

# COMBUSTION SYMPOSIUM

Papers presented before the joint symposium of the Divisions of Gas and Fuel Chemistry and Petroleum Chemistry at the 76th Meeting of the American Chemical Society, Swampscott, Mass., September 10 to 14, 1928

## Introduction

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COMBUSTION is without exaggeration the most important reaction to the human race. All human and animal existence depends upon combustion as its source of energy. The first real progress man made in his ascent or descent from the anthropomorphic missing link depended upon his control of fire or combustion; and in many ways our further progress depends upon more intelligent and efficient control of combustion.

Originally used to create a flickering light and worshipped as the "Fire God," further experience and knowledge led to more efficient uses for combustion as a source of heat, and relatively recently as a source power in the internal-combustion engine. Although the flickering luminous flame has been known since long before "Hector was a pup," we are still studying these "simple" diffusion flames, and apparently the first adequate mathematical treatment is presented in this symposium. The "flicker" and temperature of, and radiation from, flames, as well as some unusual structures of Bunsen flames which may tend to reestablish the worship of the "Fire God," are also representative of further progress in our study of stationary flames.

Since Berthelot and LeChatelier discovered the detonation wave and developed a photographic method for studying the propagation of flame through explosive or inflammable mixtures, the study of flame propagation has been steadily increasing in popularity. Like most such intensive studies, "the more we work the more work we find to do." The five papers dealing with flame propagation not only indicate the relations existing between the rate of flame propagation, rate of chemical action, physical properties of the mixture and pressure propagation, but also raise new questions to be answered only by further work.

These studies of flame propagation are closely allied with the use of combustion as a direct source of power. Internal-combustion engines are used because of their high efficiency and convenience as the source of power for all kinds of transportation—vessels, submarines, railroads, mines, automobiles—but are absolutely essential only for airplanes or dirigibles. The lifting ability of a plane depends upon its velocity through the air, which in turn depends upon the power of the motor. Until the internal-combustion engine was available with its low weight per horsepower, the weight of the power plant always exceeded the lifting capacity of the plane. Just as the internal-combustion engine made possible the airplane, so is further development of the airplane dependent upon still lower weights per unit of power. The efficiency of present plane and propeller design is so high that there is little opportunity for improvement along these lines. But if the weight of the motor and fuel could be reduced, or its power proportionately increased, so much more "pay load" could be carried. The one practical way to reduce the weight of the motor or to increase its power and efficiency is to increase its compression ratio. This compression, or expansion, ratio is limited by that peculiar form of combustion known as engine knock or detonation. A large part of this symposium is devoted to papers on the mechanism of combustion and auto-ignition temperatures of fuels in an attempt to find the true cause of engine detonation, the importance of which can hardly be overemphasized.

The chairman wishes to thank the officers of the Divisions of Gas and Fuel Chemistry and Petroleum Chemistry and authors of the many excellent papers for the splendid cooperation without which this symposium would not be possible.

## Diffusion Flames

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In general, flames may be divided into two classes: flames of the Bunsen type in which the combustible gas and air are premixed before ignition occurs and flames in which the combustible gas and air meet coincidentally with the occurrence of combustion. To this second class of flames the authors have applied the term "diffusion flames."

An analysis of this type of flame has been made which has led to a theory of its mechanism. A mathematical presentation of the theory is given and also the results of an extensive experimental investigation of the deductions therefrom. As a consequence of this work considerable light is shed on the physical characteristics, the mechanism, and the general properties of this very common class of flames.

WHENEVER two gas streams, one a combustible gas and the other a gas capable of supporting combustion, impinge or meet under conditions such that combustion occurs, a surface of flame will be produced. It is to flames of this character as distinguished from flames produced in a mixture of oxygen and a combustible gas that we have given the name "diffusion flames." The flame of a match, of a candle, and of the familiar gas-jet burner are all of this type, and it will be readily appreciated that this class of flames is not uncommon.

Many investigations have been made on the Bunsen type flame; an adequate theory has been advanced to account for the shape and general properties of the characteristic Bunsen cone, and the mechanism of combustion in this case is fairly well understood. Diffusion flames, on the other hand, have

received but scant attention. A comprehensive search of the literature did not reveal a single attempt to account for the shapes and properties of diffusion flames, except in a general descriptive way.

A typical flame of the class with which we are concerned can be produced readily in the apparatus shown in Figure 1, the essential part of which consists of two concentric tubes. Combustible gas flows upward through the inner tube of radius  $L$ , and at the opening  $AA$  comes in contact with the air which flows through the outer tube of radius  $R$ . Any radial distance is represented by  $r$ , and  $y$  is any vertical distance measured from  $AA$ . The rate of flow of gas to that of air, as measured by flowmeters, is kept in the ratio  $L^2$  to  $R^2 - L^2$ , which means that the velocity of the gas is maintained the same as the velocity of the air. If the gas is ignited at  $AA$ , it will, under proper conditions, burn with a steady flame of definite shape.

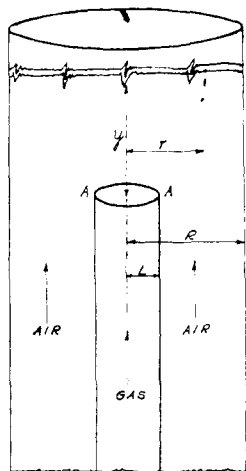


Figure 1—Diagram of Experimental Burner

Flames produced in this manner in cylindrical tubes are called cylindrical flames. Flat flames are produced when the cylindrical tubes are replaced by parallel plane surfaces. In this case the combustible gas flows between the two inner, and the air between the two outer, walls. If  $2L$  is the distance between the two outer walls, and if the velocities of gas and air are to be identical, the rate of flow of gas compared with that of air must have the ratio of  $L$  to  $R - L$ .

#### Proposed Theory

If the problem of determining the physical characteristics of these flames is to permit of mathematical treatment certain fundamental assumptions must be made. Let us therefore assume that (a) the velocity of the gas and air up the tube in the region of the flame is constant; (b) the coefficient of interdiffusion of the two gas streams is constant; (c) the interdiffusion is wholly radial; and (d) admixture of the two gas streams occurs by diffusion only.

At first these assumptions seem to be improbable. Thus, owing to the high temperature developed by the flame and the consequent expansion of the gases, there will certainly be large differences in velocity at different points on the vertical axis of the tube. On the other hand, owing to these temperature variations the coefficient of interdiffusion would be expected to vary. It is to be noted, however, that any increase in velocity due to rise in temperature tends to be counterbalanced by a corresponding increase in the diffusion in so far as its effect on the size and shape of the flame is concerned. Assumptions (a) and (b) when taken in conjunction may therefore be advanced as heuristic and possibly as legitimate. Assumption (c) will be valid only for fairly tall flames. For short flames the axial diffusion would play an important part, but the mathematical treatment remains essentially the same.

For the present let us confine ourselves to tall flames and neglect axial diffusion. Since we are concerned with steady flames and are thus forced to postulate stream-line flow, it is evident that the only combustion that can take place is due to the interdiffusion of oxygen and the combustible gas. Combustion is therefore considered to be confined to a surface, called the flame front, where oxygen and combustible gas meet to combine and form the neutral products of complete combustion. Experiment confirms this statement,

since in all flames of this type there is a very distinct flame front, the thickness of which in most cases is so small that it may be treated as a geometrical surface. With this fact in mind it is logical to define the flame front as "the locus of those points where the rate of diffusion of combustible gas outward and the rate of diffusion of oxygen inward have the ratio required by the stoichiometrical equation for complete combustion of the combustible gas."

Having defined the problem, we may now proceed to its solution, and for this purpose the following symbols will be employed:

- $v$  = velocity of gas or air (assumed constant)
- $R$  = radius of outer tube
- $L$  = radius of inner tube
- $r$  = radial distance
- $x$  = radial distance of flame front
- $y$  = vertical distance above orifice of inner tube
- $k$  = coefficient of interdiffusion
- $C_1$  = initial concentration (partial pressure) of combustible gas
- $C_2$  = initial concentration (partial pressure) of oxygen
- $C$  = concentration of combustible gas at any point
- $C_0 = C_1 + C_2/i$
- $t$  = time
- $i$  = number of molecules of oxygen which combine with one molecule of combustible gas to effect complete combustion

In the mathematical analysis we have to solve the equations of diffusion for the gas and for the oxygen, subject to certain boundary and initial conditions, and also subject to the condition that at the flame front the molecules of gas and oxygen combine to form neutral products of combustion. But the flame front is not yet determined, so that one of the boundary conditions is indeterminate. This difficulty, however, can be easily overcome by the following simple device: Since the oxygen combines with the gas to form a neutral product, for purposes of mathematical analysis the oxygen may be regarded as negative combustible gas. Thus a concentration  $C_2$  of oxygen will be equivalent to a concentration  $-C_2/i$  of gas. In this case, therefore, we have positive gas diffusing into negative gas and the flame front will be the surface where the concentration of combustible gas is zero.

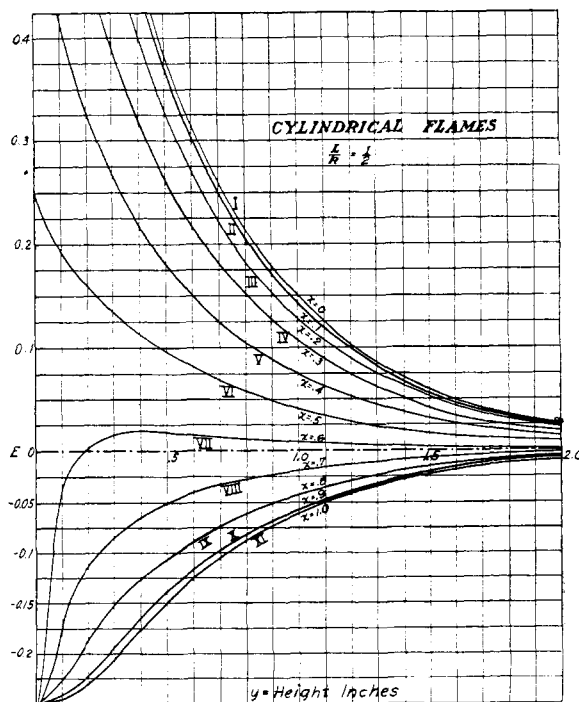


Figure 2—Curves Showing Relation between  $E$  and  $y$  when  $L/R = \frac{1}{2}$

Our problem thus reduces to one of diffusion of a single gas having a certain initial distribution and subject to certain boundary conditions.

The equation of diffusion is

$$\frac{\delta C}{\delta t} = k \left( \frac{\delta^2 C}{\delta r^2} + \frac{1}{r} \frac{\delta C}{\delta r} \right)$$

but since we have assumed a constant velocity  $v$ ,  $y = vt$ .

Hence

$$\frac{\delta C}{\delta y} = \frac{k}{v} \left( \frac{\delta^2 C}{\delta r^2} + \frac{1}{r} \frac{\delta C}{\delta r} \right) \quad (1)$$

The initial concentration is

$$C = C_1 \text{ from } r = 0 \text{ to } r = L \text{ at } y = 0$$

$$C = -C_2/i \text{ from } r = L \text{ to } r = R \text{ at } y = 0$$

and the boundary conditions are  $\delta C/\delta r = 0$  when  $r = 0$  and when  $r = R$ . The solution of equation (1) which satisfies the given conditions is

$$C = C_0 \frac{L^2}{R^2} - \frac{C_2}{i} + \frac{2LC_0}{R^2} \sum_{\mu} \frac{J_1(\mu L)}{(J_0(\mu R))^2} \frac{J_0(\mu r)}{e^{-\frac{k\mu^2 y}{v}}} \quad (2)$$

where  $\mu$  assumes the value of all the positive roots of the equation,  $J_1(\mu R) = 0$ , and  $J_1$  and  $J_0$  are Bessel's functions of the first kind.

The equation for the flame front is obtained by putting  $C = 0$  and  $r = x$ , whence

$$\sum_{\mu} \frac{J_1(\mu L)}{(J_0(\mu R))^2} e^{-\frac{k\mu^2 y}{v}} = \frac{R^2 C_2}{2LiC_0} - \frac{L}{2} = E \text{ (say)} \quad (3)$$

The shape of the flame front will be given by the values of  $x$  and  $y$  which satisfy this equation.

The height of the flame is given by the value of  $y$  in equation (3) when (a)  $x = R$  for an underventilated flame, and (b)  $x = 0$  for an overventilated flame.

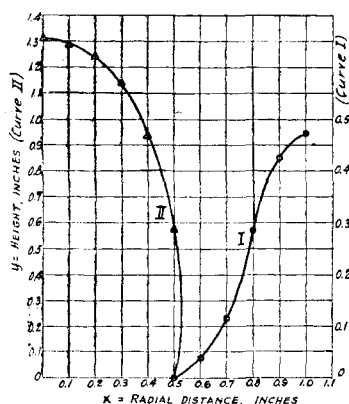


Figure 3—Curve I, Underventilated Cylindrical Flame; Curve II, Overventilated Cylindrical Flame

2. In drawing these curves it was assumed that

$$L = \frac{1}{2} \text{ inch}$$

$$R = 1 \text{ inch}$$

$$k = 0.0763 \text{ square inch per second}$$

$$v = 0.610 \text{ inch per second which corresponds to a flow of 1 cubic foot per hour in the inner tube}$$

The value adopted for  $k$  is the diffusivity of methane, which was the gas generally used in our experimental work. The method of employing the curves of Figure 2 may be best illustrated by means of an example:

Suppose that the combustible gas employed is methane, the concentration of which we take to be unity, and that air is used in the outer tube; then

$$C_1 = 1$$

$$C_2 = 0.21$$

$$C_0 = C_1 + C_2/i = 1.105$$

$$i = 2$$

since  $\text{CH}_4 + 2\text{O}_2 = \text{CO}_2 + 2\text{H}_2\text{O}$  is the stoichiometrical equation. From equation (3)

$$E = R^2 C_2 / 2LiC_0 - L/2 = -0.155$$

From the curves in Figure 2 corresponding to this value of  $E$ , we find a set of values of  $x$  and  $y$ .

$$\begin{array}{ccccc} x = 1.0 & 0.9 & 0.8 & 0.7 & 0.6 \\ y = 0.47 & 0.43 & 0.29 & 0.11 & 0.04 \end{array}$$

If pure oxygen were used instead of air, then  $C_2 = 1$ , and  $C_0 = C_1 + C_2/2 = 1.5$ , and  $E = 0.083$ .

From Figure 2 we find the values of  $x$  and  $y$  for this value of  $E$  thus:

$$\begin{array}{ccccc} x = 0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 \\ y = 1.31 & 1.29 & 1.24 & 1.14 & 0.94 & 0.58 \end{array}$$

The results of the above calculations are shown graphically in Figure 3. Curve I shows the shape of the underventilated flame where the outer tube contained air, and curve II, that of the overventilated flame where oxygen was substituted for air. The vertical scale of curve I is double that of curve II. Our experimental results will subsequently be compared with these theoretical curves.

### Flat Flames

Using the same notation as before and assuming that the combustible gas flows through a duct bounded by two parallel walls whose distance apart is  $2L$ , and that the air flows in an outer duct whose width is  $2R$ , we have the equation of diffusion

$$\frac{\delta C}{\delta y} = \frac{k}{v} \frac{\delta^2 C}{\delta r^2}$$

The solution of this equation fitting the boundary conditions is

$$C = C_0 \frac{L}{R} - \frac{C_2}{i} + \frac{2C_0}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin \frac{n\pi L}{R} \cos \frac{n\pi r}{R} e^{-\frac{k n^2 \pi^2 y}{v R^2}} \quad (4)$$

Putting  $C = 0$  and  $r = x$ , we have the equation for the flame front

$$\sum_{n=1}^{\infty} \frac{1}{n} \sin \frac{n\pi L}{R} \cos \frac{n\pi x}{R} e^{-\frac{k n^2 \pi^2 y}{v R^2}} = \frac{\pi}{2} \left\{ \frac{C_2}{iC_0} - \frac{L}{R} \right\} = E \quad (5)$$

Again, let us consider a particular case. Suppose

$$\begin{array}{ll} R = 1 \text{ inch} & C_2 = 0.21 \\ L = \frac{1}{2} \text{ inch} & i = 2 \\ k = 0.0763 \text{ square inch per second} & v = 1.33 \text{ inch per second} \\ C_1 = 1 & \end{array}$$

This value of  $v$  is taken simply for convenience of computation since, as will be shown later, the vertical dimension of any flame is directly proportional to  $v$ , and it is thus of little significance what particular value we assign to  $v$ .

$$\text{Now } E = \frac{\pi}{2} \left( \frac{C_2}{iC_0} - \frac{L}{R} \right) = -0.113$$

If enriched air containing 50 per cent oxygen is substituted for ordinary air, then  $C_2 = 0.5$  and  $E = 0.052$ . Figure 4 shows a set of curves for flat flames corresponding to those given in Figure 2 for cylindrical flames. If from these curves we read off the values of  $x$  and  $y$  corresponding to the above values for  $E$ , we find, when  $E = -0.113$ ,

$$\begin{array}{ccccccccc} x = 1.0 & 0.9 & 0.8 & 0.7 & 0.6 & 0.5 & 0.4 & 0.3 \\ y = 1.50 & 1.45 & 1.27 & 0.98 & 0.57 & 0.32 & 0.17 & 0.05 \end{array}$$

and when  $E = 0.052$

$$\begin{array}{ccccccc} x = 0 & 0.1 & 0.2 & 0.3 & 0.4 \\ y = 2.32 & 2.24 & 2.07 \text{ and } 0.02 & 1.76 \text{ and } 0.13 & 0.96 \text{ and } 0.80 \end{array}$$



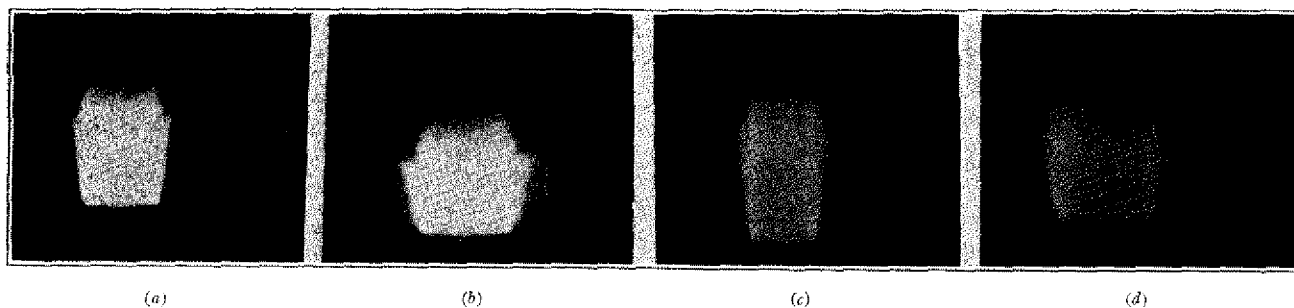
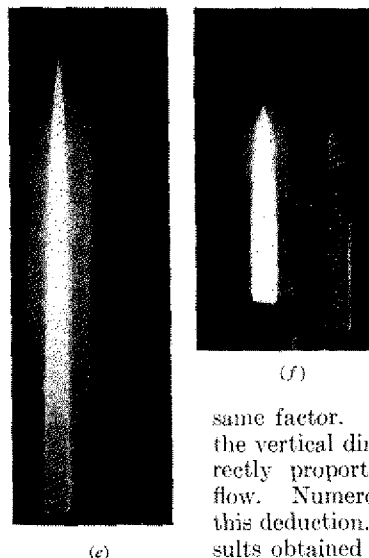


Figure 6—Photographs of Some Typical Diffusion Flames



The agreement is seen to be good. Similarly, photographs of under-ventilated flames indicate that the substitution of nitrogen causes an elongation of the flame in all cases.

**EFFECT OF VARIATION IN FLOW**—In equation (3) if  $v$  is multiplied by a factor,  $M$ , then the equation remains unaltered if  $y$  is multiplied by the same factor. It follows, therefore, that the vertical dimensions of a flame are directly proportional to the velocity of flow. Numerous experiments confirm this deduction. We quote one set of results obtained for overventilated flames. (Table III) Similar results could readily be given for underventilated flames.

Table III

AIR Cu. ft.	METHANE Cu. ft.	HEIGHT OF FLAME ( $h$ ) Inches	HEIGHT OF FLAME CU. FT. CH <sub>4</sub>
7.9	0.38	1.23	4.56
13.5	0.75	3.37	4.50
18.0	1.00	4.47	4.47
23.8	1.32	5.82	4.40
29.5	1.64	7.25	4.42
37.1	2.06	9.00	4.36
41.1	2.28	9.90	4.32

The ratio of the height of the flame to the velocity of flow is seen to be practically constant.

**EFFECT OF A CHANGE IN  $i$**  (where  $i$  is the number of moles of oxygen combining with one mole of combustible gas)—From equation (3) it is evident that an increase in  $i$  results in a decrease in the value of  $E$ , and as we have seen above, a decrease in  $E$  will cause an outward displacement of the flame front. Hence an increase in the value of  $i$  will result in taller overventilated and shorter underventilated flames. Table IV contains the results of three experiments performed to prove this conclusion.

Table IV

EXPT.	$R$ Inch	$L$ Inch	$h$ Inches	AIR	CITY GAS	METH- ANE	ETH- ANE	$i$
1	$\frac{3}{8}$	$\frac{1}{4}$	1.44	6	2			1.05
2	$\frac{3}{8}$	$\frac{1}{4}$	0.87	6		2		2.0
3	$\frac{3}{8}$	$\frac{1}{4}$	0.62	6			2	3.5

It is seen that there is a progressive decrease in the height of the flame which was underventilated, with an increasing value of  $i$ . Here again it is possible to show that there is not only a qualitative but also a quantitative agreement of experiment with theory: the value of  $E$  in each case is calculated from equation (3), and by means of curve XI,

Figure 2, the theoretical height of the flame can be computed. Strictly speaking, the radius of the outer tube should have been exactly double the radius of the inner tube—i. e.,  $R$  should have been  $\frac{1}{2}$  inch instead of  $\frac{3}{8}$  inch, but the fact that the outer tube was a little too large does not affect the result very much.

The city gas had a heating value of approximately 530 B. t. u. per cubic feet, which gives a value of  $i$  approximately equal to 1.05. Table V contains the calculated and experimental heights of the flames in the three cases.

Table V

EXPT.	GAS	$i$	$E$	$h$ (calcd.) Inches	$h$ (exptl.) Inches
1	City gas	1.05	-0.083	1.66	1.44
2	Methane	2.0	-0.155	0.93	0.87
3	Ethane	3.5	-0.194	0.67	0.62

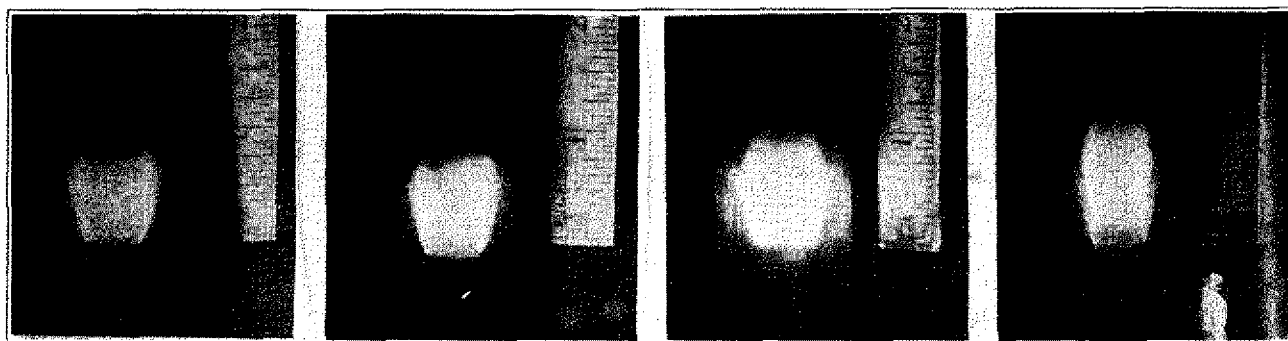
The discrepancy between the calculated and experimental values in this table is to be attributed to the variations in diffusion coefficient of the three gases. This is especially true of the city gas, which contained a large per cent of hydrogen, tending to shorten the flame.

**EFFECT OF VARIATION IN PRESSURE**—Since the coefficient of diffusion of a gas is inversely proportional to the pressure, and since  $v$  is also inversely proportional to the pressure provided the total flow measured under standard conditions is kept constant, it is obvious that equation (3) will be unaffected by a change in pressure. The height of a flame would therefore be independent of pressure if all the other factors are kept constant. This is borne out by experiment.

In Figure 7 (a) and (b),  $R = \frac{1}{2}$  inch,  $L = \frac{3}{16}$  inch, air = 4 cubic feet per hour, and  $\text{CH}_4 = 2$  cubic feet per hour, the gases being measured under standard conditions. However, the pressure employed for 7 (a) was 1 atmosphere while that of 7 (b) was 1.5 atmospheres. The size and shape of these two flames by careful measurement are practically identical.

**EFFECT OF PREHEATING GAS AND AIR**—The effect of increased velocity due to the heat developed in the flame has been assumed to be offset by a corresponding increase in the coefficient of diffusion (see theoretical assumptions). If this were strictly true, then it would be logical to assume that preheating the gas and air should increase both the velocity of flow and the coefficient of diffusion, but in such a way that the effect of the one would neutralize that of the other with the result that the flame dimensions would not be altered.

Several experiments were performed in which an electric furnace about 14 inches long was placed around the outer tube of Figure 1. In this way the gases passing through the concentric tubes were preheated. The results obtained are shown in Figure 7 (c) and (d) which should be compared with Figure 7 (a). Table VI presents the data. The temperatures shown are those recorded by a thermocouple placed alongside of the outer tube in the furnace. The actual temperature of the gases was of course considerably lower.



(a) Atmospheric pressure

(b) Pressure, 3/2 atmospheres

(c) Preheat at 510° C.

(d) Preheat at 370° C.

Figure 7—Photographs of Flames Showing Effect of Pressure and Preheat

Table VI

FIGURE	R	L	FLAME HEIGHT	AIR	METHANE	TEMPER- ATURE
	Inch	Inch	Inch	Cu. ft./hr.	Cu. ft./hr.	° C.
7 (a)	1/2	3/16	0.78	4	2	20
7 (c)	1/2	3/16	0.69	4	2	370
7 (d)	1/2	3/16	0.70	4	2	510

It would thus appear that preheating may have some slight effect on the height of the flame, but more experiments will have to be performed to determine accurately the magnitude of this effect.

**EFFECT OF ADDITION OF PRIMARY OXYGEN TO COMBUSTIBLE GAS**—Substitution of oxygen for part of the combustible gas in the inner tube will decrease the value of  $C_1$  and of  $E$  in equation (3); the flame front will be displaced inward and the effect will be similar to the case where an inert gas is added. We have, however, to distinguish two cases: (a) where the addition of oxygen is so slight that combustion is confined to the flame front; (b) where sufficient oxygen is added for combustion to take place in the gas stream with the consequent formation of a Bunsen cone. In the second case the shape and size of the flame will not conform to equation (3).

That the flame front is displaced inward by the addition of oxygen to the combustible gas was confirmed by experiment.

**EFFECT OF VARIATION OF WIDTH OF DUCTS IN CASE OF FLAT FLAMES**—Equation (5) gives the shape of the flame front of a flat flame. If in this equation  $R$  and  $L$  are multiplied by the common factor  $M$ , and the gas flows are kept constant, then the velocity  $v$  will be reduced to  $v/M$ , and  $x$  and  $y$  will both have to be multiplied by  $M$  to keep the equation unaltered. From this it follows that the height of the flame will be increased  $M$  times. It will be recalled that in cylindrical flames a variation in the dimensions of the tubes had no effect on the height of the flame so long as the flow remained constant. Except for this difference between flat and cylindrical flames, the previous discussions concerning the influence of temperature, pressure, addition of inert gas, etc., on cylindrical flames also hold good for flat flames.

Experiments were performed on flat methane flames, and the height of a particular flame was found to be 0.9 inch. When the size of the ducts was doubled the height of the flame as measured on the photograph was 1.6 inches. The photographs, however, were very indistinct, so that accurate measurement was impossible. The above result should therefore be regarded as a qualitative proof of the theoretical deduction that the height of a flat flame is directly proportional to the width of the ducts.

The experimental evidence produced above gives us confidence that our assumptions concerning the mechanism of diffusion flames are fundamentally correct, since all the deductions made from the theory have been verified by experiment. There still remains, however, a very potent method of testing the theory—namely, the chemical analysis of the products of combustion at different points in the flame.

#### Chemical Analysis of Gases in Diffusion Flames

In calculating the size and shape of any flame it is necessary to know the coefficient of diffusion of the combustible gas, but this coefficient as measured at atmospheric temperatures does not give proper results when applied in these flame calculations. It is therefore necessary to find the coefficient of diffusion which applies to flames. This was done in the case of methane by assuming a value for the coefficient which gave the best agreement with a particular experiment, and the value thus found was used for all further calculations on methane flames.

It is also possible, however, to use a different method for determining the coefficient of diffusion. By careful chemical analysis the constitution of the gas at different points along the axis of the concentric tubes can be determined and curves drawn showing the content of carbon dioxide, nitrogen, etc., against height. A value of the coefficient of diffusion is now selected which, when employed in the theoretical calculation of the same curves of composition *vs.* distance along the  $y$  axis (Figure 1), will make the theoretical and experimental

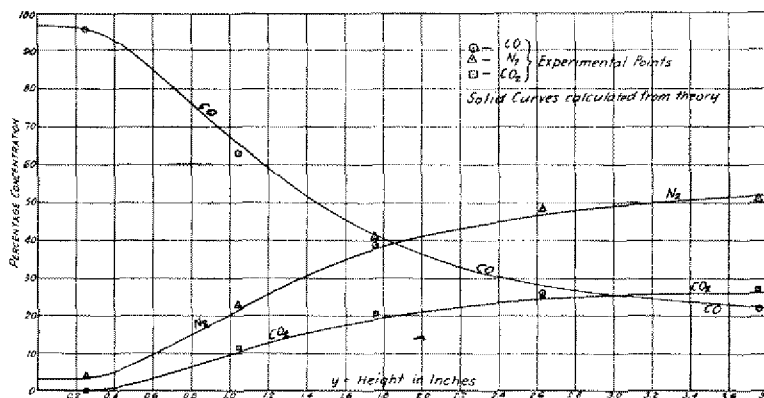


Figure 8—Curves Showing Concentrations of Carbon Monoxide, Nitrogen, and Carbon Dioxide on Axis of a Cylindrical Carbon Monoxide Flame

curves agree as closely as possible. The value of the coefficient so determined is now adopted as applying to the combustible gas in question.

The remarkable agreement of the size and shape of flames as calculated, employing a diffusion coefficient based on chem-

ical analysis in the manner just described, with the photographic measurements of all flames from the particular gas, affords strong support to our theory of diffusion flames. An illustration of this procedure for the case of carbon monoxide flames is given by the following series of experiments.

Flow of carbon monoxide = 4 cubic feet per hour  
 Flow of air = 5.55 cubic feet per hour  
 $R = 0.631$  inch  
 $L = 0.408$  inch  
 $L/R = 0.645$   
 The carbon monoxide contained 3.2 per cent nitrogen.

A small water-cooled sampling tube was introduced vertically into the flame and small samples of gas were withdrawn from different points on the axis of the tubes. The samples were taken at such a rate that the shape of the flame and the conditions of flow were not affected. Duplicate determinations were made in every case. The results of the analysis are given in Table VII.

Table VII

$y$ Inches	N <sub>2</sub> Per cent	CO <sub>2</sub> Per cent	CO Per cent	O <sub>2</sub> Per cent
0.25	3.8	0.0	95.8	0.4
1.04	23.0	11.2	62.8	0.2
1.75	41.0	20.3	38.6	0.2
2.63	48.4	25.1	25.6	0.2
3.75	50.9	26.9	21.9	0.0

In Figure 8 these results are shown graphically, together with the curves which were calculated theoretically on the assumption that the coefficient of diffusion for CO = 0.104 square inch per second. The agreement between the theoretical curves and the experimental points is evident.

The method of calculating the concentrations of the various constituents yielding the theoretical curves shown on Figure 8, while complicated and laborious, is sufficiently straightforward to require no detailed description. The procedure adopted was to consider the interdiffusion of the two gases to take place as though no flame were present. The mixture of gas so calculated for any given point was then assumed to react and the products thus obtained gave the final calcu-

lated analysis at the point in question. From chemical analysis the value of the coefficient of diffusion of carbon monoxide was calculated to be 0.104 square inch per second according to the procedure described above. This value was used to determine the theoretical heights of a number of carbon monoxide flames. In Table VIII the data concerning these flames together with their measured and calculated heights are given.

Table VIII

$R$ Inch	$L$ Inch	AIR Cu. ft./hr.	CARBON MONOXIDE Cu. ft./hr.	FLAME HEIGHT Experimental Inches	Theoretical Inches
0.63	0.42	4.2	3	0.92	0.94
0.63	0.42	8.0	6	1.75	1.75
0.63	0.42	3.25	3.75	1.02	1.02
0.63	0.42	5.55	6.25	1.75	1.76

In the last two experiments the flame was "inverted"—i. e., air was passed up the inner tube and carbon monoxide up the outer tube. The agreement between the experimental and calculated heights of these carbon monoxide flames needs no further comment.

### Conclusion

The theory of diffusion flames proposed herein shows such good agreement with the experimental facts that we feel justified in the hope that its adoption, in essentials at least, may lead to a better understanding of, and further contributions concerning, this very common and interesting class of flames. The authors feel that a more fundamental investigation of the phenomena described here on the basis of the kinetics of the chemical reactions involved might yield both interesting and profitable results.

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## Measurement of the Temperatures of Stationary Flames<sup>1</sup>

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The concept of temperature as applied to flames is discussed. A number of proposed methods for measuring the temperatures of flames are critically reviewed and the optical method of Kurlbaum-Fery is described and examined in detail. This method depends upon comparing the brightness temperature of a continuous radiator with the brightness of the radiation from the flame colored with an alkali-metal vapor at a given spectral line. From a consideration of the laws of radiation it is shown that the true flame temperature is equal to the brightness temperature of the comparison radiator, as read with an optical pyrometer, when the spectral line is just reversed as seen in a spectrometer.

Curves representing flame temperature as a function of air-gas ratio as measured by the line-reversal method are given for Pittsburgh natural gas, methane, propane, and carbon monoxide. These results are compared with measurements depending on the flame gases heating a

solid radiator contained in the flame and with the calculated results for the maximum temperature attainable at complete combustion.

AN INVESTIGATION of the temperature of stationary flames is being carried on at the Pittsburgh Experiment Station of the U. S. Bureau of Mines in connection with studies of flame propagation. Experiments are being made with stationary flames preliminary to measurements on flames produced by coal-mine explosives. Although Kurlbaum<sup>2</sup> in 1902 described a method for the measurement of the temperature of carbon-containing flames such as the candle, illuminating gas, and acetylene flames, nevertheless very few measurements of the temperatures of stationary flames are recorded in the literature. Recourse is taken to the calculated flame temperature, utilizing the  $\Delta H$  of the reaction, the specific heats of the products, and the degrees of dissociation of carbon dioxide and water. Owing to our lack of knowledge of the true specific heats, especially

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<sup>2</sup> *Physik. Z.*, **3**, 187, 332 (1902).