalent orifice size at sea level from Table 6.

Orifice Size (Decimal or DMS)	Gas Pressure at Orifice - Inches Water Column 3	3.5	4	5	6	7	8	9	10
.008	.17	.18	.19	.23	.24	.26	.28	.29	.30
.009	.21	.23	.25	.28	.30	.33	.35	.37	.39
.010	.27	.29	.30	.35	.37	.41	.43	.46	.48
.011	.33	.35	.37	.42	.45	.48	.52	.55	.59
.012	.38	.41	.44	.50	.54	.57	.62	.65	.70
80	.48	.52	.55	.63	.69	.73	.79	.83	.88
79	.55	.59	.64	.72	.80	.84	.90	.97	1.01
78	.70	.76	.78	.88	.97	1.04	1.10	1.17	1.24
77	.88	.95	.99	1.11	1.23	1.31	1.38	1.47	1.55
76	1.05	1.13	1.21	1.37	1.52	1.61	1.72	1.83	1.92
75	1.16	1.25	1.34	1.52	1.64	1.79	1.91	2.04	2.14
74	1.33	1.44	1.55	1.74	1.91	2.05	2.18	2.32	2.44
73	1.51	1.63	1.76	1.99	2.17	2.32	2.48	2.64	2.78
72	1.64	1.77	1.90	2.15	2.40	2.52	2.69	2.86	3.00
71	1.82	1.97	2.06	2.33	2.54	2.73	2.91	3.11	3.26
70	2.06	2.22	2.39	2.70	2.97	3.16	3.38	3.59	3.78
69	2.25	2.43	2.61	2.96	3.23	3.47	3.68	3.94	4.14
68	2.52	2.72	2.93	3.26	3.58	3.88	4.14	4.41	4.64
67	2.69	2.91	3.12	3.52	3.87	4.13	4.41	4.69	4.94
66	2.86	3.09	3.32	3.75	4.11	4.39	4.68	4.98	5.24
65	3.14	3.39	3.72	4.28	4.62	4.84	5.16	5.50	5.78
64	3.41	3.68	4.14	4.48	4.91	5.23	5.59	5.95	6.26
63	3.63	3.92	4.19	4.75	5.19	5.55	5.92	6.30	6.63
62	3.78	4.08	4.39	4.96	5.42	5.81	6.20	6.59	6.94
61	4.02	4.34	4.66	5.27	5.77	6.15	6.57	7.00	7.37
60	4.21	4.55	4.89	5.52	5.95	6.47	6.91	7.35	7.74
59	4.41	4.76	5.11	5.78	6.35	6.78	7.25	7.71	8.11
58	4.66	5.03	5.39	6.10	6.68	7.13	7.62	8.11	8.53
57	4.84	5.23	5.63	6.36	6.96	7.44	7.94	8.46	8.90
56	5.68	6.13	6.58	7.35	8.03	8.73	9.32	9.92	10.44
55	7.11	7.68	8.22	9.30	10.18	10.85	11.59	12.34	12.98
54	7.95	8.59	9.23	10.45	11.39	12.25	13.08	13.93	14.65
53	9.30	10.04	10.80	12.20	13.32	14.29	15.27	16.25	17.09
52	10.61	11.46	12.31	13.86	15.26	16.34	17.44	18.57	19.53
51	11.82	12.77	13.69	15.47	16.97	18.16	19.40	20.64	21.71
50	12.89	13.92	14.94	16.86	18.48	19.77	21.12	22.48	23.65
49	14.07	15.20	16.28	18.37	20.20	21.60	23.06	24.56	25.83
48	15.15	16.36	17.62	19.88	21.81	23.31	24.90	26.51	27.89
47	16.22	17.52	18.80	21.27	23.21	24.93	26.62	28.34	29.81
46	17.19	18.57	19.98	22.57	24.72	26.43	28.23	30.05	31.61
45	17.73	19.15	20.52	23.10	25.36	27.18	29.03	30.90	32.51
44	19.45	21.01	22.57	25.57	27.93	29.87	31.89	33.96	35.72
43	20.73	22.39	24.18	27.29	29.87	32.02	34.19	36.41	38.30
42	23.10	24.95	26.50	29.50	32.50	35.24	37.63	40.07	42.14
41	24.06	25.98	28.15	31.69	34.81	37.17	39.70	42.27	44.46
40	25.03	27.03	29.23	33.09	36.20	38.79	41.42	44.10	46.38
39	26.11	28.20	30.20	34.05	37.38	39.97	42.68	45.44	47.80
38	27.08	29.25	31.38	35.46	38.89	41.58	44.40	47.27	49.73
37	28.36	30.63	32.99	37.07	40.83	43.62	46.59	49.60	52.17

Table 2 Orifice Flow Rates

Orifice Size, D.M.S.	Pressure—In. of Water									
	2	3	4	5	6	7	8	9	10	11
1	78,500	96,400	111,000	124,100	136,000	147,000	157,100	167,000	176,500	185,100
2	73,600	90,500	104,100	116,300	127,200	139,000	147,100	156,400	165,300	173,900
3	68,500	84,100	97,000	108,200	118,500	129,000	137,000	145,500	153,900	161,500
4	66,000	81,000	93,500	104,200	114,100	124,000	132,000	140,100	148,100	155,700
5	63,700	78,300	90,300	100,900	110,200	120,000	127,400	135,400	143,100	150,200
6	62,700	77,000	88,900	99,400	108,900	117,000	125,900	133,900	141,400	148,600
7	60,900	75,000	86,200	96,400	105,500	114,000	122,000	129,800	137,000	144,000
8	59,700	73,400	84,500	94,500	103,500	112,000	119,700	127,000	134,100	141,000
9	58,000	71,200	82,100	91,900	100,500	109,000	116,100	123,500	130,500	137,000
10	56,500	69,400	80,000	89,500	98,000	106,000	113,100	120,100	127,000	133,200
11	55,000	67,500	77,900	87,000	95,300	104,000	110,100	117,100	124,000	130,100
12	53,900	66,100	76,400	85,400	93,500	101,000	108,000	114,900	121,300	127,500
13	51,600	63,400	73,100	81,700	89,500	97,000	103,400	110,000	116,200	122,100
14	50,000	61,400	70,800	79,100	86,600	94,000	100,000	106,100	112,100	118,000
15	48,000	60,000	68,300	76,400	83,600	92,000	96,600	102,800	108,800	114,100
16	47,200	58,000	66,900	74,700	81,900	89,000	94,600	100,500	106,100	111,700
17	45,200	55,500	64,000	71,500	78,300	85,000	90,500	96,200	101,600	106,800
18	43,400	53,300	61,500	68,800	75,400	82,000	87,200	92,700	98,000	103,000
19	41,500	51,000	58,800	65,700	72,000	78,000	83,200	88,500	93,500	98,300
20	39,100	48,000	55,400	62,[illegible]00	68,000	75,000	78,600	83,600	88,500	93,000
21	38,100	46,700	53,900	60,300	66,100	72,000	76,500	81,400	86,000	90,400
22	37,200	45,600	52,600	58,900	64,500	70,000	74,600	79,400	84,000	88,300
23	35,800	44,000	50,700	56,700	62,100	68,000	71,900	76,500	81,000	85,100
24	34,800	42,700	49,300	55,100	60,400	66,000	69,900	74,400	78,600	82,000
25	33,700	41,400	48,000	53,700	59,000	64,000	68,500	73,000	77,200	81,200
26	32,600	40,100	46,500	52,100	57,200	62,100	66,500	70,800	74,900	78,700
27	31,300	38,500	44,600	50,000	54,900	59,600	63,900	68,000	72,000	75,700
28	29,800	36,600	42,400	47,500	52,100	56,600	60,600	64,500	68,200	71,700
29	27,900	34,300	39,700	44,500	48,800	53,000	56,700	60,400	63,900	67,200
30	25,000	30,800	35,700	40,000	43,900	47,600	51,000	54,300	57,500	60,500
31	21,700	26,700	30,950	34,700	38,100	41,400	44,300	47,100	49,800	52,500
32	20,300	24,950	28,900	32,400	35,600	38,700	41 460	44,100	46,600	49,000
33	19,300	23,700	27,450	30,800	33,800	36,700	39,300	41,800	44,200	46,500
34	18,600	22,800	26,400	29,600	32,500	35,300	37,800	40,300	42,600	44,800
35	18,250	22,400	26,000	29,100	31,900	34,600	37,000	39,400	41,600	43,800
36	17,100	21,000	24,300	27,200	29,800	32,400	34,700	37,000	39,100	41,100
37	16,300	20,000	23,200	26,000	28,500	31,000	33,200	35,300	37,200	39,200
38	15,510	19,080	22,100	24,800	27,200	29,600	31,700	33,800	35,800	37,700
39	14,910	18,300	21,200	23,800	26,100	28,400	30,400	32,400	34,300	36,100
40	14,500	17,800	20,600	23,050	25,250	27,400	29,300	31,200	33,000	34,700
41	13,900	17,100	19,800	22,200	24,350	26,450	28,300	30,150	31,900	33,600
42	13,200	16,200	18,800	21,050	23,100	25,100	26,900	28,650	30,300	31,900
43	11,950	14,700	17,000	19,050	20,900	22,700	24,300	25,900	27,400	28,800
44	11,190	13,730	15,900	17,800	19,500	21,200	22,700	24 200	25,600	27,000
45	10,120	12,450	14,400	16,100	17,650	19,200	20,600	21,950	23,200	24,400
46	9,900	12,180	14,100	15,800	17,350	18,850	20,200	21,500	22,700	23,900
47	9,300	11,410	13,210	14,800	16,200	17,600	18,800	20,000	21,100	22,200
48	8,730	10,710	12,400	13,900	15,250	16,550	17,700	18,850	19,900	20,900
49	8,050	9,860	11,400	12,730	13,930	15,070	16,100	17,080	18,000	18,850
50	7,400	9,060	10,470	11,700	12,820	13,850	14,800	15,700	16,550	17,330
51	6,770	8,300	9,590	10,720	11,730	12,680	13,540	14,370	15,170	15,880
52	6,090	7,460	8,620	9,640	10,550	11,400	12,180	12,900	13,630	14,280
53	5,340	6,550	7,560	8,450	9,250	10,000	10,680	11,330	11,950	12,500
54	4,560	5,590	6,450	7,210	7,900	8,530	9,120	9,670	10,200	10,700
55	4,070	4,990	5,760	6,440	7,050	7,620	8,140	8,640	9,110	9,550

Table 3 Orifice Size (D.M.S.) vs Input Rates at Various Inlet Pressures

Caution: It is very important that the burner orifice centerline be collinear with the centerline of the venturi AND the mixing tube. An orifice that is off-center can create a mixture that is less than homogeneous producing a gas/air mixture that will not burn properly with minimal carbon monoxide.

Table 4 below is another method to provide the same input rate but cross-referencing the heating value with the specific gravity of the gas.

Heating Value, B.t.u. per Cu.Ft.	Specific Gravity (Air = 1.0)											
	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
400	1.41	1.63	1.83	2.00	2.16	2.31	2.45	2.59	2.70	2.83	2.95	3.06
500	1.13	1.31	1.46	1.60	1.73	1.85	1.96	2.07	2.16	2.27	2.36	2.45
525	1.08	1.24	1.39	1.52	1.64	1 76	1.87	1.97	2.06	2.16	2.25	2.33
550	1.03	1.19	1.33	1.45	1.57	1.68	1.78	1.88	1.97	2.06	2.15	2.23
575	0.983	1.14	1.27	1 39	1.50	1.61	1 70	1.80	1.88	1.97	2.05	2.13
600	0.942	1.09	1.22	1.33	1.44	1 54	1.63	1.73	1.80	1.89	1.97	2.04
700	0.81	0.932	1.04	1.12	1.24	1.32	1.39	1.48	1.54	1.62	1.69	1.75
800	0.707	0.816	0.912	1.00	1.08	1.15	1.22	1.30	1.35	1.41	1.48	1.53
825	0.685	0.791	0.885	0.970	1.05	1.12	1.19	1.26	1.31	1.37	1.43	1.48
850	0.665	0.769	0.860	0.942	1.02	1.09	1.15	1.22	1.27	1.33	1.39	1.44
875	0.646	0.746	0.835	0.915	0.987	1.05	1.12	1.19	1.24	1.29	1.35	1.40
900	0.628	0.725	0.811	0.890	0.960	1.03	1.09	1.15	1.20	1.26	1.31	1.36
950	0.595	0.687	0.769	0.842	0.910	0.972	1.03	1.09	1.14	1.19	1.24	1.29
1000	0.565	0.653	0.730	0.800	0.864	0.924	0.980	1.04	1.08	1.14	1.18	1.22
1025	0.551	0.636	0.712	0.781	0.842	0.900	0.955	1.01	1.06	1.10	1.15	1.19
1050	0.538	0.621	0.696	0.762	0.823	0.880	0.934	0.985	1.03	1.08	1.12	1.16
1075	0.526	0.606	0.679	0.745	0.804	0.859	0.911	0.961	1.00	1.05	1.10	1.14
1100	0.514	0.594	0.664	0.727	0.785	0.840	0.891	0.938	0.982	1.03	1.07	1.11
1125	0.502	0.580	0.649	0.711	0.767	0.820	0.871	0.920	0.961	1.00	1.05	1.09
1150	0.491	0.567	0.635	0.696	0.751	0.802	0.852	0.899	0.940	0.985	1.02	1.06
1175	0.481	0.555	0.621	0 681	0.735	0.786	0.834	0.878	0.920	0.965	1.00	1.04
1200	0.471	0.544	0.608	0.666	0.720	0.770	0.816	0.860	0.900	0.945	0.985	1.02

Table 4 Orifice Capacities Factor for Heating Values & Specific Gravity (Basis= 800 Btu/Ft³,Sp.Gr=0.60)

Example:

What orifice size is needed to supply the correct volume of gas to a burner rated at 20,000 Btu/Hr on natural gas at 7 inches W.C. pressure, 0.60 specific gravity and with a heating value of 1100 Btu/Ft³? From the table above, find the heating value in the left column. Find the specific gravity at the top of the table. The factor for heating value and specific gravity is 0.727. Multiplying 0.727 by 20,000 (the input rate to the burner) results in 14,540 Btu/Hr. Now go to table 3 and under the 7 inch W.C. heading you will find the correct orifice lies between number 49 and 50. Take the larger number. This will be the orifice size that will produce the required flow. This is basically the determination we made with the previous example. Just another way to skin the same cat!

Mixer Face:

The burner face is the first component that “sees” the gas/air mixture. It is in some burners the component upon which the air shutter and gas orifice is mounted or affixed. At the point of injection, there does not exist a homogeneous mixture of gas and air. This occurs downstream of the burner throat and well into the burner tube. There are certainly configurations that encompass designs very specific to any one given mounting arrangement. Each burner manufacturer will have designs specific to any one given configuration.

Venturi Throat:

The venturi throat is a constriction in the mixing tube that accelerates the gas/air mixture as it travels down the mixing tube and into the burner head. It basically works as a converging / diverging nozzle to increase the velocity of the mixture. This increase in velocity serves to aid the entrainment of primary air into the burner head and creates diffusion of the gas into the entrained air. It is critical to achieve a homogenous mixture prior to reaching the burner head. The venturi throat and mixing tube accomplish that. There is a definite relationship between the throat area and the port area. For acceptable combustion and proper flame appearance, that ratio varies depending upon the type of fuel gas burned. For example, a throat to port ratio of 0.22 to 0.91 for natural gas and a throat to port ratio of 0.24 to 0.68 for manufactured gas will produce a primary aeration that is identical for both gases so that acceptable combustion may be had.

Mixing Tube:

The turbulence from the mixing process provides for a homogeneous mixture that is accumulated in the burner head and then ejected through the burner ports. The pressure driving the process must be constant and maintained through the burning process. This pressure is dependent upon the type of gas and its specific gravity. Proper mixing is also dependent upon the **angle of divergence** of the mixing tube. Generally, for atmospheric burners, a 2 to 3 degree angle is suggested. It is very important to note that if the angle of divergence approaches or exceeds 3.5 degrees, friction losses due to enlargement may be appreciable. **Where greater flexibility and better operating characteristics are obtained, a venturi-type mixing tube is preferable to a straight-sided tube.**

It has been determined from tests on numerous burners that a mixing tube with an internal slope of 3.5 degrees or less will follow the formula below for **aspiration of primary air**:

P = {[(pd)^0.25/(H)^0.50][2.5X10^5(AmAp)/(R)^0.50][(540)^0.50/(T)^0.50]}

Formula 3—Aspiration of Primary Air for a Mixing Tube<3 Degrees

P = Primary air required for complete combustion (percentage)
p= Pressure of gas, measured in inches W.C.
d=Specific gravity of gas
Am=Average area of throat and mixer tube outlet
Ap=Total area of ports measured in inches squared
R=Input rate measured in Btu/Hr.
H=Heating value measured in Btu/Ft^3
T=Average absolute temperature of gas/air mixture in burner head (°F+460)

Let me repeat, this formula is used for burners with an internal mixing tube slope less than 3 degrees. For burners with slopes **greater than 3 degrees**, use the following formula :

R=KF(a)F(b)[(pd)^0.25][(540)^0.50/(T)^0.50]/Q^0.45(dm)^0.50

Formula 4—Inputs for Mixing Tube for Slopes Greater Than 3 Degrees

R=Ft^3 of gas/air mixture per FT^3 of gas
K=Factor for throat size and venture slope
F(a)=Factor for throat to port area
F(b)= Factor for port size and depth
P=Pressure of gas
D=Specific gravity of gas
dm=Specific gravity of gas/air mixture
Q=Input in Ft^3/Hr.
T=Absolute temperature of gas/air mixture in burner head

In looking at formula 3, the first term, **[(pd)^0.25/(H)^0.50],** describes the air injecting ability of the burner. The properties of a fuel gas; i.e. specific gravity (density) and heating value have a significant bearing on the ability of the burner to entrain primary air. Those two factors, coupled with the gas pressure, are the major factors in a burner's ability to aspirate. According to Louis Shnidman, reference 1, 'if the specific gravity of the gas is increased, the greater will be the percentage of primary air injected. This assumes that the burner input rate, gas pressure and the heating value of the gas remain constant. Similarly, air entrainment increases as the gas pressure increases, other conditions remaining the same.' Table 5 below will indicate typical values when dealing with three gases and their specific gravities and heating values. As you can see, the ability of the burners to inject air increases as the pressure increases for any one given gas. Now, for general design purposes, it is recommended that a value of **0.036** for the term **[(pd)^0.25/(H)^0.50]** be employed unless pressure drop is excessive, in which case, the direct calculation with a suitable value for H should be made.

VALUES OF [(pd)^0.25/(H)^0.50] FOR TYPICAL FUEL GASES AND DISTRIBUTION PRESSURES					
TYPE OF GAS	HEATING VALUE	Spec. Gr.	VALUES OF [(pd)^0.25/(H)^0.50)]		
	Btu/ Ft^3	Air = 1.00	2.00" W.C.	4.00" W.C.	7.00" W.C.
Manufactured	530	0.41	0.0385	0.0475	N/A
Natural	1029	0.57	N/A	0.037	0.0435
Mixed	800	0.55	N/A	0.0415	N/A

Table 5 Values for [(pd)^0.25/(H)^.050]

The second term of Formula 3, **[2.5X10^5(AmAp)/(R)^0.50],** describes the average area of the mixing tube throat and outlet and the total area of the burner ports relative to the total input the burner must accommodate. As you might expect, the average throat area and the mixing tube outlet area (Am) as well as the total port area (Ap), are major factors of a burner for controlling primary air injection. Referring to Table 6 below, it can be seen that as the need for increased input rates increases, the air injection capability of any one given burner design is definitely dependent upon the average mixing tube area times the port area, measured in square inches.

		AVERAGE MIXTING TUBE AREA X PORT AREA -----INCHES²						
		PRIMARY AIR--% THEORETICALLY REQUIRED						
INPUT RATE BTU/HR.	30	40	50	60	70	80	90	100
10,000	0.012	0.039	0.095	0.196	0.365	0.702	1.000	1.519
20,000	0.049	0.156	0.379	0.786	1.460	2.810	4.000	6.080
30,000	0.111	0.350	0.854	1.770	3.290	6.320	9.000	13.670
40,000	0.197	0.622	1.520	3.150	5.840	11.200	16.000	24.300
50,000	0.308	0.973	2.370	4.910	9.140	17.560	25.000	37.970
60,000	0.443	1.400	3.420	7.070	13.150	25.280	36.000	
70,000	0.603	1.910	4.650	9.640	17.890	34.420		
80,000	0.788	2.490	6.065	12.580	23.350			
90,000	0.996	3.150	7.680	15.920	29.600			
100,000	1.220	3.890	9.490	19.650	36.500			

Table 6—Air Injection at Various Input Rates

EXAMPLE:

A burner having a number of ports is to be designed for a normal input rate of 10,000 Btu/Hr and a primary air injection equivalent of 60 % of air theoretically required for complete combustion. These values are selected by the designer. This is the air theoretically required for complete combustion. For this condition, the product of **throat area and port area** should be at least 0.196 inches. Now, we shall also assume that it is not desirable to burn more than 15,000 Btu/Hr per square inch of port area. Again, this value is chosen by the designer. The port area can tentatively be set at 0.67 square inches. As a result, the average of the throat area and the mixing tube outlet area would be 0.2925 inches square. (Throat area x port area = 0.196 in². Throat area x 0.67 in² = 0.196 in². Throat area = 0.2925 in²). This is equivalent to a diameter at average cross-sectional area of throat and mixing tube outlet of approximately 0.61 inches squared. ($A = \pi/4xD^2$; 0.2925/0.7854)^0.50 = D; D= 0.6102 inches.) To convert this value to the corresponding throat diameter for uniform mixing tube slope, it is only necessary to subtract the product of the length of the mixing tube from the throat to outlet and the tangent of the angle between the mixing tube axis and wall. Thus, in the previous example, with the length of the mixing tube as 5.00 inches and the slope two degrees (2 °), the throat diameter will be 0.61 –(5 X 0.0349) or 0.456 inches. Tables 7 & 8 below will put this information into context and be much more descriptive as compared to the text. Table 7 is for conditions of low pressure and low specific gravity whereas Table 8 is for normal pressure and normal specific gravity.

Throat Area In^2	Port Area In^2	Product of Throat & Port Areas, In^2	Throat to Port Area Ratio	Input Rate Btu/Hr per In^2 of Port Area	Throat Dia In	Number of 36 DMS Ports Required
0.200	0.980	0.196	0.204	10200	0.505	110
0.250	0.785	0.196	0.318	12700	0.565	88
0.300	0.654	0.196	0.458	13500	0.618	74
0.350	0.560	0.196	0.625	17850	0.667	63
0.400	0.490	0.196	0.816	20400	0.713	55
0.425	0.461	0.196	0.922	21700	0.735	52
0.422	0.442	0.196	1.000	22400	0.750	50

Table 7 --Burner Design Data for 10K Btu/Hr and 60% Primary Aeration for Extreme Conditions of Low Gas Pressure and Low Specific Gravity

Throat Area In^2	Port Area In^2	Product of Throat & Port Areas, In^2	Throat to Port Area Ratio	Input Rate Btu/Hr per In^2 of Port Area	Throat Dia In	Number of 36 DMS Ports Required
0.1500	0.6400	0.0960	0.2340	15600	0.465	72
0.2000	0.4800	0.0960	0.4170	20800	0.505	64
0.2500	0.3840	0.0960	0.6510	26000	0.565	43
0.3000	0.3200	0.0960	0.9370	31200	0.618	36

Table 8 --Burner Design Data for 10K Btu/Hr and 60% Primary Aeration for Normal Pressure and Average Specific Gravity

Notice the variation in the values relative to each table. Low pressure and low specific gravity do have an effect on performance and sometimes necessitate changes in design.

The third term of Formula 3, **[(540)^0.50/(T)^0.50]** describes the temperature of the gas-air mixture in the mixing tube and the burner head. For a majority of burners, particularly where intermittent operation is involved, an assumed gas-air temperature of **400 F°** should provide an adequate margin for primary air injection.

The reason to look at Formulas 3 and 4 is to indicate that empirical formulas do exist that define the design and configuration of atmospheric burners. This is not guesswork on the part of competent designers, and there is a method to the madness. I will have to admit that in times past much less rigor was applied to burner design and "cut-and- try" was the order of the day. It does become obvious that there is flexibility in design **IF** physical room exists for the burner and the design is not constrained due to an enclosed space.

Burner Head:

The gas/air mixture is swept towards and accumulated in the burner head and then distributed to the individual burner ports. As we have seen, the burner head temperature and pressure play a great role in the equal distribution of the homogenous mixture. It is very important to design the burner head to take into consideration the number of ports required, the port spacing and the number of rows. These ports are generally cast or machined into the burner head depending upon the burner design. There is a standing argument as to whether cast ports or drilled ports provide for a better flame pattern with less flame noise.

Burner Ports:

I would now like to show several configurations that will highlight the variety of burner port designs.

Figure 13—Burner Base (Head), Burner Ports, Burner Cap, Burner Ring

Another view of the burner cap and the burner ports is given as Figure 14 below.

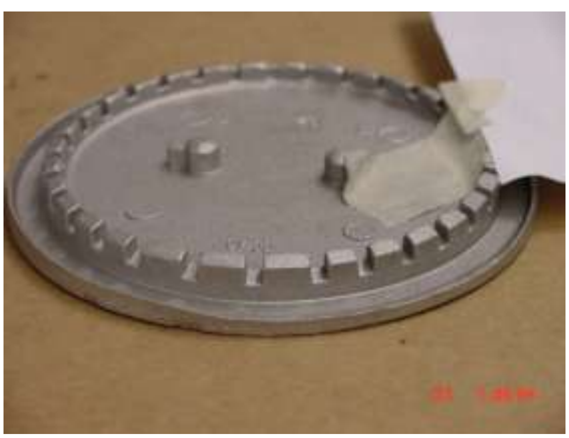


Figure 14—Burner Cap with Burner Ports and Positioning Pins

In this design, the burner ports are cast into the profile of the burner cap. The cap sits into the burner base to form a four -sided port profile. The burner base has an indented or recessed configuration to accommodate the assembly of the burner cap. Please note also that the ports are regularly spaced but are NOT the same dimensionally. This results from the need to modify the flame profile and the flame height. When you have a burner grate with tynes directly above a burner flame, there is a possibility of flame impingement; consequently, sooting or carboning due to quenching or rapid cooling of the flame on the grate. (Please see Figure 3) This is a case for flame modification and is accomplished by altering the profile of the burner port or ports. Port spacing and placement is also critical to preclude sooting.

BURNER PORT SIZE:

Burner port size (diameter) for primary air injection is of such insignificance that it may be neglected in problems of burner design from the standpoint of air entrainment. That is not the case with port depth. Burner port depth has a pronounced effect on the injection of primary air, especially when varied between extreme values. Table 9 below will show the difference.

We are saying with Table 9 is that a burner operating on manufactured gas at six (6) inches W.C. and with a port rate of 20,000 Btu/Hr per square inch, the primary air injection decreases from 108.5 to 93 % when the port depth was increased from 0.0469 to 0.750 inches with a port diameter of drill size # 36. Again, looking at the table below for 30,000 Btu/Hr per square inch per port, the percentage drops from 80.8 to 69.5 %. As the port depth increases, it must be remembered that this variation is by design. The engineer or designer would select the port depth depending upon the material and the fabrication method. This extreme could represent a significant "off-quality" relative to manufacturing state-of-the-art. Similar tables exist for other gases.

Table 10 is an indication of port size relative to the point where flames will coalesce or blend. A non-coalescing flame is certainly desirable.

EFFECT OF PORT DEPTH ON PRIMARY AIR INJECTION--MANUFACTURED GAS

	PRIMARY AIR INJECTED, % OBSERVED	
PORT DEPTH # 36 Drill Size	20,000 Btu/Hr per square inch of port area	30,000 Btu/Hr per square inch of port area
0.0469	108.500	80.800
0.1250	107.100	79.400
0.2500	102.000	76.800
0.3125	100.000	75.900
0.3750	97.900	73.500
0.5000	95.900	71.900
0.7500	93.500	69.500

Table 9—Primary Air Injection vs Burner Port Depth

BURNER PORT SPACING:

Now, let us take a look at port spacing. As spacing between ports of an equal size is decreased from one (1) inch, edge to edge, to 0.250 inches, there is relatively little effect on the lifting limits of the flame. Between 0.250 inches and 0.125 inches there is a slight increase in primary air required to produce lifting of the burner flames. Port spacings greater than 0.250 inches have no real effect on yellow-tip limit. Closer spacing will give a definite yellow-tip appearance. A 0.125 inch spacing will require about a 3% greater primary air to eliminate yellow-tips. Unfortunately, some experimentation is required to "fine-tune" a burner. The port spacing, will to some degree, be dependent upon the desired input, number of ports required to produce a suitable flame pattern and the number of port rows required.

The number of rows of ports does not affect the lifting limits for any one given gas. The range of burner flexibility is limited by increasing the number of rows of ports and requires an increase in primary aeration to eliminate yellow tips. With one row of ports and a Btu rating (Btu per port x port diameter) from 10 to 40, it is required to have between 23 to 31% primary air to eliminate yellow-tipping. Two and four rows of ports over the same range of inputs would require between 27 and 34 % and 30 to 35% primary air respectively.

Table 10 will give the recommended port size and recommended port number for a slotted-port burner. Similar tables exist for drilled or cast ports.

Gas Used	Drilled Port D.M.S.	Slotted Port--Inches (Width) Where Flames Do Not Coalesce	Slotted Port--Inches (Width) Where Flames Coalesce
Natural	30-32	0.0937	0.0625
Mixed	34-36	0.0781	0.0469
Manufactured	38-40	0.0781	0.0469
Butane or Propane	32	0.0938	0.0625
All Gases	34	0.0938	0.0625

Table 10 Recommended Maximum Port Sizes

PORT LOADING:

Port loading is also critical for obtaining flame stability. Port loading is simply the amount of gas/air mixture passing through the total port area. The expression is as follows:

Port Loading = Total Burner Input / Total Port Area

Increasing the port loading tends to increase the tendencies for flame lifting. Decreasing the port loading may create flashback. It is truly a balancing act to create a burner that operates properly and avoids lifting and flashback. Keep in mind that we need to avoid these conditions while maintaining good combustion. This is for all gases the burner may use. Table 10 above shows the recommended "starting point" for selecting the port diameter for various gases. The second column is for drilled or cast ports and the third column is for slotted or ribbon ports.

In summary, port size, port depth and port spacing definitely **DO** have an influence on the lifting limits of a burner flame. The number of rows has no real effect on the lifting limits, flashback or air entrainment.

RELATIONSHIPS:

Let's look now at one very important relationship. We will consider the distance of the orifice to the venturi throat.

Distance of Orifice to Venturi Throat

This distance definitely has an effect on the injection of primary air into the mixing tube. Table 11 will demonstrate the effect that distance will have. This table basically shows that with a throat diameter of 0.4376 inches, the variation in primary air injection with small incremental changes in orifice to throat distances is in the range of 0.70 to 3.30 throat diameters. Notice how the percent primary air injection is changed.

EFFECT OF DISTANCE OF ORIFICE TO THROAT ON INJECTION OF PRIMARY AIR

INCHES	THROAT DIAMETERS	PRIMARY AIR %
0.3125	0.7100	58.2000
0.5625	1.2800	61.1000
0.8125	1.8500	62.1500
1.0625	2.4400	62.5000
1.3125	3.0000	60.7000
1.4375	3.2800	59.1000

Table 11—Effect of Distance of Orifice to Throat on Injection of Primary Air
(Throat diameter=0.4376, Input = 10,500 Btu/Hr @ 7"W.C.)

EXAMPLE OF ATMOSPHERIC GAS BURNER DESIGN

We are now going to design an atmospheric gas burner. Our burner will be designed to fire natural gas but will have the flexibility to operate satisfactorily on liquefied petroleum; i.e. propane or butane, manufactured gas or mixed gas. Please keep in mind that the heating value for natural gas is approximately 1100 Btu/Ft^3 and the specific gravity is 0.65. Please look at the "Gas Facts" page in the appendix to this course for data related to other gases.

The following example is taken from reference 1; i.e., *Gaseous Fuels* by Mr. Louis Shnidman. Shnidman is one of the foremost references for gaseous fuels and burner design. Even though it was published in 1954, the principals do **NOT** change. Gas combustion is a chemical process, and that process was defined adequately years ago. Burner performance obeys very definite laws. Burner designs, as mentioned earlier, may be "upshot", "inshot", target, etc but the fundamental design criteria remain the same regardless of configuration. For the most part, gas burner designs are made by engineers operating within their engineering departments. As such, design criteria and design standards have been established relative to the burner types themselves. The assumptions given below may or may not be in line with any manufacturer's basic standards and operating procedures. Companies such as MABE, Sourdillion, Ishpording, Copreci, DAKO, SABAF, Bompani and Harper-Wyman all have their own procedures and standards that govern burner design, but calculations such as the ones below are still very relevant to the overall process and certainly demonstrate the methodology and the thought processes behind the designs regardless of burner configuration.

Assumptions:

In making the calculations for our example, the following **assumptions** are given:

A = Throat area = 0.35 to 0.45 times port area for **smooth** mixer tubes walls with **high air injection**

A = Throat area = 0.45 to 0.60 times port area for **rough** mixer tube walls with **high air injection**

A = Throat area = 0.25 to 1.00 times port area for various primary air percentages

B = Orifice to throat distance = 0.7 to 3.3 throat diameters

C = Slope of mixing tube = Preferably 2 degrees but not greater than 3.5 degrees

D = Length of mixing tube—immaterial, but for good mixing the length should not be less than 6 inches. Please note: the "six inch" rule is used to insure adequate mixing. If homogeneous mixing can occur with a mixing tube of less than six inches, so be it. Figure 5 is an example of a burner with a mixing tube considerably shorter than this number. In our design example, we have chosen this length knowing that for a rough cast iron tube, this dimension has proven to work.

E = Primary air inlet openings = 1.25 to 2.25 times total port area

F = Port size, port depth, total area = see text

R = Large enough radius to permit free area of shutter in "E" above. For small burners this would be a minimum of 3 inches.

The following two figures will be used for reference and can be referred to during the calculations presented. Figure 15 gives the basic terminology, whereas Figure 16 shows the calculated dimensions and the final design.

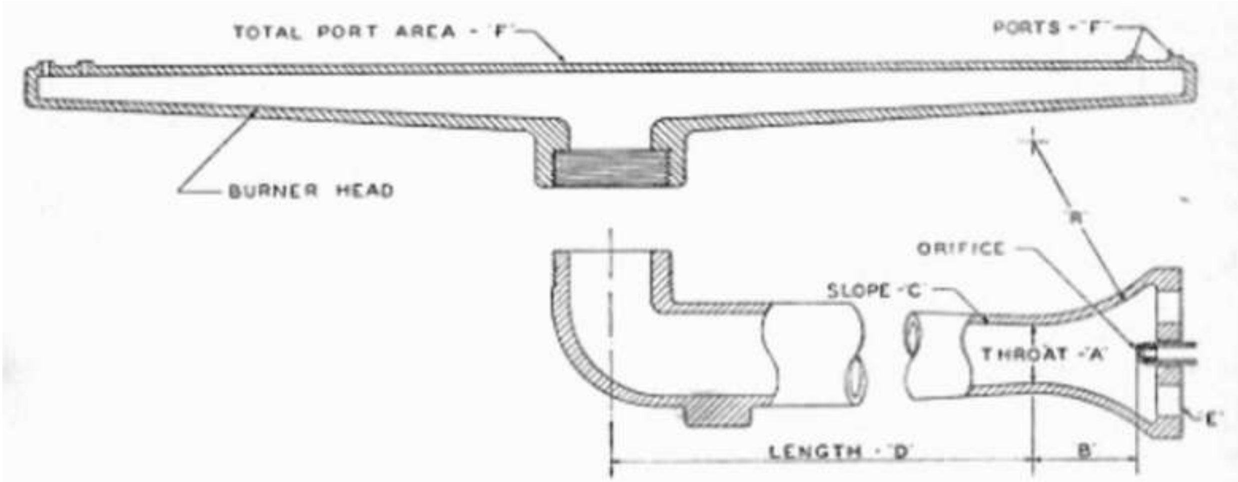


Figure 15 Permissible Relationship of Gas Burner Parts

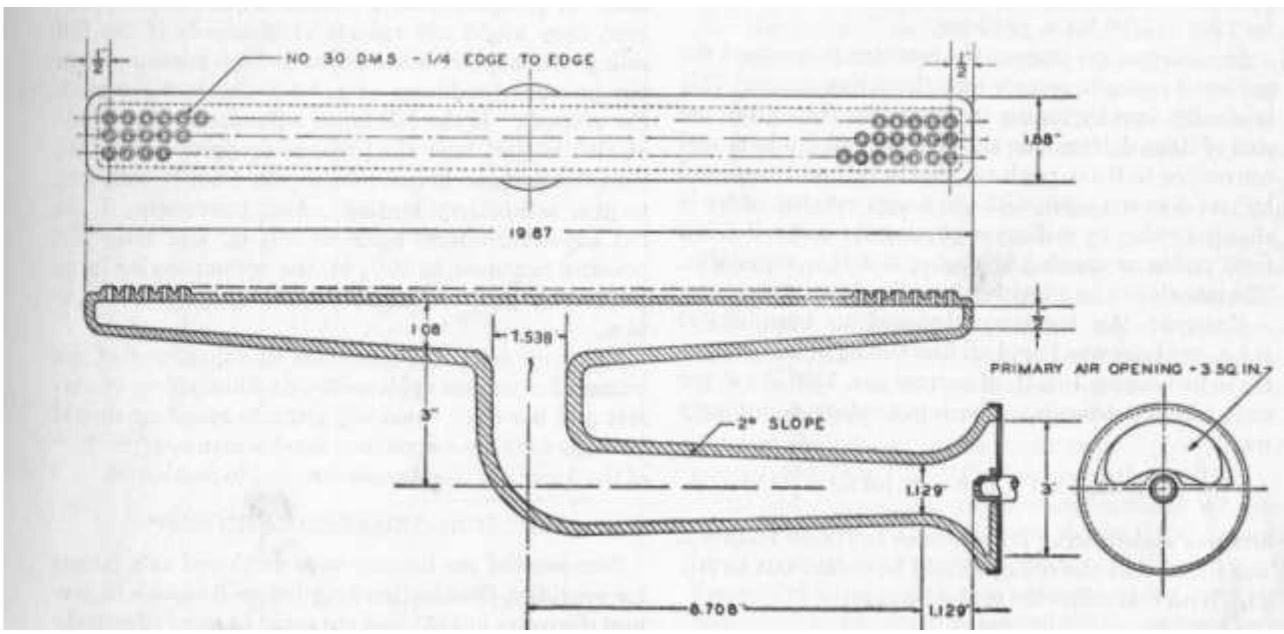


Figure 16 Finished Burner Design

Goal:

To design a rectangular burner that operates successfully in firing a space heater with 30,000 Btu/Hr input. This is TOTAL burner input. As we have seen from the text, port loading is total burner input divided by total port area. Please do not confuse the two. The fuel will be natural gas with a heating value of 1100 Btu/FT^3, and a specific gravity of 0.65. The normal gas pressure will be 7.00 inches water column (W.C.). The burner shall operate satisfactorily in case a pressure regulator is installed on the appliance and the normal burner pressure is maintained at 3.5" W.C. Sixty (60%) percent primary air injection is desired. This value is chosen by the designer and assumes that 40% of the total contribution of combustion air is secondary air. We will need to make sure that that superstructure and burner enclosure can provide adequate primary and secondary air for complete combustion. The pressure of

3.5 inches W.C. is the pressure "down-stream" of the regulator. The pressure of 7.00 inches W.C. is "up-stream" of the regulator. Our burner will be made from cast iron with a wall thickness that will accommodate the port depth chosen by the designer.

CALCULATIONS:

Total Port Area

15,000 Btu/Hr per inch^2 of port area is selected to provide acceptable burner flames. This value is selected by the designer and certainly can vary depending upon company policy and the standards dictated by the engineering department for the burner type in question.

30,000 Btu/ Hr / 15,000 Btu/Hr-in^2 = 2.00 Inches^2 for the total port area

Port Size and Number

From Table 3, a number 30 drill size at 3.5 inches W.C. will produce an input between 30,800 and 35,700 Btu/ Hr. Select this orifice size. For a number 30 drill size (0.1285 inches in diameter—from Table 12.)

Area of number 30 DMS = 0.01296 inches^2. This value is taken from Table 12.

2.00 in^2 / 0.01296 in^2 per port = 154 ports of number 30 DMS (150 ports will be used in this case)

At this point, a "sanity check" is probably in order. It is time to make sure that our combustion chamber can accommodate a burner with the number of ports chosen. Can I get the thing in the space allowed by the overall configuration of the heater? Now is the time to discover if that is possible. If not, go back and rework the assumptions.

Designation	Diam., In.	Area, Sq.In.	Designation	Diam., In.	Area, Sq.In.	Designation	Diam., In.	Area, Sq.In.
1/2	0.5000	0.1963	3	0.213	0.03563	3/32	0.0938	0.00690
31/64	0.4844	0.1843	4	0.209	0.03431	42	0.0935	0.00687
15/32	0.4688	0.1726	5	0.2055	0.03317	43	0.0890	0.00622
29/64	0.4531	0.1613	6	0.204	0.03269	44	0.0860	0.00582
7/16	0.4375	0.1503	13/64	0.2031	0.03241	45	0.0820	0.00528
27/64	0.4219	0.1398	7	0.201	0.03173	46	0.0810	0.00515
Z	0.413	0.1340	8	0.199	0.03110	47	0.0785	0.00484
13/32	0.4063	0.1296	9	0.196	0.03017	5/64	0.0781	0.00479
Y	0.404	0.1282	10	0.1935	0.02940	48	0.0760	0.00454
X	0.397	0.1238	11	0.191	0.02865	49	0.0730	0.00419
25/64	0.3906	0.1198	12	0.189	0.02806	50	0.0700	0.00385
W	0.386	0.1170	3/16	0.1875	0.02761	51	0.0670	0.00353
V	0.377	0.1116	13	0.185	0.02688	52	0.0635	0.00317
3/8	0.375	0.1104	14	0.182	0.02602	1/16	0.0625	0.00307
U	0.368	0.1064	15	0.1800	0.02545	53	0.0595	0.00278
23/64	0.3594	0.1014	16	0.1770	0.02461	54	0.0550	0.00238
T	0.358	0.1006	17	0.1730	0.02351	55	0.0520	0.00212
S	0.348	0.09511	11/64	0.1719	0.02320	3/64	0.0473	0.00173
11/32	0.3438	0.09281	18	0.1695	0.02256	56	0.0465	0.001698
R	0.339	0.09026	19	0.1660	0.02164	57	0.0430	0.001452
Q	0.332	0.08657	20	0.1610	0.02036	58	0.0420	0.001385
21/64	0.3281	0.08456	21	0.1590	0.01986	59	0.0410	0.001320
P	0.323	0.08194	22	0.1570	0.01936	60	0.0400	0.001257
O	0.316	0.07843	5/32	0.1563	0.01917	61	0.039	0.001195
5/16	0.3125	0.07670	23	0.1540	0.01863	62	0.038	0.001134
N	0.302	0.07163	24	0.1520	0.01815	63	0.037	0.001075
19/64	0.2969	0.06922	25	0.1495	0.01755	64	0.036	0.001018
M	0.295	0.06835	26	0.1470	0.01697	65	0.035	0.000962
L	0.29	0.06605	27	0.1440	0.01629	66	0.033	0.000855
9/32	0.2813	0.06213	9/64	0.1406	0.01553	67	0.032	0.000804
K	0.281	0.06202	28	0.1405	0.01549	1/32	0.0313	0.000765
J	0.277	0.06026	29	0.1360	0.01453	68	0.031	0.000755
I	0.272	0.05811	30	0.1285	0.01296	69	0.0292	0.000670
H	0.266	0.05557	1/8	0.1250	0.01227	70	0.028	0.000616
17/64	0.2656	0.05542	31	0.1200	0.01131	71	0.026	0.000531
G	0.261	0.05350	32	0.1160	0.01057	72	0.025	0.000491
F	0.257	0.05187	33	0.1130	0.01003	73	0.024	0.000452
E 1/4	0.2500	0.04909	34	0.1110	0.00968	74	0.0225	0.000398
D	0.246	0.04753	35	0.1100	0.00950	75	0.021	0.000346
C	0.242	0.04600	7/64	0.1094	0.00940	76	0.020	0.000314
B	0.238	0.04449	36	0.1065	0.00891	77	0.018	0.000254
15/64	0.2344	0.04314	37	0.1040	0.00849	78	0.016	0.000201
A	0.234	0.04301	38	0.1015	0.00809	1/64	0.0156	0.000191
1	0.228	0.04083	39	0.0995	0.00778	79	0.0145	0.000165
2	0.221	0.03836	40	0.0980	0.00754	80	0.0135	0.000143
7/32	0.2188	0.03758	41	0.0960	0.00724			

Note: Designations are in fractions of an inch, in Standard Twist Drill letters, or in Standard Twist Drill numbers, the latter being the same as Steel Wire Gage numbers.

D.M.S. used subsequently in this chapter refers to "Drill Manufacturers' Standard" and is equivalent to Standard Twist Drill or Steel Wire Gage Numbers.

Table 12-- Drill Sizes vs Diameter vs Orifice Area

Port Depth

We will select cast iron as our material of choice for the burner. The ports will be cast into the burner with a port depth of 0.375 inches. We designate the port depth initially.

Port Spacing and Number of Rows

Three rows of ports will be used and spaced 3/8 inches (0.375 ") apart for good flame carryover and prevention of flame coalescence. Remember Figure 2? We would like to see individual flame patterns emanating from the ports. A coalescing flame pattern is not desirable. The distance between ports, edge-to-edge, will be designated as 0.250 inches. Again, this is a design choice and can be altered to accommodate the space available.

Width of Burner Head

Three port diameters = 3 x 0.1285 inches = 0.3855 inches

Space between two rows = 2 x 0.375 inches =0.7500 inches

Space from outer rows to burner side = 2 x 0.375 inches = 0.7500 inches

TOTAL = 1.8855 inches

Length of Burner Head

We have determined that three (3) rows of ports will be specified. This will provide for 50 ports per row.

50 Port diameters = 50 x 0.1285 = 6.4250 inches

49 Spaces between ports = 49 x 0.250 inches = 12.250 inches

2 Spaces between edge of ports and burner side=2 x 0.500 inches = 1.000 inches

TOTAL = 19.6750 inches

Again, this dimension may be altered as required by space available for the overall burner and the burner head. This gives a burner head measuring 19.675 inches in length by 1.8855 inches in width with three (3) rows of ports, 50 ports per row, spaced 0.250 inches edge-to-edge.

Throat Area and Throat Diameter

For a rough mixing tube, a throat area to port area ratio of 0.50 will be selected. This was one of our assumptions made earlier for a burner with high air injection.

2.0 inches^2 x 0.50 = 1.00 inches^2. This says that our throat area is 50% of our total port area.

1.0 inches^2 = 1.129 inch throat diameter

(NOTE: Area of circular section $A=\pi/4(D)^2$); therefore 1.00 in^2 = $(0.7853)(D)^2$, D=(1.000/0.7853)^0.50 = 1.129 inches, throat diameter.

Orifice to Throat Distance

We will use one throat diameter as the orifice to throat distance. This is somewhat arbitrary and a greater distance could be chosen. We are operating within our initial assumptions. This dimension is then 1.129 inches.

Length of Mixing Tube

Orifice face to be directly below edge of burner in this instance. If the mixing tube enters the center of burner head from below, the mixing tube distance from the edge of the orifice to the face of the centerline of the head would be (0.50 x 19.675) or 9.837 inches

9.837 inches – 1.129 inches = 8.708 inches distance from the throat to the vertical center line.

Now might be a good time to take a look at Figure 16 to see the dimensions applied to the finished burner. This will help you to identify the configuration the numbers define.

Angle of Divergence of the Mixing Tube

Use a 2 ° slope as a good average. Again, this is somewhat arbitrary, but the slope should be no greater than 3.5 degrees for proper mixing and good burner operation.

Size Opening (Internal) into Bottom of Burner Head

Assume a 3 inch vertical distance between the center horizontal line of the mixing tube and the bottom of the burner head. With this being the case, the total mixer length = 8.708 + 3.00 = 11.708 inches.

With an angle of divergence being 2° (tangent of 2° = 0.03492) the diameter of the opening in the bottom of the burner head would be: 1.129 + (11.708 x 0.03492) = 1.538 inches in diameter.

Size Opening in Burner Head for Each Side of Mixer Tube Entrance

For a mixing tube entering the center of the burner head from below, the area on each side of the burner head should be 1.50 times 0.5, the total port area or 2.00 x 0.50 x 1.50 = 1.500 inches^2 . The internal width of the burner head is 1.8855 inches – 0.50 inches (thickness of two walls) = 1.3855 inches. Now, 1.500/1.3855 = 1.082 inches or the internal depth of the burner head at the mixer entrance.

This internal depth may decrease to about 0.50 inches at each end of the burner if the enclosure is "tight". This is shown in Figure 16.

Size of Primary Air Inlet Openings

Please remember that the "rule of thumb" is 1.50 times the port area, 1.500 x 2.00 = 3 inches ^{2} for one opening or 1.500 inches ^{2} for two openings. The air shutter must be designed to allow for unobstructed flow of primary air into the burner face.

Gas Orifice Size

A fixed orifice will be specified for our burner. From Table 4, the factor for 1100 Btu per cubic foot and a specific gravity of 0.65 = 0.757. Now, 30,000 Btu/Hr x 0.757 = 22, 710 Btu/Hr. From Table 3, under 7 inches W.C., 22,710 falls opposite orifice size number 43.

Primary Air Injection

The product of average mixing tube area and port area; (1.38 x 1.38 x 0.7854) x 2.00 = 2.99. From Table 6, 2.99 at 30,000 Btu/Hr = 69 % primary air (approximate). We must interpolate to get this value. From Table 14, it can be observed that with an input of 15,000 Btu per hour per square inch port area and a ratio of throat to port area of 0.50%, approximately 55% primary air can be expected to be injected into the burner.

	Maximum Input Rate--Btu/Hr--Square Inch Port Area				
	Throat to Port Area--Ratio "K"				
Precent Primary Air	0.250	0.500	0.750	1.000	
30	45000	63600	78000	90000	
40	25300	35800	43800	50600	
50	16200	22900	28000	32400	
60	11250	15900	19500	22500	
70	8250	11700	14300	16500	
80	6300	8950	10900	12600	
90	5000	7070	8660	10000	
100	4050	5730	7100	8100	

Table 13-- Maximum Gas Input Rate for Various Primary Air Entrainment Percentages and Throat to Port Area Ratios (Room temperature and low distribution pressure conditions).

	Maximum Input Rate--Btu/Hr--Square Inch Port Area				
	Throat to Port Area--Ratio "K"				
Precent Primary Air	0.250	0.500	0.750	1.000	
30	28300	40000	49600	56500	
40	15900	22500	27500	31800	
50	10160	14400	17600	20350	
60	7070	10000	12250	14130	
70	5180	7350	8970	10350	
80	3960	5620	6850	7910	
90	3140	4440	5440	6280	
100	2540	3600	4460	5080	

Table 14-- Maximum Gas Input Rates for Various Primary Air Entrainment Percentages and Throat to Port Area Ratios. (400 ° F Air-Gas mixture temperature and low pressure conditions).

Lifting and Yellow-Tips

From Table 15 it will be noted that a burner with number 30 D.M.S. ports and 15, 000 Btu per hour per square inch of port area will not produce lifting flames until 72% primary air is injected. This is above our design figure of 60 %, and therefore the flames would not lift. From Table 16 it can be determined that yellow-tips would not appear until the primary air is reduced to about 22 %.

Percent Primary Air at Lifting Btu/Sq. In Port Area									
Port Size	Natural			Butane			Manufactured		
	15,000	20,000	25,000	15,000	20,000	25,000	15,000	20,000	25,000
50	57	52	48						
46	65	58	53	59	49	44	106	104	102
36	71	64	55	68	59	52	114	109	106
30	72	65	58						
75	67	60	74	65	57	118	112	108	
0.25	96	87	78	82	73	64	133	125	119

Table 15 Comparative Lifting Limits for Various Port Sizes on Three Fuel Gases

	MFG Gas				Natural Gas				Butane Gas			
	% Primary Air at Yellow-Tip Limit			Rate Below Which Yellow-Tips Disappears No Primary Air Btu/Hr-Sq.In	% Primary Air at Yellow-Tip Limit			Rate Below Which Yellow-Tips Disappears No Primary Air Btu/Hr-Sq.In	% Primary Air at Yellow-Tip Limit			Rate Below Which Yellow-Tips Disappears No Primary Air Btu/Hr-Sq.In
Port Size	15M	20M	25M		15M	20M	25M		15M	20M	25M	
0.250	19	20	21		38	39	39		58	58	58	
26DMS	6	9	11	6500	24	26	28		48	50	52	
36DMS	2	5	7	12500	19	21	22		38	42	45	
46DMS				28000	11	13	15			32	38	
60DMS				95000				46500				

Table 16 Comparative Yellow-Tip Limits for Various Size Ports on Three Fuel Gases (0.75" port depth and 1.00" port spacing.)

<u>Height of Inner Cone of Flame</u>

The following equation for calculating the height of the inner cone of a flame has been developed.

$$h=KaR$$

Formula 5—Height of Inner Cone

Where h =Height of inner cone in inches

K = Constant depending upon primary air

a = Area of port in inches squared

R = Gas rate per port area

Now K = 12.5 (from chart 1)

a = 0.01296 in²

R = 1.5 (15,000/10,000) = 1.500

h = 12.5 x 0.01296 x 1.5 = 0.243 inches height of inner cone.

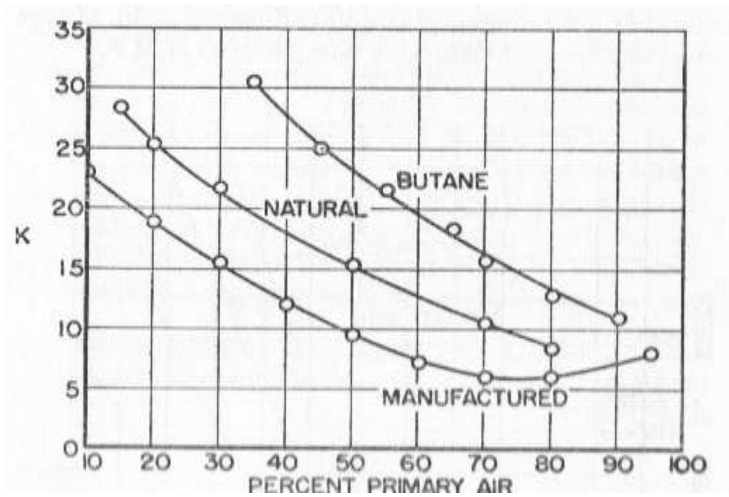


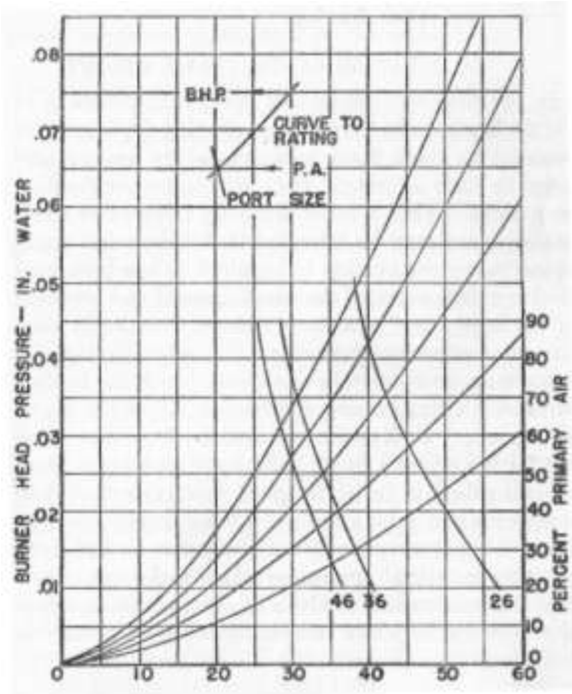
Chart 1 Variation of "K" in Formula 4 with Primary Air for Natural, Manufactured and Mixed.

Height of Outer Mantle

From Chart 2, outer mantle for 0.250 inch port spacing and number 30 ports is 0.75 inches per 10,000 Btu per hour per square inch of port area.

(15,000/10,000) x 0.75 = 1.125 inches for a single row of ports

1.125 x 3 = 3.3375 inches outer mantle height for three rows of ports.



Gas Rate—1,000Btu/Hr per Inch^2 of Port Area

Chart 2 Burner Head Pressures for Various Port Sizes, Primary Air and Inputs Rates for Natural Gas.

Noise of Extinction

The noise of extinction for natural gas with the port size indicted for number 30 ports, would be negligible. Data in chart 21 is applicable to manufactured gas rather than natural gas.

Other burner head shapes could have been selected or other port forms used to accomplish the same result. However, it is believed that this example will illustrate the method of applying the data presented in the preceding sections.

I am sure you have noticed that many of the decisions made are dependent upon 1.) the combustion chamber space available and 2.) the total burner input. We must design the burner to fit the product. There are definitely constraints. This example can be repeated over and over with different burner configurations adapted to a wide range of products.

CONCLUSIONS:

I certainly hope you have gained some insights as to what is required when a burner design is needed. As I have mentioned before, every company specializing in the production and fabrication of burner equipment has their own standards developed over years of trial and error. What works and what doesn't is confined to "company confidential" documentation and in most cases is protected by patents, usually international patents. To date, I do not believe there exists, on the open market, any software packages that facilitate burner design. I do know that individual companies have software developed for their own purposes. This code is guarded closely and represents intellectual property not shared with individuals or other companies. I work with burner manufacturers on a consistent basis, and they require a yearly update of their confidentially agreement. Absolutely NO exchange of information relative to design is allowed nor should be allowed. Our greatest challenge in this country is retaining our intellectual property and preventing "knock-offs" from corporate entities with low moral standards.

For the most part, the very best approach for applying a gas burner to a product, if you do not specialize in gas burner design, is to contact a reputable vendor that does design and produce such a product. They can tailor the burner to your exact specifications for input and space and provide you with a workable product. I do hope that taking this course will allow you to gain knowledge so that an intelligent conversation can result between you and the vender of choice. That is the very purpose for writing this paper. I want to thank you for your time, and I definitely hope it was not too "painful".

Bob Jackson, PE (State of Tennessee-1974)

APPENDIX

GAS FACTS

- 1 Btu = 252 Calories = 1055 Joules = 778 Ft-lbs
- 1 Kw-hr (Kwh) = 3,412 Btu
- 1 Bar = 14.504 PSI
- 28 inches water column (W.C.) = 1 PSI = 2 inches of Hg = 7Kpa = 70 mBar
- 1 Btu/Ft³ = 0.0373 MJ/M³ = 8.9 Kcal/M³
- There is a 1.77% difference in the heating value between dry gas and saturated gas with the saturated gas having a lesser value.
- As per the National Fuel Gas Code (ANSI Z223.1/NFPA54), above 2,000 feet, the appliance must be derated 4% for every 1,000 feet above sea level.
- For carbon monoxide; i.e. CO, particulate in the product of combustion:
  1.) 1% = 10,000 PPM
  2.) 0.10% = 1,000 PPM
  3.) 0.01% = 100 PPM
  4.) 0.001% = 10 PPM
- 1 Therm = 100,000 Btu = 100 Ft³ of natural gas.
- Approximately 10 Ft³ of air is needed for every 1,000 Btus/ Hr of gas
- 100,000 Btus generates about 1 gallon of water.
- Characteristics of Fuel Gasses

NATURAL GAS

SPECIFIC GRAVITY = 0.56
HEATING VALUE= 1007 Btu/Ft³
FLAME TEMPERATURE = 3416 ° F
FLAME SPEED PROPOGATION = 26.00 Inches/Sec
LIMITS OF FLAMABILITY = 5 to 15 %
IGNITION TEMPERATURE = 1202 ° F
AIR REQUIRED FOR COMPLETE COMBUSTION = 9.6 Ft³ air / Ft³ gas

PROPANE GAS

SPECIFIC GRAVITY = 1.55
HEATING VALUE = 2588
FLAME TEMPERATURE = 3497 ° F
FLAME SPEED PROPOGATION = 32.00 Inches / Sec
LIMITS OF FLAMABILITY = 2.57 to 9.5 %
INGNITION TEMPERATURE = 932 ° F
AIR REQUIRED FOR COMPLETE COMBUSTION = 26.3 Ft³ air / Ft³ gas

BUTANE GAS

SPECIFIC GRAVITY = 2.00
HEATING VALUE = 3184 Btu / Ft^3
FLAME TEMPERATURE = 3443 ° F
FLAME SPEED PROPOGATION = 33 Inches / Sec
LIMITS OF FLAMABILITY = 1.86 to 8.41 %
IGNITION TEMPERATURE = 896 ° F
AIR REQUIRED FOR COMPLETE COMBUSTION = 32.00 $Ft.^3$ air/$Ft.^3$ gas

Effect of Elevation on Normal Barometric Pressure

Elevation (Feet)	Decrease in pressure per foot of added elevaton in inches of mercury	Normal barometric pressure a start of zone of elevations in inches of mercury
Sea level to 1,000	0.00112	29.92
1,000 to 2,000	0.00108	29.82
2,000 to 3,000	0.00104	27.78
3,000 to 4,000	0.00100	26.77
4,000 to 5,000	0.00096	25.81
5,000 to 6,000	0.00920	24.87

DEFINITION OF TERMS

Air-Gas Ratio—The ratio of combustion air supply flow rate to the fuel gas supply flow rate. This ratio does **NOT** include any secondary air and is given as a percentage, i.e. Ft^3 / Hr (air) / Ft^3 / Hr (gas).

Air Shutter—An adjustable device on the primary air openings of a burner, used to control the amount of primary air introduced into the burner body. The opening or closing of the air shutter may alter the appearance of the burner flame and / or the flame characteristics; i.e., floating, blowing off, etc.

Aldehyde—A class of compounds, which may be produced during **incomplete** combustion of a fuel gas. Aldehydes have a pungent and distinct odor.

Altitude—Elevation above sea level, measured in feet or meters. Generally, burner inputs are adjusted downward relative to increasing altitude due to the decreasing amount of atmospheric air; consequently, combustion air.

ANSI (American National Standards Institute)—The American National Standards Institute is a private non-profit organization that oversees the development of voluntary consensus standards for products, services, processes, systems, and personnel in the United States. The organization also coordinates US standards with international standards so that American products can be used worldwide. For example, standards make sure that people who own cameras can find the film they need for them anywhere around the globe.

Atmospheric Pressure—The pressure exerted on the earth's surface by the atmosphere above it. Atmospheric pressures will decrease as the altitude increases above sea level.

British Thermal Unit—(Btu) The quantity of heat required to raise the temperature of one pound of fresh water one degree F. Btus are the basic measurement in the English system for indicating the caloric value of energy released during the combustion process.

Burner—An atmospheric gas burner is a device designed to entrain air necessary for combustion, premix that air, and deliver that air-gas mixture to the combustion zone. Most atmospheric burners are designed to burn natural gas, propane gas, butane gas, mixed gas and manufactured gas.

Burner Flexibility—The ability of a burner to be converted thereby allowing for the combustion of other gases; i.e., natural to propane, natural to butane, mixed gas to natural etc. Please note: in order for a burner to work properly, the correct orifice, the correct air shutter opening and the correct delivery pressure must be used. When converting from one gas to another, an orifice change and a regulator change are generally required**. IT IS IMPERATIVE TO CHECK THE USERS MANUAL PRIOR TO MAKING THE CONVERSION FROM ONE GAS TO ANOTHER. MAKE SURE THE PROPER COMPONENTS ARE USED AND EXPERIENCED PERSONNEL ARE AVAILABLE FOR THE CONVERSION PROCESS.**

Burner Port(s)—The opening in a burner head in which the air-fuel mixture is discharged for burning. A very critical calculation is port loading in which the Btu/Hr per port is determined. This value may indicate a burner flame that will "float", "lift" or " flash back ".

Butane Gas—A hydrocarbon fuel gas heavier than methane and propane with the chemical composition of C_4H_{10}. It is a major constituent of liquefied petroleum (LP) gas.

Carbon Dioxide—Carbon dioxide (CO_2) is a constituent of air. The percentage of carbon dioxide is a measure of **complete** combustion.

Carbon Monoxide—Carbon monoxide (CO) is a product of combustion and a measure of **incomplete** combustion. Carbon monoxide can pose a health risk if present in certain amounts and inhaled for over a lengthy time.

Combustion—A reaction between a fuel and air initiated by a heat source. This is, generally, a rapid oxidation and is accompanied by the generation of heat and light. (Please note: there are fuels and oxidizers that are "hypergolic" and combust when in contact with each other. These substances will not be considered in this discussion.)

Combustion Air—The air supplied to a burner in the combustion process. This air will be primary air and secondary air and will contain the oxygen necessary to sustain the combustion process.

Products of Combustion—Constituents resulting from the combustion of fuel and the oxygen in air, including inert gases, aldehydes, water vapor, NO(x), but excluding excess air.

Density—The weight of a substance per unit volume. In English measurements, this would be lbs / Ft^3.

Dilution Air—Air that enters a vent, draft hood or other device and serves to reduce the temperature of the products of combustion and the concentration of any carbon monoxide.

Discharge Coefficient—This coefficient is the ratio of the actual flow of fuel gas through burner orifice to the flow, which would be expected through the same orifice under the same conditions of operation if the orifice were a "perfect one". This multiplier is always less than 1.00 and is dependent upon the internal characteristics of the device; i.e., channel length, angle of approach, etc.

Draft Hood—A device built into an appliance, or made part of a vent system designed to 1.) assure the ready escape of the products of combustion in the event of no draft, backdraft, or stoppage beyond the draft hood; 2.) prevent a backdraft from entering the appliance and 3.) neutralize the effect of stack action of a chimney or gas vent upon the operation of the appliance.

Downdraft—Excessive high air pressure existing at the outlet of chimney or stack which tends to make gases flow downward in the stack or vent system.

Energy--A scalar physical quantity, which is a property of objects, and systems. According to the First Law of Thermodynamics, energy is conserved by nature and can neither be created or destroyed. Energy is often defined as the ability to do work. For our purposes here, we will use the units as Btu/Hr.

Excess Air—Air that results, in excess, relative to the process of complete combustion. This value is usually expressed as a percentage of the air required for complete combustion.

Flame Rollout—A condition in which the burner flame exceeds the volume of the combustion chamber. This may be momentary, upon ignition, or permanent depending upon the input of the burner. It is not a good condition and may pose a very hazardous threat relative to combustibles in and around the combustion zone and the appliance.

Flame Velocity—The speed at which the flame moves through the air-fuel mixture. This is usually measured in inches per second and becomes critical when looking at lifting and " blow-off" at the burner ports.

Flammability Limits—The Upper Explosive Limit (UEL) and Lower Explosive Limit (LEL) are always given as a percentage of the gas in an air-gas mixture. There will be no combustion unless the air-gas mixture is between the UEL and the LEL.

Flashback—This is a very undesirable condition in which the velocity of the burner flame is greater than the velocity of the air-gas mixture being discharged through the burner ports. This may result in burning at the orifice, which is a condition that can create overheating and sooting.

Floating Flames—An undesirable condition indicating that there may be incomplete combustion. Floating flames are reaching for oxygen, consequently combustion air.

Flow Rate—This is a measure of the flow of a fluid in a conduit or a mechanical device. In our study, it is the flow of gas and / or air being entrained into the burner. It is measured in Ft^3/Hr or CC / Hr.

Flue—Some products must have openings for the products of combustion to escape. These products are generally vented to the outside so that the products will not accumulate inside the dwelling.

Fuel—Any substance, which is combustible, may be called a fuel.

Fuel Gas—Any substance in a gaseous form used for the purpose of combustion.

Gas Meter—A gas meter is a mechanical device that indicates the quantity and the rate of a fuel gas flowing through accompanying piping.

Heating Value—All combustibles have heating values, generally measured in Btu/ Ft^3. This is the energy released per volume of gas ignited during the combustion process. In America we use the Gross or Higher Heating Value whereas in Europe the net or Lower Heating Value is used for calculating purposes.

Hydrocarbon—Any number of compounds composed of Hydrogen and Carbon atoms.

Ignition—The act of initiating the combustion process.

Ignition Temperature—The minimum temperature at which combustion is initiated.

Impingement—The act of burner flames hitting an adjoining colder surface. This may cause a sudden drop in flame temperature and deposition of carbon onto the adjoining surface. This occurrence is also called quenching.

Incomplete Combustion——Incomplete combustion occurs where there is not enough oxidant available to combine and react with fuel. When this occurs, carbon monoxide is produced. In the process of combustion, using an atmospheric burner, incomplete combustion is generally the rule and not the exception BUT we do measure the level of incomplete combustion, making sure the percentage is not in hazardous quantities.

Inerts—Non-combustible substances in a fuel or in flue gases. Nitrogen and carbon dioxide are examples of inert substances. An inert gas or constituent has no caloric value.

Injection—The drawing of primary air into the head of a burner prior to mixing with fuel. This is usually accomplished by designing a converging / diverging section of the venture downstream of the burner head.

Input Rate—The input rate may be expressed in units of Ft^3 / Hr or Btu / Hr. Normally, Btu/Hr for gas-fired products is the way input is defined.

Lean Mixture—A lean mixture is one in which the quantity of fuel, relative to the air-gas combination, is less than needed for complete combustion.

Lifting Flames—A condition in which the burner flames separate from the burner ports. This is also called "blowing off" and is a very undesirable condition.

Limit Gases—Limit gases are used for test purposes only in gas laboratories. The major constituent is usually greater than 95% of the total mix.

Limits of Flammability—Air-gas mixtures will only burn within certain limitations. The ratio of fuel and air must be within the Upper and Lower Explosive Limits and is always given as a percentage of the gas / air mixture.

Liquefied Petroleum Gases—The terms "Liquefied Petroleum Gases", "LPG" and "LP" Gases include any fuel gas which is composed, predominantly, of any of the following hydrocarbons, or mixtures of them: propane, butane, propylene or isobutene.

LNG—Liquefied Natural Gas

Manufactured Gas—A fuel gas, which is artificially produced by some process, as opposed to natural gas, which is found in nature. Manufactured gas, generally, is no longer used in North America but is produced in other parts of the world. It is basically made from coke or coal and has a composition that varies from city to city. The heating value is approximately 500 Btu / Ft ^{3}.

Methane—CH(4). Methane is found in nature and is the major constituent of natural gas.

Mixed Gas—A gas fuel in which the heating value of the mixture is enhanced by blending natural, propane, butane, etc.

Mixer or Mixing Tube—That portion of a burner in which the gas and entrained air are combined into a homogenous mixture in preparation for ignition.

Natural Gas—Basically 90% methane with other light hydrocarbons making up the remainder of the "mix". The heating value of natural gas will vary depending upon the region in which it is found.

NGPA—Natural Gas Policy Act (of 1978)

Odorant—Some gases, including natural gas, are odorless and colorless in their natural state. An odorant is added for the purposes of detecting a gas leak. This is done in the city of use and is mandated by law.

Orifice—An opening in a plug or "spud" which controls the flow of fuel gas into a burner for mixing. An orifice, properly sized, can provide for complete combustion. When improperly sized, can create a nightmare for the engineer or technician.

Parts per Million—Generally used as the measure of carbon monoxide in the products of combustion.

1%	10,000 PPM
0.10%	1,000 PPM
0.01%	100 PPM
0.001%	10 PPM

According to the American Gas Association, 0.08 % or 800 PPM is the maximum concentration of carbon monoxide allowed in the products of combustion.

Port—The portion of a burner in which the air-gas mixture is discharged and ignited. There will be multiple ports on most atmospheric gas burners.

Port Loading—Port loading is Btu/ Hr-In² or Btu / Hr-Ft² and is a very important factor in burner design. Overloading can create flame irregularities such as blowing off, floating and incomplete combustion.

Pressure—Pressure is the force exerted on the earth due to the atmosphere. It is measured in pounds per square inch (PSI), millibars, inches of mercury or inches of water (water column pressure).

Pressure Drop—The loss of pressure in a gas delivery system, generally, is a measure of the drop in water column pressure between the gas inlet and the burner orifice. Pressure drop **is the enemy** and one of the most problematic issues for a gas-fired product.

Pressure Regulator- A mechanical device for controlling the downstream pressure relative to the delivery pressure. It is typically measured in PSI or inches water column.

Primary Air—The air entrained by the injection of fuel gas into the head of a burner. This air is mixed with the fuel gas and then delivered to the burner head and ultimately the burner ports.

Propane Gas —Often referred to as LP (Liquefied Petroleum). It is also called "bottled gas". HD5 propane is approximately 90 % C(3)H(8) with a specific gravity of approximately 0.50. The heating value and specific gravity will vary depending upon the location in which it is found.

Rich Mixture—A rich mixture is one in which the gas in an air-gas mixture is greater than would be necessary for complete combustion.

Saturated Gas vs Dry Gas— In the natural gas industry, all of the gas calculations are accomplished considering only a dry basis. Standard temperature and pressure are calculated on a dry basis.

Secondary Air—Secondary air is that air available at the burner ports and is available at the point of combustion.

Soft Flame—A flame that is partially deprived of primary air. This flame may "float" over the burner ports and appear to move from point to point around the burner.

Soot—Small particles of carbon that result from incomplete combustion and impingement. They may be deposited on the burner, vent system and other adjoining surfaces, including cooking utensils.

Specific Gravity—Weight per unit volume relative to the weight per unit volume of air. Specific gravity is relative to weight / volume of air.

Standard Conditions (STP)—Pressure and temperature usually selected to be the reference points and conditions for measuring the properties of gases. In appliance work, standard conditions are 30 inches of mercury and 60 degree F.

Static Pressure—The pressure exerted by a motionless gas, usually measured in PSI or inches water column.

Therm—A unit of energy equal to 100,000 Btu.

Total Air—Primary air plus secondary air plus excess air supplied to a burner.

Total Pressure—The sum of static pressure plus gage pressure. Total pressure is also called velocity pressure.

Town Gas—Also known as manufactured gas.

Toxicity—The natural gases such as natural, methane, propane, butane etc are not toxic. The only way they can harm an individual is by displacing the air so suffocation occurs. Manufactured gases were very toxic because they contained significant quantities of carbon monoxide, which is toxic.

Ultimate Carbon Dioxide—The Stoichiometric percentage of carbon dioxide resulting from complete combustion.

Vent—The structure of a gas-fired device that allows for the discharge of the products of combustion. For most appliances, this is a sheetmetal structure that accepts dilution air for cooling and provides for the reduction of concentrated carbon monoxide.

Venturi—That portion of a burner in which the air-gas mixture is propelled into the burner head for ignition. It usually is a converging/diverging device.

Water Column Pressure—Abbreviated as W.C. and is a measure of pressure. One inch W.C. is equivalent to 0.578 ounces per square inch.

Wobbe Index—The main indicator of the interchangeability of fuel gases and is defined as follows:

I(w) = Higher Heating Value of Gas / (Specific Gravity of gas)½

Yellow Tipping—A condition in which the burner flames exhibit a yellow color at the very tip of the flame. Yellow tipping may be an indicator of sooting.

1400 LP-Air Gas—Propane gas, with a heating value of 2500 Btu/Ft^3, mixed with air to produce a heating value of 1400 Btu / Ft^3. This is often done by gas utilities and is called “peak shaving”,the purpose being to approximate the heating value of natural gas.

LIST OF SYMBOLS USED

ANSI = American National Standards Institute

Btu = British Thermal Unit

vol, (V) = volume (Ft^3)

T(a) = absolute temperature (° R or ° K)

T, t = temperature (° F or ° C)

C = centigrade

F = Fahrenheit

cc, (cm^3) = cubic centimeter

cu ft, (Ft^3) = cubic foot

cu in, (In^3) = cubic inch

cm, (m^3) = cubic meter

ρ = density (lbf / Ft^3)

Sp.Gr = specific gravity

Q = flow rate (Ft^3 / hr.)

P = pressure (inches W.C. or PSI)

H.V. = heating value (Btu / Ft^3)

m = pound mass

µ = compressibility factor (ratio of volume observed to volume of ideal gas)

n = number of moles of gas

K = orifice factor

A = area ($inches^2$)

R = universal gas constant (1545 Ft-lbf / lb-mole ° R)

AF = air-fuel ratio

FA = fuel-air ratio

fpm = feet per minute

fps = feet per second

ft = feet

ft-lb = foot pound

gal = gallon

HHV = higher heating value, Btu/Ft^3

LHV = lower heating value, Btu/$Ft.^3$

in = inch

in-lb = inch-pound

W.C. = inches water column

Kcal = kilocalorie

l = liter

lb = pound

UEL = upper explosive limit (%)

LEL = lower explosive limit (%)

ppm = parts per million

psf = pounds per square foot

psi = pounds per square inch

psia = pounds per square inch, absolute

psig = pounds per square inch, gage

SCF = standard cubic foot (measured at 60 º F and 14.7 psia)

sec = second

STP = standard temperature and pressure (60 º F and 14.7 psia)

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