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DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
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DESIGN OF GAS BURNERS FOR DOMESTIC USE

Contents

1. Introduction

This Letter Circular has been prepared for the purpose of giving general information regarding the action of, and the most favorable design for, burners of the type commonly employed in domestic and some industrial gas-burning appliances. The information given is to a considerable extent based upon the experimental work reported in Technologic Paper No.193 of the Bureau of Standards entitled, "The Design of Atmospheric Gas Burners", a publication now available only in libraries. All of the information in that publication likely to be of direct value to the designer of an appliance has been included, in many cases in a form much more convenient than the original. Other sources of information have been employed, and many of the conclusions are based upon the results of observations which have not been published. No attempt is made to state in detail sources of information or the experience upon which the conclusions are based.

To make the information in this paper convenient for reference, the various steps in systematically designing a burner, and the principal formulas which may be used are brought together in the summary. Because of the varied character of appliances these condensed directions should be used with caution; it is hardly possible to represent the best design for burners for all sorts of applications by means of a single formula. It is, therefore, recommended that the discussion of principles be carefully studied, since an understanding of the principles involved is fundamental to correct burner design.

2. The Relation of the Burner to the Appliance in which it is used

A brief preliminary warning should be given against assuming that a burner of given design is the best for all possible services. The Bureau of Standards has never recommended or approved a "standard" burner for general use or even for all appliances of any one type, because such a standard is not considered desirable. A burner to be good must be designed with reference to the appliance in which it is to be used, and no burner can be tested and judged to be superior or even satisfactory except as an integral part of the whole appliance. Representations to the effect that a particular burner is recommended by the Bureau of Standards or has been built in accordance with the Bureau's specifications are therefore misleading.

3. The Operation of a Gas Burner, with Definitions

All commercial fuel gases consist of hydrocarbons (chemical compounds of the elements hydrogen and carbon) or mixtures of hydrocarbons in varying proportions with hydrogen and carbon monoxide, which are fuels, and nitrogen and carbon dioxide, which are not. "Blue gas" and "producer gas", neither of which is extensively used alone for domestic purposes, are the only commercial fuel gases that do not contain hydrocarbons as a

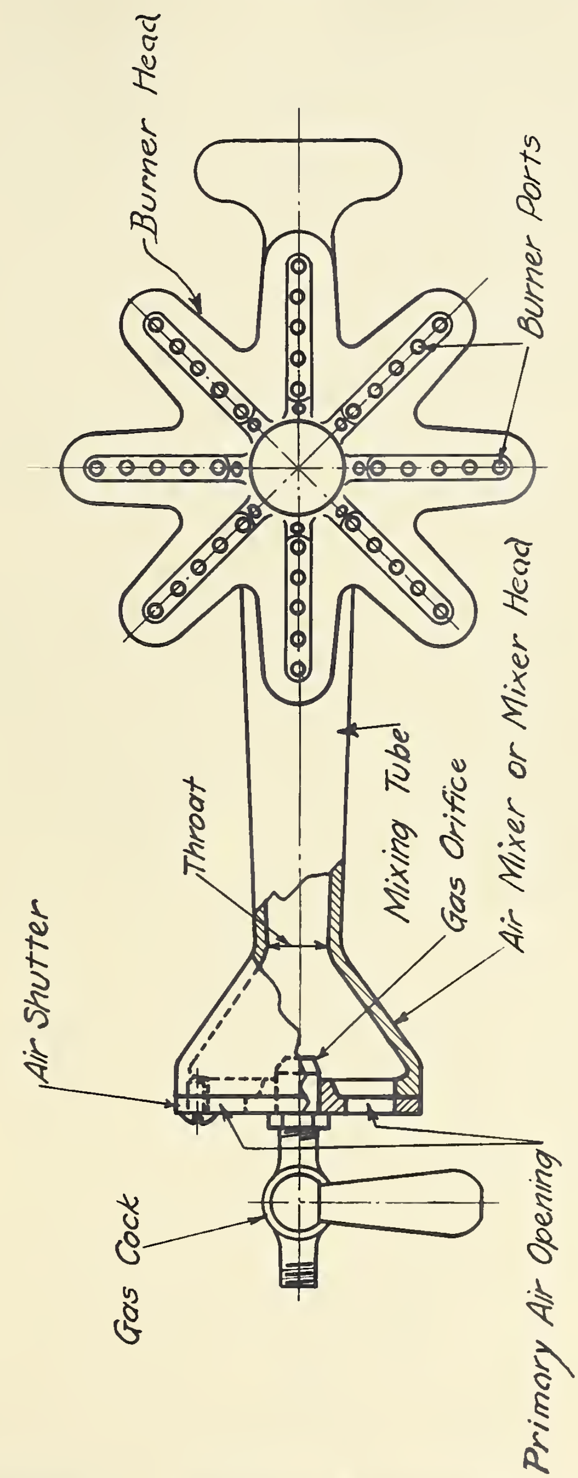
constituent of major importance. The hydrocarbons of importanc in domestic fuel gas supplies include methane, CH_4; ethane, C_2H_6; propane, C_3H_8, butane, C_4H_{10}; pentane, C_5H_{12}, ethylene, C_2H_4; and benzene (benzol), C_6H_6.

The burning of the gas is the chemical combination of the hydrogen and carbon contained in the gas, in whatever form, with oxygen of the air to form water vapor and carbon dioxide. Combustion is "complete" only when water and carbon dioxide are the only substances remaining in which either hydrogen or carbon occurs. A given quantity of fuel gas will supply hydrogen and carbon to combine with the oxygen in a perfectly definite amount of air which may readily be determined by analyzing either the original gas or its "products of combustion. This definite amount of air will be called the "air required for complete combustion". Its careful definition has been necessary to distinguish it from the amount of air which must circulate through an appliance, e.g., a water heater, but only a part of which reaches the flame and takes part in combustion.

Nearly all gas burners employed in domestic appliances are of the Bunsen or "blue-flame" type and this paper relates to this type only. In these burners a portion of the air required is mixed with the gas as it enters the burner and is called "primary air". The mixture of primary air and gas is for convenience frequently called simply "the mixture". The remainder of the air required for complete combustion is called "secondary air", but this term is somewhat loosely used to mean all the air in the neighborhood of, but outside, the flame, and is also more definitely used to denote all the air, except primary air, which flows through a partially closed "burner box" or "combustion chamber". The difference between the total flow of primary and secondary air through such a combustion chamber and the "air required for complete combustion" is called the "excess of secondary air".

Figure 1 shows a sketch of a commonly used range burner. The different parts of the burner are indicated according to the nomenclature commonly used, and a description of the operation of this burner will be applicable to all others of the Bunsen type. The gas, after passing through the controlling "cock" issues from the "orifice" with high velocity and enters the "mixing tube" (also called "mixer" and "injecting tube"), the elongated portion of the burner which leads to the "burner head" in which the "ports" are situated. The constricted portion of the mixing tube is distinguished as the "throat" and the enlarged portion, which the gas and air first enter, as the "mixer head". The access of air to the mixer head is usually subject to control by an "air shutter".

As the gas leaves the orifice it possesses a considerable amount of "kinetic energy" or energy of forward movement. This energy is in part transferred to the air in the mixer head and throat, imparting a forward movement to it also. Air flows into the mixer head to replace that which has thus moved into the "burner head".



ATMOSPHERIC STAR BURNER—DOMESTIC TYPE

4. What Takes Place in the Flame

When the mixture of gas and air flowing through the ports is ignited the chemical combination of the oxygen of the primary air with the constituents of the fuel gas takes place in a thin greenish-blue conically shaped zone called the inner or primary "cone" or the "zone of primary combustion". It is often supposed that the entire space bounded by the visible "cone" is a region of vigorous chemical reaction, but such is not the case. When not obscured by fluttering or other conditions that interfere with observation, the zone of primary combustion is found to be paper-thin, and the reaction between gas and primary air is begun and substantially completed while they are flowing through the minute distance represented by the thickness of the zone. The stationary position, with reference to the burner, of the zone in the moving gas stream is the result of an equilibrium or balance between the flow of the primary mixture and the tendency of the flame front to move into the unburned mixture. The position is maintained by the conduction of heat from the gases which have already reacted into the stream of those which have not reacted, raising them to a somewhat indefinite "ignition temperature".[1] When this

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1. The term "ignition temperature" here used as a matter of convenience must not be understood to refer to a definite physical property such as density or specific heat. In any combustible mixture of gases there is some reaction at temperatures much below the ignition temperature. The rate of this reaction increases continuously as temperature is increased. There is a correspondingly increasing rate at which heat is produced by the reaction. The only definite meaning that can be assigned to the term "ignition temperature" is the temperature at which the heat produced by chemical reaction exceeds the rate at which heat is lost.

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temperature is reached the heat of reaction in a portion of the mixture suddenly raises the temperature of that portion, without waiting for conduction,and causes the completion of the reaction almost instantaneously. The conical shape of the combustion zone results from the fact that, as the gas stream leaves the port, heat first begins to be rapidly conducted and the zone of reaction begins to travel inward from the boundary of the stream to the center, which it reaches only after the stream has moved some distance from the port. If a change of composition or temperature of the gas mixture increases the rate at which the flame front will move into it, the stream will not move so far before the center is reached, and the cone is shortened. Hence, the size of the cone is said to depend upon the "ignition velocity" of the primary mixture. It also depends upon the velocity of the mixture as it leaves the port.

If the primary air is just sufficient to supply one atom of oxygen for each atom of carbon in the hydrocarbons, the hydrocarbons are practically completely converted into hydrogen

and carbon monoxide in the primary zone. If less oxygen is present it forms as much carbon monoxide as possible and the remaining hydrocarbon usually decomposes to some extent into hydrogen and carbon. The carbon occurs as finely divided glowing particles which impart the luminous yellow color to the flame. Because of its great chemical stability and low carbon content, methane alone of the hydrocarbons does not usually become sufficiently heated to yield carbon and a yellow flame in this way. This decomposition of the hydrocarbo. to form hydrogen and carbon is extremely slow in comparison with the primary reaction with oxygen, and, therefore, continues while the gas travels a considerable distance beyond the primary zone. If an amount of air more than sufficient to convert the carbon of the hydrocarbons to carbon monoxide enters the primary zone, the excess reacts with a portion of the carbon monoxide and hydrogen, originally present or formed from the hydrocarbons, to produce carbon dioxide and water. The relative amounts of carbon monoxide and hydrogen burned under these conditions depend upon the original concentrations and the temperature in the manner represented by the "water-gas equilibrium", which will be familiar to students of physical chemistry.

The remaining reactions of importance, those in which carbon monoxide, hydrogen and any residual hydrocarbon are finally oxidized by secondary air, also take place in a very thin zone which is sometimes called the "outer cone" or "mantle" of the flame. In this secondary zone, oxygen and the combustible gases are exactly equivalent and combine without leaving any surplus of either. Inside the zone there is a fairly high concentration of carbon monoxide and hydrogen, but no uncombined oxygen. At a very short distance, but outside the zone, there is much free oxygen but no combustible material, unless the temperature is too low to permit vigorous reaction, in which case the zone of secondary combustion will be invisible or nearly so.

A steady, clearly defined secondary zone that forms a closed surface is, therefore, the visual indication that secondary air reaches the region of the flame in sufficient quantity to oxidize the combustibles completely while they are still hot enough to burn.

When inert gas, from products of combustion or otherwise, mingles with the secondary air or when the supply of air is insufficient, the zone of secondary combustion moves outward and may waver and become "ragged" in appearance. Under such conditions carbon monoxide is likely to escape, especially if the gases come into contact with a relatively cool object before reaching the secondary zone. Contrary to common supposition, the appearance of the primary cones is of no value in determining whether combustion is complete unless judged by an experienced adjuster already familiar with the requirement for primary air of the particular gas used, when burned in an appliance of the design under observation. It is the appearance of the secondary zone which is of general

importance in determining whether combustion is complete.

The behavior of the carbon in a luminous flame is interesting, though not very important, because such flames are avoided in good practice. Carbon reacts at flame temperature with both water vapor and carbon dioxide, hydrogen and carbon monoxide being formed in the first case, carbon monoxide only in the second case. The carbon formed in or shortly beyond the primary zone thus tends to react with the products of combustion which diffuse inward from the secondary zone and may entirely disappear before the secondary zone is reached. The solid particles of carbon are relatively slow to react as compared with the gaseous molecules, however, and may not only fail to be completely oxidized inside the secondary zone, but may pass entirely through it and the surrounding region of high temperature, and cool too much to burn completely. In this case we have a smoky flame. Carbon once formed in the flame requires much more favorable conditions for its complete oxidation than does any of the other combustible substances, hence any appearance of a yellow color in a Bunsen flame is to be avoided.

5. The Air Required for Complete Combustion of Various Gases

When the composition of a gas supply is known from analysis the amount of "air required for complete combustion" may be easily computed by the use of simple chemical equations. The compositions of different gas supplies and even of the same gas supply at different times vary so much, and actual analyses are so infrequently published, that this method of determining the air required is seldom available to the appliance designer. It may be assumed with sufficient accuracy for most purposes connected with design that nine cubic feet of air will be required per thousand Btu liberated and that the products of combustion will have a volume of ten cubic feet (including water vapor) per thousand Btu, volumes of gas being referred to 60°F and 30 inches of mercury. If, for example, a burner is to inject 50 per cent of the air required as primary air and the appliance is to take 100 per cent excess secondary air, it should be designed to take 4.5 cubic feet per hour of primary and 13.5 cubic feet of secondary air per 1000 Btu of its hourly "rating".

6. The Requirements which Determine Satisfactory Burner Design[2]

2. Bureau of Standards Technologic Paper No.304 entitled, "A Method for Testing Gas Appliances to Determine their Safety from Producing Carbon Monoxide", contains a more complete discussion of this subject. It can be purchased from the Superintendent of Documents for 10 cents.

The following major requirements must be met in order that a burner shall be satisfactory:

1. Combustion must be complete. Neither carbon nor carbon monoxide must escape from the flame.

2. The flames must not lift or be blown from the ports.

3. The flame must not "backfire" (or "flashback").

4. The heat must be applied as efficiently as is consistent with good practice in other respects.

5. The flame must travel readily from port to port when the gas is lighted.

6. The distribution of heat with respect to its application must be satisfactory. Attention to this requirement is of importance in some appliances but not in others.

7. Unusually difficult or expensive construction must not be involved unless it results in compensating advantages.

Not only must these requirements be met under a single condition of service, but large variations both in the conditions of gas supply and the service demanded must be provided for by the designer in most cases. With simple changes that can be made by the gas fitter, an appliance that is widely distributed must work at normal pressures of three inches or ten inches of water and with gases having a considerable range of composition and properties. After being set up and adjusted it must not be unusable with pressure variations as great as 1.5 times the minimum pressure. Rather wide changes in specific gravity, "ignition velocity", volume of air required for complete combustion and other properties may be combined with these changes of pressure. A factor of safety must be provided for inexact workmanship during manufacture and for a certain amount of change in use, including the effect of accumulated dirt and unfavorable conditions of "draft". A "top burner" must give good service at full rating when heating laundry water or at ten or twenty per cent of full rating when keeping food warm; and some other appliances are expected to give only less varied service.

7. The Compromises Involved in Burner Design

These requirements are simple to meet individually; complying with them as a group is not so simple because changes that are favorable with respect to one requirement are in many cases unfavorable with respect to another. This makes it necessary to exercise good judgment in determining how far to go in sacrificing one characteristic for the sake of improving another. Some of the more important of these necessary compromises will be indicated.

Not all of the secondary air which passes through a burner box reaches the flame at a time when reaction is possible; hence one must always have an excess of secondary air and this excess must be made large enough to insure that combustion will be

complete under unfavorable conditions that arise in service or result from imperfect workmanship. On the other hand an excess of air carries away heat; therefore, in order to obtain high efficiency it should be kept at a minimum. The spacing of the burner with respect to the object heated, especially the top burner of a range, often involves the same conflict between efficiency and completeness of combustion. Since primary air always enters the flame under conditions which give it the best possible opportunity to react, an increase in the amount of primary air makes possible a more than equal reduction in secondary air, and an improvement in efficiency without sacrificing completeness of combustion. But an increase in primary air renders the flame less stable and more likely to blow off or backfire. The tendency to blow off can be counteracted by making the ports larger or decreasing the velocity, through them, of the primary mixture; the tendency to backfire can be counteracted by making the ports smaller or increasing the velocity of the mixture.

The relationship of primary air to the stability of the flame is so important that it should be fully discussed. If we start with a flame in which there is no primary air there is obviously no possibility of backfiring and the mixture must issue at a very high velocity to cause the flame to "lift" (blow from the port). The flame is also difficult to extinguish by a cross current of wind.

If the proportion of primary air in the mixture is graduall increased, the rate of gas supply at which lifting occurs will decrease at each step, and the rate of gas supply at which backfiring occurs will increase at each step. Hence, the available range of rates of heat supply will diminish until a condition is reached such that the flame will burn at only one rate of gas supply, and either lifting or backfiring will result from the slightest variation. If still more air is introduced it is impossible to light the burner at all. If a port of smaller diameter is drilled, the rate of gas supply at which a given mixture of gas and air will cause lifting is reduced somewhat, but the rate at which backfiring occurs is reduced much more. Hence, a higher percentage of primary air may be employed, but the amount of heat that can be delivered by a single port is diminished. The height of the flame is also reduced and much more heat is transmitted to the burner, which is usually undesirable.

In order to increase the amount of primary air, for the purpose of increasing efficiency and insuring complete combustion, it is therefore necessary, in general, to make the ports smaller and enough more numerous to increase considerably their total area; but improvement in this direction is accompanied by increased cost and difficulties in manufacturing. To carry this development to its conclusion and introduce all the air required as primary air may require that the burner head approximate a porous plate with its so-called "surface combustion". It is difficult to inject enough primary air into such a burner at ordinary service pressures, and the heating of the

burner creates an additional problem.

The result of the most satisfactory compromises between the amount of primary air entrained and the other factors mentioned depends upon the purpose for which the burner is to be used. Range burners which must give service at widely varied rates seem to be most satisfactory when designed and adjusted to take about 50 to 60 per cent of the air required as primary air. Efficiency and completeness of combustion are more important and a variable output of heat less important in the case of a radiant heater, hence higher percentages of primary air are employed, usually 60 to 85 per cent of that required for combustion. The demand from a water heater burner does not vary greatly, efficiency is important, and the size and form of the burner are not closely limited. For these reasons it would be best to design the burner of a water heater for high primary air; but the inferior care given to such a burner, the fact that it is not under frequent observation and is often lighted and extinguished automatically result in the need for greater safety from the danger of an unstable flame. The consideration of safety has usually prevailed, and the average water heater burner probably takes less primary air than the average range burner. In such a case as that of the burner for an unvented "gas-steam radiator", in which efficient transfer of heat is not very important and an abundance of secondary air is always present, the amount of primary air makes little difference provided it is sufficient to prevent a luminous flame and the liberation of carbon.

The effect of designing an appliance to take high primary air must not be confused with the effect of adjusting an appliance to take high primary air; the effects on efficiency are usually exactly opposite. Designing an appliance to take more primary air increases efficiency because it permits the closer confinement of the flame and a reduction in the total amount of air which carries away heat uselessly; it is effective in thus increasing efficiency only when accompanied by other changes in construction which it makes possible. Adjusting a completed appliance to take more primary air does not materially change the secondary air or the application of the flame, and usually reduces efficiency. In the interest of efficiency an appliance should therefore be designed to take as much primary air as possible without danger from unstable flames, and when placed in service it should be adjusted to take as little primary air as possible without creating a hazard or a nuisance because of incomplete combustion. This should not be interpreted as a general recommendation that appliances be adjusted to have very low primary air, since the beginning of incomplete combustion is hard to judge, and the small gain in efficiency does not warrant incurring the risk of it. The adjuster should, however, have in mind the effect on efficiency of changing primary air, and the conditions which limit desirable changes in both directions.

8. The Entrainment of Primary Air

For the reasons given, all phases of burner and appliance design depend largely upon the extent to which primary air can and should be entrained. Because it is easily possible to reduce the amount of primary air to any extent desired by limiting the opening for air in the burner casting or by closi an air shutter, it is very convenient to build all burners in the form that will permit the entrainment of a maximum amount of air and to control the amount admitted by the means mentioned. In the discussion which follows, the effect of various details of construction upon the entrainment of air will be given, and the combination which results in maximum air injection will be described.

The total volume of air entrained by a stream of gas depends upon the following factors:

1. The volume of gas delivered per unit time.
2. The fall of pressure through the orifice.
3. The specific gravity of the gas.
4. The size and form of the orifice
5. The position of the orifice
6. The area of opening at the air shutter.
7. The design of the injecting tube (or mixing tube).
8. The dimensions and shape of the burner head.
9. The total area of the burner ports and to some extent the number and form of the ports of which the total is made up.
10. The temperature of the burner.

9. The Orifice

The flow of gas through an orifice under the small pressure of the usual city supply may be represented for practical purposes by the following equation:

$$q = aK\sqrt{\frac{h}{d}}$$

in which q is the quantity of gas delivered per unit of time, a is the area of the orifice, h is the fall of pressure through the orifice (ordinarily with the gas cock wide open, h is nearly the pressure above atmospheric of the gas in the supply line), d is the specific gravity of the gas referred to air, (air = 1.00) and K is an "orifice constant" or "coefficient of discharge" that depends mainly upon the form of the orifice and the units employed.

Usually the orifice has the form of a cylindrical hole through a metal plate of appreciable thickness, or a cylindrical hole opening at one end into a cone which is concentric with the hole. The cylindrical portion is called the "channel". The conical portion may occupy the whole thickness of the metal, in which case we may regard the channel as of zero length. In Technologic Paper No. 193, to which reference was made at the

beginning of this Circular, any orifice without a channel was called a "sharp edged orifice" without regard to whether the conical portion was on the side of the approach or the discharge. The term has come to have a special meaning in the field of gas measurement and should be limited to an orifice which has the conical portion at the outlet and which opens rapidly enough to be independent of the thickness of the metal. If the rate of flow of gas, "q", is expressed in cubic feet per hour, the area of the orifice, "a", in square inches, and the fall of pressure, "h", in inches of water column, the value of K for a sharp edged orifice is about 1000. Probably a majority of the orifices used for gas appliances have a 120° cone on the inlet side, the angle of the common twist drill. Since the surface of this cone approaches the axis of the channel at an angle of 60°, the "angle of approach" is said to be 60°. If the cone occupies the full depth of the metal in the case of a 60° approach, the value of K is about 1090. With sharper angles of approach the value of K increases. For an 8° angle it is about 1450. Increasing the length of the channel from zero at first increases and then decreases the value of K; the increase is a maximum when the length of the channel is about half its diameter and amounts to some 20 per cent of the value of K for a sharp edged orifice. After the maximum is passed, K diminishes but slowly and does not reach the value for an orifice without a channel until the length of the channel is at least ten or fifteen diameters.

For the average drilled orifice, the area of which is computed from the nominal size of the drill and which has an angle of approach of 60° and a channel at least as long as its diameter, the value of K may be assumed to be 1300 without much error. The formula then becomes

$$q = 1300\ a \sqrt{\frac{h}{d}}$$

The formula does not very accurately represent the effect upon flow of changing either the size of the drill for such orifices or the pressure of the gas, but is probably accurate enough for most practical purposes. Generally, the flow increases somewhat less than in proportion to the nominal area and more than in proportion to the square root of the pressure. The first effect probably results from the fact that the hole is larger than the drill by a fraction that is inappreciable for a large drill but of greater relative importance for a small one; the second effect from the fact that the hole is not a perfect "sharp edged orifice", for which the relationship between pressure and flow was derived.

10. The Effect of the Form of Orifice on the Entrainment of Air

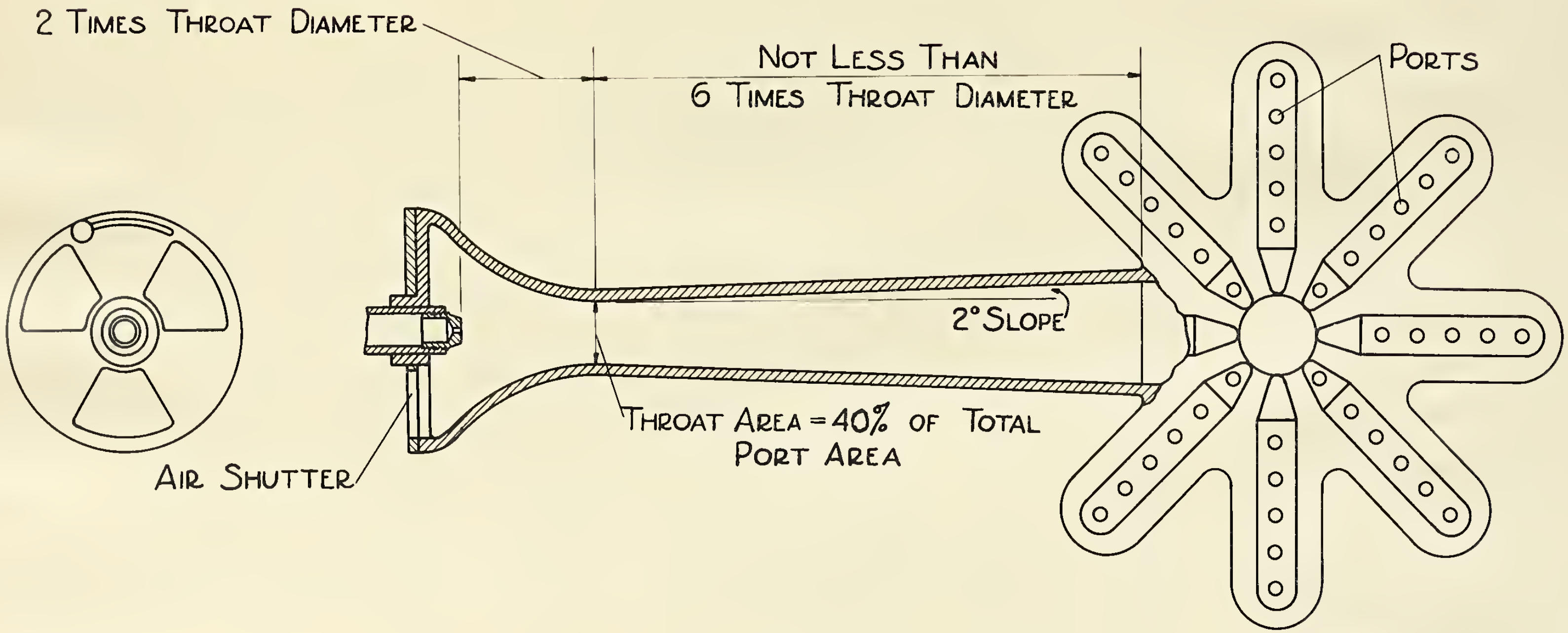
The amount of air entrained by the gas stream is closely dependent upon its kinetic energy, and anything that tends to dissipate this energy, including friction in the orifice itself and turbulence as the gas enters the mixing tube, reduces the amount of air entrained. The loss of energy by friction is least in an orifice without a channel, and within any convenient range it makes no difference what angle of approach is used if the cylindrical channel is missing. The loss of entraining power is greater the longer the channel, but the variation is not proportional. The mechanical difficulty of making orifices of accurate size but entirely without channels is considerable, and most of the effect of a channel is produced in a length equal to about half the diameter; hence no attention need usually be given to the length of channel beyond making it as small as is convenient in manufacture. Such an orifice will give only about 5 to 7 per cent less air entrainment than one with a perfect sharp edge.

The question of turbulence is at least as important. Orifices intended to be similar, but which are actually different because of a visible burr, or even an imperfection that is not readily detected by the eye, may produce a turbulent jet which will inject ten per cent less air than a good jet. An orifice may be readily tested for turbulence by passing a strea of gas through it and igniting. A long, straight, slender flame results from an orifice that will produce good entrainment, a spreading or irregularly shaped flame from one that will not. For good entrainment the direction of the jet must be accurately along the center line of the mixing tube.

11. The Form of the Mixing Tube

The form of the mixing tube which will result in a maximum entrainment of air has been the subject of a long series of experiments which led to the result represented in Figure 2. Usually in the design of a burner, the number of ports and their size are determined by considerations of greater importance than their effect upon the entrainment of air, hence the other dimensions of the burner, which the designer is usually at liberty to alter, are specified with reference to the area of the ports. The optimum throat area, 43 per cent, was determined with a cold burner of a construction which favored high entrainment. Obviously the most favorable area depends directly upon the resistance to flow through the mixing tube and burner head, and since this resistance may be increased by obstructions to flow in the casting and by the heating of the burner, the optimum throat diameter may be somewhat less than 43 per cent in practice, but is rarely much, if any, less than 40 per cent.

RELATIVE DIMENSIONS OF DIFFERENT PARTS OF A BURNER WHICH WILL INJECT APPROXIMATELY THE MAXIMUM AMOUNT OF AIR FOR A GIVEN PORT AREA



Make Air-Shutter Opening At Least 1.25 Times Port Area

The area of the throat is the most important of the several relative dimensions given. If a pipe of uniform cross section equal to that of the mixing tube at the entrance to the burner head is substituted for the mixer shown, the change results in a reduction of the amount of air entrained by about fifty per cent. The length and taper of the tube beyond the throat must be such that the stream expands gradually without eddies or change of direction until the "velocity head" at the throat has been largely converted into"pressure head". This requirement permits considerable variation from the form shown without serious loss of entraining power; but alterations should be made with caution, and sudden enlargements or changes of direction of the passage must be entirely avoided if good entrainment is necessary.

12. The Momentum of the Gas Stream and Its Relation to the Entrainment of Air

It has been found, as an experimental relationship,[3] that

3. See Technologic Paper No.193, Design of Atmospheric Gas Burners.

for a given burner the momentum (the product of mass and velocity) of the jet of gas as it leaves the orifice, bears a sufficiently constant ratio to the momentum of the mixture of gas and primary air as it passes any definite cross section of the burner to permit the use of a constant in most problems of design. A theoretical demonstration of this relationship involves assumptions which are not justified except by the result of the experiments themselves, hence the rule is entirely empirical.

In the statement of the rule and the equations developed from it the following symbols will be used.

a = the area of the orifice
b = the density of the fuel gas
q = the volume of the gas flowing through the orifice per unit time
m = the mass of gas flowing through the orifice per unit time
v = the velocity of the gas flowing through the orifice
A = the area of any definite cross section of the passages through the burner.
D = the density of the mixture of gas and primary air
Q = the volume of the mixture flowing through the burner in unit time
M = the mass of the mixture flowing through the burner in unit time
V = the velocity of the mixture past the cross section of area A.
P = the total area of the ports

a_1, d_1, q_1, A_1, D_1, etc., represent one set of simultaneous conditions and results of operation of a burner and a_2, d_2, q_2, etc., another set of simultaneous conditions and results of operation of the same burner.

The constant ratio of momenta is represented by the equation

$$\frac{MV}{mv} = C, \text{ a constant} \qquad (1)$$

For all burners which are geometrically similar and differ only in size, C should have the same value.

By definition

$$V = \frac{Q}{A}$$

$$v = \frac{q}{a}$$

$$M = DQ \text{ and}$$

$$m = dq$$

Substituting these values in equation (1),

$$\frac{aDQ^2}{Adq^2} = C$$

Solving for $\frac{Q}{q}$

$$\frac{Q}{q} = \sqrt{AC}\sqrt{\frac{d}{aD}} \qquad (2)$$

The arbitrarily chosen cross section A is a constant for a given burner, hence $\sqrt{AC}$ is also a constant and may be represented by k. Then

$$\frac{Q}{q} = k\sqrt{\frac{d}{aD}} \qquad (3)$$

The injecting power of the burner is thus represented by a characteristic constant "k" which may be defined by rearranging equation 3 into the form

$$k = \frac{Q}{q}\sqrt{\frac{aD}{d}} \qquad (4)$$

Since the value of C is the same for burners of different sizes but the same geometrical form, the value of $\frac{k}{\sqrt{A}}$ should be the same for geometrically similar burners. For the purpose of predicting a value of k, it is most convenient

to take the section A through the ports so that

$A = P$, where P is the total "port area".

With no restriction of air by a shutter, a cold burner of the design shown in Figure 2, which has all parts perfectly machined and aligned, and employs a perfect sharp-edged orifice, has a value of k equal to about 1.2 $\sqrt{P}$, where P is the total area of the ports in square inches and the volume delivered is expressed in cubic feet per hour. To allow for imperfections in manufacture, heating in use, etc., the value of "k" should probably not be assumed greater than 0.8 $\sqrt{P}$, and even this value should be checked by testing a reasonable number of burners after manufacture is begun.

Equation (3) may obviously be put into many forms. Instead of the ratio of the volume of the mixture to the volume of gas we may want the volume of the mixture

$$Q = kq\sqrt{\frac{d}{aD}} \qquad (5)$$

or the volume of air injected

$$Q - q = kq\sqrt{\frac{d}{aD}} - q \qquad (6)$$

or the ratio of the volume of air to the volume of gas

$$\frac{Q - q}{q} = k\sqrt{\frac{d}{aD}} - 1 \qquad (7)$$

Frequently we wish to solve for the area of the orifice, which is given by the equation

$$a = k^2 \frac{d}{D}\left(\frac{q}{Q}\right)^2 \qquad (8)$$

From the equation already given for the flow of gas through an orifice,

$$q = 1300\, a\sqrt{\frac{h}{d}}$$

$$a = \frac{q}{1300}\sqrt{\frac{d}{h}}$$

Substituting this value of a in equation (3) and simplifying, we get

$$Q^2 D = 1300\, k^2 q\sqrt{hd} \qquad (9)$$

If we write equation 3 in the form

$$Q^2 D = k^2 q^2 \frac{d}{a}$$

and substitute for D its value

$$D = 1 - \frac{q}{Q} \quad (1 - d) \qquad (10)$$

and solve for Q, we get

$$Q = 1/2\ q\ (1-d) + 1/2 \sqrt{q^2\ (1-d)^2 + 4k^2q^2\ \frac{d}{a}}$$

$$Q - q = \frac{q}{2} \left(\sqrt{(1-d)^2 + \frac{4k^2d}{a}} - 1 - d \right)$$

and the ratio of the volume of primary air to the volume of gas is

$$\frac{Q - q}{q} = 1/2 \left(\sqrt{(1-d)^2 + 4\ \frac{k^2d}{a}} - 1 - d \right) \qquad (11)$$

Similarly $\underline{a}$ may be eliminated as in equation 8, when the ratio of air to gas becomes

$$\frac{Q - q}{q} = 1/2 \left(\sqrt{(1-d)^2 + \frac{5200k^2}{q} \sqrt{hd}} - 1 - d \right) \qquad (12)$$

When comparing the operation of a burner under two sets of conditions, it is not always necessary to solve for the burner constant $\underline{k}$. For the purpose of these problems one set of conditions may be represented by symbols with the subscript 1 and the other set by symbols with the subscript 2. Such equations as the following are easily derived from equation (3).

$$\frac{a_2}{a_1} = \left(\frac{Q_1}{q_1}\right)^2 \left(\frac{q_2}{Q_2}\right)^2 \frac{d_2\ D_1}{d_1\ D_2} \qquad (13)$$

and

$$\frac{Q_2}{q_2} = \frac{Q_1}{q_1} \sqrt{\frac{a_1\ d_2\ D_1}{a_2\ d_1\ D_2}} \qquad (14)$$

13. Problems Illustrating the Computation of Primary Air

Problem 1.

A burner supplied with gas of 0.75 specific gravity through an orifice drilled with a No.43 standard twist drill (area, 0.0062 sq.in.) entrains 9.8 cubic feet of air per cubic foot of gas. What is the value of the burner constant "k"?

Solution:

From equation (10)

$$D = 1 - \frac{q}{Q} \quad (1-d)$$

$$= 1 - \frac{1}{10.8} \quad (1 - 0.75) = 0.97$$

Equation 4 applies

$$k = \frac{Q}{q} \sqrt{\frac{aD}{d}} = 10.8 \sqrt{\frac{0.0062 \times 0.97}{0.75}}$$

$k = 0.966$

Problem 2.

With the burner of problem 1, what will be the ratio of entrained air to gas of 0.45 specific gravity if the burner is equipped with a No. 30 (standard twist drill) orifice having an area of 0.00833 sq. in?

Solution:

Equation (11) applies

$$\frac{Q - q}{q} \doteq 1/2\left(\sqrt{(1-d)^2 + 4\frac{k^2 d}{a}} - 1 - d\right)$$

$$= 1/2\left(\sqrt{0.65 \times 0.65 + \frac{4 \times 0.966 \times 0.966 \times 0.45}{0.00833}} - 1.45\right)$$

$$= 6.4$$

Hence, the volume of air entrained will be 6.4 times the volume of gas.

Problem 3.

If propane is to be used with the burner of Problem 1, what is the largest orifice that can be used and still permit the entrainment of primary air equal to 65 per cent of that required for complete combustion?

Solution: Propane requires 23.9 volumes of air for complete combustion.

$$\frac{Q}{q} = 23.9 \times 0.65 + 1 = 16.5$$

$$d = 1.56$$

$$D = 1 + \frac{0.56}{16.5} = 1.034$$

$$k = 0.966$$

Equation (8) applies

$$a = k^2 \frac{d}{D}\left(\frac{q}{Q}\right)^2 = \frac{0.966 \times 0.966 \times 1.56}{1.034 \times 16.5 \times 16.5} = 0.00516$$

which is the size of a No. 46 standard twist drill.

Problem 4.

If propane is to be used and the burner of Problem 1 is to be equipped with an adjustable orifice, what is the lowest pressure at which 50,000 Btu per hour can be delivered and 65 per cent of the air required for complete combustion can be entrained as primary air?

Solution: The following conditions are the same as in Problem 3.

$$\frac{Q}{q} = 16.5$$

$$d = 1.56$$

$$D = 1.034$$

$$k = 0.966$$

The heating value of propane is 2575 Btu per cu. ft. The volume of gas required is therefore

$$q = 50{,}000/2575 = 19.4 \text{ cu. ft. per hour}$$

$$Q = 16.5 \times 19.4 = 320 \text{ cu. ft. per hour}$$

Equation (9) applies

$$Q^2 D = 1300\, k^2\, q \sqrt{hd}$$

$$\sqrt{hd} = \frac{320 \times 320 \times 1.034}{1300 \times 0.966 \times 0.966 \times 19.4} = 4.51$$

$$hd = 20.3$$

$$h = 13 \text{ in. of water}$$

This is the lowest pressure at which propane, supplied to the burner at the prescribed rate, will entrain the amount of air required.

Problem 5.

It is known from experience that an industrial burner of particular form has a value of about $k = 0.8\sqrt{P}$. It is desired to burn butane at the rate of 50,000 Btu per hour with primary air only. What will be the necessary area of the ports if the gas is supplied at 20 in. pressure?

Solution:

Butane has a heating value of 3350 Btu per cu. ft., has a specific gravity of 2.1 and requires 31 volumes of air for complete combustion. Therefore,

$$q = \frac{50,000}{3350} = 14.9 \text{ cu.ft. per hour}$$

$$\frac{Q}{q} = 32$$

$$Q = 478 \text{ cu.ft. per hour}$$

$$d = 2.1$$

$$D = 1.034$$

$$k = 0.8\sqrt{P}$$

$$k^2 = 0.64\ P$$

Equation (9) applies

$$Q^2D = 1300\ k^2\ q\sqrt{hd}$$

$$478 \times 478 \times 1.034 = 1300 \times 0.64\ P \times 14.9\sqrt{20 \times 2.1}$$

$$P = 3.94 \text{ sq.in.}$$

Hence, a burner with 3 square inches of port area should permit the desired air entrainment. Whether the flames would blow from the ports is another question.

Problem 6.

With the conditions otherwise as in Problem 5, it is found that a port area of 4 sq.in. is necessary to prevent lifting. At what gas pressure can the desired entrainment of air be effected?

Equation (9) again applies

$$478 \times 478 \times 1.034 = 1300 \times 0.64 \times 4 \times 14.9\sqrt{h \times 2.1}$$

$$h = 10.8 \text{ in. of water column.}$$

Problem 7.

When a given burner is supplied with gas of 520 Btu and specific gravity 0.43 through a No.40 orifice, area (0.0075 sq.in.) the air entrained is 75 per cent of that required for complete combustion and is just sufficient for good operation. What is the largest orifice that can be used with satisfactory air entrainment for a 625 Btu gas of 0.62 specific gravity? If the burner operates at normal rating at 6 in. pressure with the 520 Btu gas, at what pressure will it give normal rating with the 625 Btu gas?

Solution:

We can use with sufficient accuracy the approximation that nine cubic feet of air will be required per thousand Btu

liberated. Under the initial conditions therefore the "air:gas ratio" is 9 x 0.520 x 0.75 = 3.51 and

$$\frac{Q_1}{q_1} = 4.51$$

Similarly, $\frac{Q_2}{q_2} = 5.22$

$d_1 = 0.43$, $d_2 = 0.62$

$D_1 = 0.874$, $D_2 = 0.927$

$a_1 = 0.0075$

Equation (13) applies:

$$\frac{a_2}{a_1} = \left(\frac{Q_1}{q_1}\right)^2 \left(\frac{q_2}{Q_2}\right)^2 \frac{d_2\ D_1}{d_1\ D_2}$$

$$a_2 = 0.0075 \times \frac{4.51}{5.22} \times \frac{4.51}{5.22} \times \frac{0.62}{0.43} \times \frac{.874}{.927} = 0.0076$$

Hence, the sizes of orifices which will give equally satisfactory air entrainment for the two gases are practically identical.

The formula for the flow through an orifice gives

$$q_1 = 1300 \times 0.0075 \sqrt{\frac{6}{0.43}}$$

$$q_2 = 1300 \times 0.0076 \sqrt{\frac{h}{0.62}}$$

$$\frac{q_1}{q_2} = \frac{0.0075}{0.0076} \sqrt{\frac{6 \times 0.62}{0.43\ h}}$$

For the same normal rating

$$\frac{q_1}{q_2} = \frac{625}{520}$$

Substituting and solving

h = 5.8 inches of water

Hence, 625 Btu gas of specific gravity 0.62 and 520 Btu gas of specific gravity 0.43 can be interchanged without readjusting appliances and without appreciably affecting the rate at which heat is supplied or the aeration of the flame.

14. Accuracy of the "Momentum Relationship"

The examples given will probably serve well enough to show how almost any problem involving the entrainment of air can be solved with a degree of accuracy corresponding to the accuracy of the general rule that the momentum of the gas jet bears a constant ratio to the momentum of the primary mixture. The accuracy of this rule is best determined by examining the variations of the "burner constant k", when pressure, size of orifice and density of the gas are changed.

The rule requires that the burner constant and the ratio of the volume of primary air to the volume of gas do not change with changes of pressure. Obviously this is not true at very low pressures, for the "air:gas ratio" falls to zero as the pressure approaches zero. When the pressure is increas from zero, "k" approaches a nearly constant value, which is well maintained throughout nearly all the common range of pressures of domestic gas supplies (about 3 - 12 inches of water column).

At very high pressures the value of "k" falls off again. The pressure range within which "k" is satisfactorily constant depends to some extent on the burner and to some extent on the density of the gas. For burners with unusually large port area and small throats, "k" increases somewhat with pressure within the usual range of service conditions. For burners with relatively small port areas and large throats "k" decreases with pressure. This reversal is more marked with a gas of low density than with a heavy gas; in other words, the flat maximum of the curve is shorter. Burners with the form of injecting tube shown in Figure 2 tend to show an increasing value of "k" up to about six inches of water column.

Within the usual range of pressures, more important deviations from the rule that "k" is independent of pressure occur as a result of the heating of the burner than because of the construction of the burner itself. This effect of increased temperature always diminishes "k", of course, and it may cause "k" either to increase or to decrease with increased pressure, depending upon whether the burner is hottest at high or at low gas rates.

The value of "k" varies with changes in the size of the orifice in very much the same way that it does with changes in pressure, i.e., "k" may increase as the size of the orifice is increased for one combination of burner and fuel gas, and may decrease for another. With a gas of very low specific gravity, "k" tends to increase as the size of the orifice is increased. The effect is reversed for gas of very high specific gravity, at any rate for burners with relatively large port areas and small throats. Burners with very small port areas and large throats show increasing values of "k", when the orifice is enlarged, with gases of all densities.

The values of "k" increase with increasing density of the gas, other conditions being constant. The effect of density is relatively less with large than with small orifices and with large throats and small ports than with relatively small throats.

All these general tendencies are in practice complicated by heating effects, by variations in the form as well as the size of the orifices, by the deflection of the gas jet from the center of the mixing tube by gravity, and probably by other causes not enumerated. The combined effects of all these factors cannot be accurately predetermined in general; they can only be ascertained for an individual appliance by observation. Hence, the formulas given in the preceding section can never be anything but approximate guides in planning or modifying a burner; but if their limitations are observed they may be very useful.

15. The Design of the Burner Head

The design of a burner should begin with the burner head. The shape and size of this part must be adapted to the space available or the area to be heated and to the distribution of heat desired. The ports must then be so arranged in the burner head that the flame at each port will receive an adequate supply of secondary air. Since excess secondary air carries away heat, efficiency can usually be improved by careful attention to the position of entry and the direction of flow of air with respect to each flame. Without doubt the best arrangement for secondary air, considering only efficiency and secondary combustion, would be to introduce the air in a thin sheath around each flame in just the amount necessary. Some excellent burners are constructed in this way. Each port for gas and primary air is at the end of a tube which is concentric with a hole in a casing or shield through which the secondary air must flow. However, such construction is relatively expensive and limits the number of ports per unit of area of the burner top. Nearly as good results may be obtained by admitting the secondary air through a slot to a row of ports and by many other arrangements, with and without means other than the shape of the main burner for directing the secondary air to where it will do the most good.

Many arrangements of this kind fail because it is difficult to get enough secondary air to flow through the passages provided for it, unless it is forced in from the outside or is "induced" by thermal convection of the products of combustion through a flue passage of considerable height. In some cases the jets of gas from the ports can be made to serve to a certain extent as injectors of secondary air. The familiar example of this is the top burner with a central opening for secondary air. If all the ports in a burner of this kind are drilled vertically, practically no air flows through the central opening when a utensil is above the burner; but if the ports around the center are drilled to direct the jets

inward at a considerable angle from the vertical, enough secondary air enters to be an important aid in combustion.

The arrangement of ports in more than two rows without access of secondary air between them is to be avoided particularly, because the oxygen is largely removed from the air by the outer rows of flames and the center row left with inadequate secondary air unless the general excess is very large.

Almost as much attention must be given to the escape of "products of combustion" as to the entry of secondary air. Such apparently trifling details as the direction of the bars of the grate above a "top burner" or the shape of the upper part of the glower of a radiant heater sometimes have a surprising effect upon the flow of air and other gases to and away from the flame.

The direction and smoothness of the passages within the burner, and the depth of the metal through which the port is drilled are very important because of the effect which these details have on the stability of the flame, particularly with respect to backfiring. It is apparent that if the velocity of the mixture through one port is only half that through the average, the lowest rate at which the burner can be operated without backfiring is about twice as high as it would be if all the ports were uniform. Several frequently occurring causes of unequal distribution of gas to the ports may be mentioned. In some burners the gas entering the burner head through the mixing tube flows past the nearest ports at a rather high velocity. To those familiar with hydraulics the effect is easily conveyed by the statement that the "velocity head" has not yet been converted into "pressure head". The result is perhaps best understood by considering that in the throat of the injector where velocity is highest the pressure is less than atmospheric, otherwise air would not flow in. As this velocity decreases in the widening passage of the burner, the pressure at right angles to the direction of the stream increases from below atmospheric to above. The second common cause of unequal pressure at the ports is the deflection of the main stream of gas against some of the ports, which causes larger flames than the average. This condition is less serious than the first, because a few flames larger than the average make much less difference in the operation of the burner than one undersized one. The third frequent cause of unequal flames is friction in the burner passages, which results in reducing the supply to distant ports and comes from making the passages too narrow. It gives the most trouble in long pipe burners such as those used on ironing machines.

An even greater source of trouble is irregular flow through an individual port, which may result from turbulence within the burner or from the fact that the gas flows into the port at an angle with its axis. The first effect is made

evident by a tendency for the height of an individual inner cone to vary irregularly; the second, in some cases at least, by a strong tendency for the cone to lift or blow off on one side.

Practically all burners of commercial types are affected to a large extent by these effects of irregular flow. Flow through a long tube removes these irregularities; and the thicker the metal through which a port is drilled the better, in general, is the performance of the burner. The decided benefit of raised ports results mainly from the fact that the drill holes are usually longer in such burners, although a better distribution of secondary air is also a factor. As an example of the effect of removing irregularities of flow it may be mentioned that no mixture of propane and air could be found which would backfire through a long tube 0.255 inch in diameter even when the velocity of the mixture was reduced to zero, but backfiring occurs with propane, under certain conditions, through ports made in an ordinary burner casting by a No.32 drill which has a diameter of 0.116 inch.

For comparison it may be mentioned that the cross-sectional areas of a No.32 drill, a No.20 drill, a No.1 drill, and the tube through which flashback would not occur have the approximate ratios 1:2:4:5, and that a given mixture of gas with primary air will backfire through a port made with a No.20 drill when supplied at a rate about five times that at which backfiring occurs with the No.32 drill.

The extraordinarily large effect of slight turbulence on backfiring may be understood if the phenomenon is observed in a glass tube about a centimeter in diameter. Contrary to the assumption frequently made, backfiring usually takes place when the average velocity of the mixture through the port is considerably greater than the velocity of propagation of flame through the mixture. The flame always starts down one side of the port; the rapid expansion of the gas in the flame then creates a local pressure which deflects the gas stream largely to the other side of the tube and reduces the velocity on the side along which the flame-front is leading. Any irregularity in flow which will give the flame an opportunity to start into one side of the port therefore results in its travel through the port.

16. The Number and Size of Ports

The number of ports to be drilled in a given burner head will usually be determined by the difficulty and cost of the machining operation. As a generalization it may be said that the more ports a burner has the better will be its characteristics, but beyond a certain number the advantage is small and not worth the extra cost of manufacture. When the number of ports has been determined their size should be chosen with a view to obtaining flames of the greatest possible stability under the probable conditions of use; i.e., the port should be made of such size that a maximum amount of primary air may be

used without backfiring at the lowest rate of flow of the most rapidly burning gas to be employed, and without lifting at the highest rate of flow of the slowest burning gas likely to be used.

The following general statements may be useful guides in the initial design of a burner, but the performance of the burner should be checked at the earliest opportunity, and the drilling of the ports altered, if necessary, in accordance with the principles discussed in this paper. For burners to be used with manufactured gas only, allow not less than one square inch of port area per 35,000 Btu per hour of maximum consumption and, if the ports are drilled, do not use larger than No.40 drills (area 0.0075 sq.in.)

For natural gas allow one square inch of port area per 10,000 Btu if possible. Do not use larger than No.30 drills (area 0.0130 sq.in.). For propane and butane allow one square inch of port area per 12,000 Btu, and do not use drills larger than No.32 (area 0.0106 sq.in.).

If slotted ports are used and the slots are far enough apart to prevent the combining of the secondary zones, do not make the widths of the slots greater than 0.07 inch for manufactured gas or 0.08 inch for natural gas, propane, etc. If slots are close together so that secondary combustion zones coalesce to form one large flame, the slots must not be more than about 0.035 inch and 0.045 inch in width for the two groups of gases.

The diameters and widths of ports suggested are chosen to avoid backfiring; the total areas, to avoid lifting or blowing from the ports. They are subject to considerable modification to correspond to various conditions of use. If gas is always burned at about the same rate, if the burner is always cool, if the ports are very carefully machined and the metal through which they are drilled is thick, and particularly if the appliance is of such a type that there is little or no advantage in the use of primary air in excess of that required to prevent the liberation of carbon, the size of the ports may be increased with advantage. On the other hand, burners which must be or are likely to be "turned down" at times, which become very hot in use, which have shallow ports, and which require high primary air for efficient or safe operation must have smaller ports than those specified. The total areas of ports are subject to considerable variation for the same reasons. Where very high air entrainment is necessary, particularly in radiant heaters with closely crowded ports, it may be an advantage to increase the port area specified and even to double it.

If a universal burner is to be made for use with all sorts of gases now used for public supply, it must obviously have the small ports necessary to prevent the backfiring of manufactured gas and the large total port area necessary to prevent the lifting of the natural gas flames. Hence, a

burner designed for universal service must have at least twice as many ports as one designed for only one gas, if it is to give equal efficiency and to have equal "factors of safety" with respect to the hazards of incomplete combustion, backfiring and lifting.

17. Modification of a Burner for Use with a Different Gas

One class of problems frequently encountered is the modification of an appliance which is regarded as satisfactory for use with one gas, to make it suitable for use with a gas of different character.

This problem is most readily attacked in two parts:

(1) Efficiency, completeness of combustion, access of secondary air, space available for combustion, etc., must be considered.

(2) The stability of the flame must be assured.

The first part of the problem is an extremely simple one if the second part does not complicate it. It is found to be very accurately true that any appliance which is supplied with two gases to produce heat at the same rate in Btu per hour, and in which the primary air constitutes the same fraction of the total required for complete combustion of each gas supplied, has the same efficiency under the two conditions, an that if combustion is complete in the one case it is complete in the other also.

Suppose, for example, that an appliance burns 40 cubic feet of 515 Btu gas per hour; that the gas requires for combustion 4.8 cu.ft. of air per cu.ft. of gas; that 2.4 cu.ft of this is supplied as primary air; that the thermal efficienc is seventy per cent; and that if the gas rate is increased to 44 cu.ft., combustion becomes incomplete. Suppose that we then burn propane which has a heating value of 2575 Btu per cu.ft. in the appliance at the rate of 8 cu.ft. per hour. Propane requires 24 volumes of air for complete combustion. Suppose 12 cu.ft. of air per cubic foot of propane is introduced as primary air. We can then say with considerable certainty that the appliance will have an efficiency of seventy per cent, that combustion will be complete, and that if the gas rate is increased to 8.8 cu.ft. per hour combustion will become incomplete.

When we try to burn propane at 8 cu.ft. per hour, however, we will probably first encounter difficulty in getting it to entrain the necessary 96 cu.ft. of primary air. We can comput from the "momentum relationship" the changes in orifice size and pressure necessary to accomplish this. Probably we will then encounter the second part of the problem, for the flames will blow from the ports. We can prevent this by reducing

the primary air, but that way leads to incomplete combustion and probably to loss of efficiency. We can also prevent the flames from blowing off by increasing the size or the number of ports or both, and this is the thing to do if possible. If for any reason it is impracticable to enlarge the port area sufficiently, we must reduce the primary air, and increase the secondary air or increase the combustion space or both, and accept the loss of efficiency.

If only one gas is to be burned with the modified appliance, changing the size of the ports will usually offer a method of adapting the appliance to the new conditions without sacrificing any of its merits; but if the appliance is to have a "universal" burner to take either manufactured or natural gas, the ports cannot be made very large because the manufactured gas will backfire. In this case, increasing the number of ports, and, if necessary, reducing their size slightly to prevent backfiring, offers the only alternative to increased combustion space and secondary air.

18. Summary

The following summary is intended to give the steps in the design of a burner in the approximate order in which they should be taken. The principal formulas likely to be of use to the designer are included.

1. Determine the general shape and size of the burner from the space available and the manner in which the heat is to be applied.

2. Determine the arrangement of ports and provide for the escape of products of combustion with a view to insuring a uniform flow of secondary air to and away from each port with as little excess as is needed.

3. Determine the number and size of ports, making the number as large as can be provided for without excessive cost, and choosing a size which will permit a maximum of primary air without danger of either backfiring or lifting. As a general rule, trouble from backfiring will be avoided with manufactured gas if ports are drilled with No. 40 drills or smaller. Propane and butane permit the use of No. 32 drills, natural gas the use of No. 30 drills. This rule is subject to modification because of the conditions of use of the burner. If it is always supplied with gas at a uniform high rate, if there is no advantage in using much primary air; and if the burner is but slightly heated during use, the size of the ports may be increased with advantage. Burners which require much primary air, which become very hot, and which are likely to be turned low, must have smaller ports. To avoid the lifting of the flames, burners for manufactured gas should have at least one square inch of port area per 35,000 Btu when gas is burned at the maximum rate. Burners for natural gas should have one square inch of port area per 10,000 Btu and burners

for propane and butane one square inch per 13,000 Btu. These figures are subject to modification for the same reasons as are those for the size of ports.

4. Design the burner head of liberal size and with deep metal, through which the ports are machined.

5. Design the passages of the burner without abrupt changes in size or direction so that the stream of gas and air will expand gradually and approach the ports at low and uniform velocity. Make the area of the burner throat equal to about 40 per cent of the port area, and other dimensions of the mixer approximately as shown in Figure 2.

6. Select tentatively, for each of as many sets of conditions as seem necessary to cover the range of conditions in which the appliance is to be used, an orifice of area $\underline{a}$, using the formula

$$q = 1300\, a \sqrt{\frac{h}{d}}$$

where $\underline{q}$ is the maximum desirable volume of gas in cu.ft. per hour, $\underline{h}$ is the maximum gas pressure in inches of water, and $\underline{d}$ is the specific gravity of the gas referred to air.

7. Assume the desired ratio of primary air to total air required for complete combustion from experience or from the discussion in this paper.

8. Assume a value for a burner constant $\underline{k}$, from experience with a burner of the same general form or from the discussion in this paper (in the absence of any previous knowledge "k" may be tentatively assumed equal to $0.8\sqrt{P}$, where P is the total area of the ports) and compute whether the burner tentatively planned will entrain the desired amount of primary air under each set of conditions assumed as representative of those to be met. Use the formula

$$\frac{Q}{q} = k \sqrt{\frac{d}{aD}}$$

or one of its modifications given in the discussion. $\underline{Q}$ is the volume of primary mixture which flows per unit time, $\underline{q}$ is the volume of gas which flows per unit time, D is the specific gravity, referred to air, of the primary mixture and $\underline{a}$ and $\underline{d}$ have the meanings stated in paragraph 6. The constant $\underline{k}$ is usually obtained by solving the same formula in which have been substituted values for the other symbols known from experience with a burner of similar form.

9. Having completed a model burner, determine by trial whether its performance is satisfactory within the range of air shutter adjustment with respect to (1) completeness of combustion at the maximum rate of heat supply with the gas

having the greatest requirement of "air for complete combustion", (2) backfiring with the most rapidly burning gas at minimum rate, and (3) lifting of the flames with the slowest burning gas at maximum rate.

10. Determine by trial the maximum primary air that will allow an ample factor of safety against unstable flames, and while using this high primary air place the burner or regulate secondary air to give as high efficiency as may be obtained while providing an ample factor of safety against incomplete combustion.

11. Select the orifice to be used with a particular gas supply by the aid of the formula given in paragraph 6, or a corresponding one for the type of orifice used if the orifice is known to give a result different from that of the formula. Then employ the formula stated in paragraph 8, and a value of the burner constant k determined by observation on the model under conditions as nearly as possible like those of service, and determine that the entrainment of primary air will be satisfactory within the range of adjustment of the air shutter. If the air required for complete combustion of the future supply of gas is not known, assume that 9 cubic feet of air will be needed per thousand Btu.