PROBLEMS OF STATIONARY FLAMES[1]

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I. INTRODUCTION

It is the purpose of this paper to present, semiquantitatively, a number of the problems involved in the measurement of flame speeds by burner methods, and some fundamental problems connected with the utilization of stationary flames by means of burners of several kinds. Since the burner is the control device by means of which the flame is made to function, the problems and uses of stationary flames are bound up inextricably with it. Of the various factors to be considered in the manipulation of stationary flames, it is becoming increasingly apparent that flame speed plays the dominant rôle and that it usually appears as the determining factor in the behavior of the flame.

It is unfortunate that burner methods of measuring flame speeds appear to be reliable within only a limited range of operating conditions. The methods are relatively simple, and within their limitations the results apply directly to a multitude of problems involving flames and burners. Some of these problems are presented very briefly, merely for illustration and without any attempt at exhaustive treatment.

II. FLAME SPEEDS BY BURNER METHODS

A. Brief review of methods of measurement and computation

When measurements of flame speed were first undertaken by burner methods, Bunsen (3) assumed that the downward velocity of the flame front just exceeded the upward velocity of the gas mixture at the moment when the flame flashed back down the burner tube. Obviously this could be true only if the velocity were uniform across the stream of gas mixture.

Gouy (7) at first considered the flame speed to be equal to the product of the velocity of the gas mixture and the sine of the angle which the side of the flame cone made with its axis. Then, finding that the surface formed by the flame front did not approximate sufficiently to a true cone

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(see figure 1) and that the result obtained depended upon what part of the flame front he used when he measured the angle, he eliminated the angle from consideration by setting the velocity of the flame equal to the volumetric rate of flow of the mixture divided by the area of the flame surface. This involves the concept of flame speed as simply the rate of transformation of the mixture, without the necessity of considering the velocity of the gas mixture and its direction of flow. The two concepts would yield identical results if the flame surface were a geometrical cone with the burner port for a base.

Gouy determined the area of the flame surface from measurements of the image of the flame projected on a screen. Considering the figure as a surface of revolution, he obtained the area by integration.

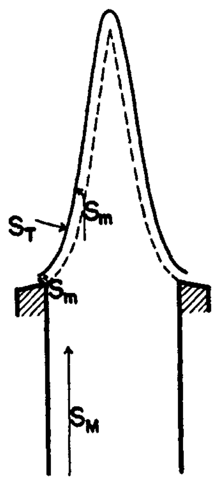

FIG. 1. Shape of typical flame surface

Michelson (8) also measured the volumetric rate of flow of the mixture and determined the actual area of the "cone" by treating measurements of enlarged photographs in the same way that Gouy had done.

Ubbelohde and Koelliker (15) concluded that the rounded tip and the curved base of the flame surface represented deviations from what they termed the "normal" flame velocity, so they measured the angle made by the "straight" portion of the flame surface with its axis, and computed the result as Gouy had done originally.

Stevens (13) was unable to obtain results with the burner which were in satisfactory agreement with the results he obtained with the "bubble" when he determined the area of a flame surface as Gouy, Michelson, or Ubbelohde had done. He recognized, as did Ubbelohde, that the approximately conical flame surface was the resultant of several components, one of which was a mixture velocity which varied from practically zero at the walls of the burner tube to a maximum at the center. Stevens, therefore, made use of only that part of the flame surface which resulted from the portion of gas mixture whose actual linear velocity was equal to the mean velocity over the cross section of the stream. He constructed on the photograph of a flame a triangle having as its base the diameter of the burner port and its sides parallel to the tangents to the flame surface at the part where the velocity of the mixture equaled the mean velocity. Considering this triangle as a section through the axis of a cone, the area of the cone was easily calculated without integration from the measured altitude and base, and values obtained from it for the velocity of the

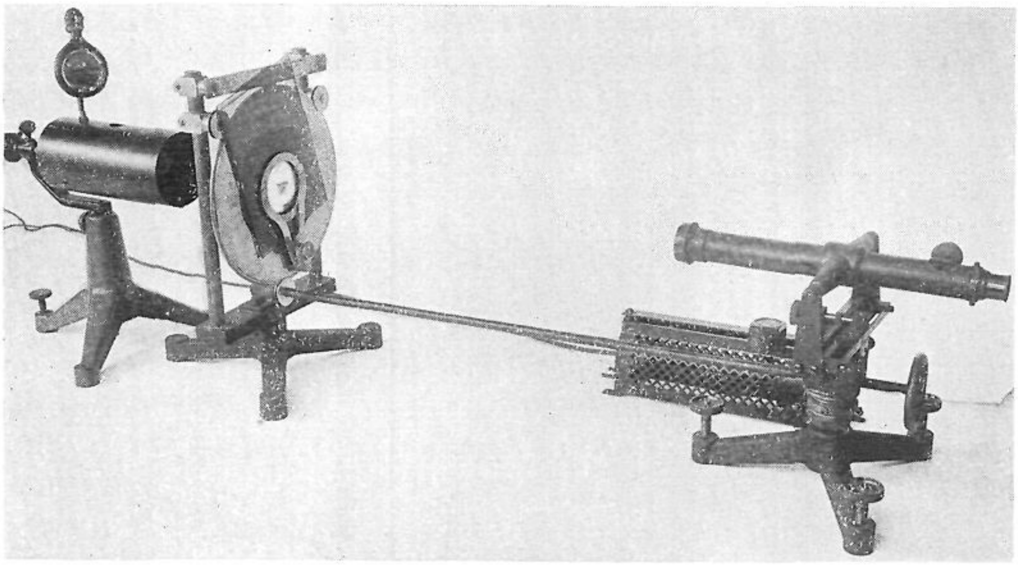

FIG. 2. Goniometer and reading telescope for measuring the angle between the two sides of the flame surface

flame front relative to mixtures of carbon monoxide and oxygen agreed with those obtained with the bubble so closely that the two methods, for many purposes, could be used interchangeably.

A number of other workers have adhered to Gouy's assumption, expressing flame speed in terms of volume of combustible mixture per second divided by the area of the flame surface. Of these, some use the actual integrated area of the flame surface and others use the area of a geometrical cone having the burner port as a base. The area of this geometrical cone has been arrived at in various ways, which have no bearing on what follows and will not be discussed here.

Since the area of the burner port divided by the lateral area of a geometrical cone of which the burner port forms the base is equal to sin α (where α is the angle between the side and the axis of the cone), the cone may also be defined by the area of the burner port and the angle α. All of these expressions would lead to the same numerical result were the flame surface a geometrical cone.

Instead of measuring and computing the area of the cone as Stevens had done, Smith and Pickering (12) chose to measure directly the angle α between the tangents and the axis, which, together with the burner port, is sufficient to define the cone. Instead of dividing the volumetric rate of flow of the combustible mixture by the area of the cone to obtain the flame speed, the rate was divided by the area of the burner port, thus obtaining the average linear velocity of flow of the mixture. The angle was measured, with the instrument shown in figure 2, at that part of the flame surface where the local velocity of flow of the mixture was equal to the average velocity, i.e., at a point $0.7r$ from the axis. The sine of the angle α, multiplied by the average velocity of the mixture (S_M), then gave the same numerical value for the flame speed (S_T) as did Stevens' method. The velocity of propagation of the flame front, in a direction normal to its surface and relative to the combustible mixture in which it moves, was then given by the equation $S_T = S_M \sin \alpha$.

B. The influence of several experimental factors on the numerical result for the flame speed

In any combustible mixture of gases of given composition, temperature, and pressure, there is a definite fixed value for the flame speed relative to the gas mixture. Consequently, if different values are obtained by different means, it must be concluded either that one of the supposedly fixed experimental conditions was not what it was supposed to be, or that the differences in the numerical result have been imposed by differences in the methods of measurement and computation, or by the apparatus.

On this basis the degree to which the numerical result is found to be independent of the method or apparatus for obtaining it may be used as a criterion of the extent to which that result approaches the supposedly correct definite fixed value assumed above to exist.

1. The numerical result is independent of the velocity of flow of the mixture, so long as the flow is laminar

With a given combustible mixture, a high velocity of flow from the port results in a long narrow flame and *vice versa*. The results presented in table 1 show that, all other conditions remaining substantially constant, the flame speed, S_T, is unaffected by changes in the mixture velocity which range from incipient flashing back to incipient blowing off of the flame.

Ubbelohde and Koelliker (15) studied the effect with mixtures of hydrogen and air. The maximum-speed mixtures showed the same flame speed until the mixture velocity reached 1300 cm. per second, which corresponds to a Reynolds number,[2] R, of over 2400. Since at the critical velocity $R = 2300$, the flow was probably no longer laminar but turbulent. This undoubtedly accounts for the increased value of the flame speed which they found at higher velocities.

2. The result depends upon the size of the port, especially if the area of the flame is used in obtaining the result

Several workers, including Ubbelohde and Koelliker (15), have concluded that burners of different sizes yield different results. Ubbelohde and Hofsäss (14) state that the error is larger with small burners and both agree that it tends to disappear as the composition of the mixture approaches that for maximum flame speed. Corsiglia (4), however, states that different sizes of burners yield the same result within the limit of experimental error. Smith and Pickering (12), for comparison, computed the flame speed from measurements of twelve flames by the method of Corsiglia as well as by their own.

TABLE 1

Effect on S_T of changing the velocity of the same mixture

GAS IN MIXTURE	VELOCITY OF MIXTURE S_M	FLAME SPEED $S_T = S_M \sin \alpha$
	(A) 9.60-mm. burner. Propane-air	
per cent	*cm. per second*	*cm. per second*
4.76	64.4	33.9
4.69	87.2	34.5
4.59	111.7	33.9
4.54	131.2	33.5
4.41	155.9	34.3
4.38	178.4	32.7
	(B) 2.75-mm. burner. City gas-air	
17.55	221.7	46.3
17.56	209.4	47.2
17.48	193.3	47.2
17.47	171.3	46.0
17.57	150.4	46.6
17.53	128.8	47.9

[2] $$R = \frac{DVd}{\mu}$$

where D = diameter of burner tube expressed in centimeters, V = velocity of fluid in centimeters per second, d = density of fluid in grams per cubic centimeter, and μ = viscosity of fluid in C.G.S. units.

Figure 3 shows curves representing the flame speed in each of three mixtures. Set A contained 62 per cent of the air required for complete combustion of the gas, set B 90 per cent (maximum S_T), and set C 103 per cent. Each mixture was used with four burners having internal diameters of 2.75, 4.45, 6.50, and 9.60 mm., respectively. Within each set the value

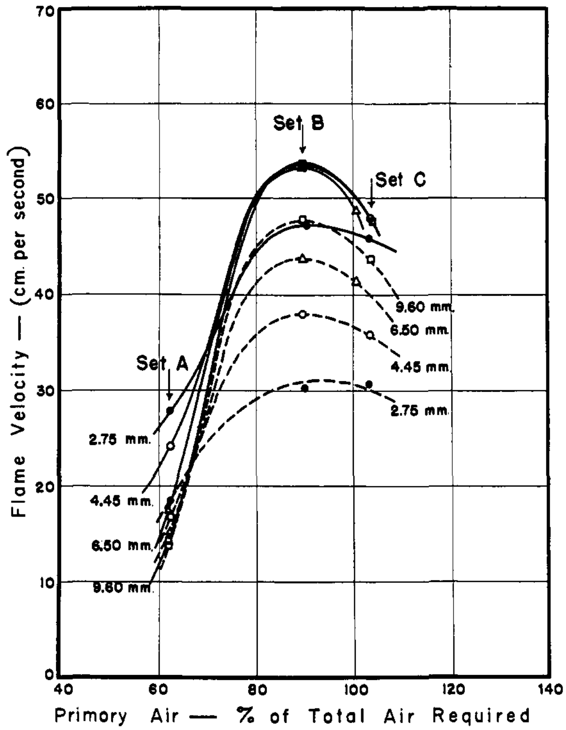

FIG. 3. Flame-speed curves. Composition, temperature, pressure, and S_M constant within each set. The solid curves result from measurements of the angle. The dotted curves result from measurements of the area of the flame surface by the method of Corsiglia.

of S_M, as well as the temperature and composition of the mixture, was kept constant as the size of the port was changed.

The solid curves result from measurements of the angle by the method of Smith and Pickering (12). With the maximum-speed mixture, the same result is obtained on the three larger burners, within the limit of experimental error. The 2.75-mm. burner is about 11 per cent lower. In the other mixtures, especially in set A with the low primary air, the results with the different burners are widely divergent. The broken curves result from measurements of the area of the flame surface, on the same photographs, by the method of Corsiglia (4). The results from the different burners are widely divergent in the maximum-speed mixture, but agree very well at about 67 per cent of the total air required. The reasons for such divergent results will be apparent from the next two figures.

Figure 4 shows the four flames of each set and the relative sizes and shapes which result when S_M and composition are kept constant within each set.

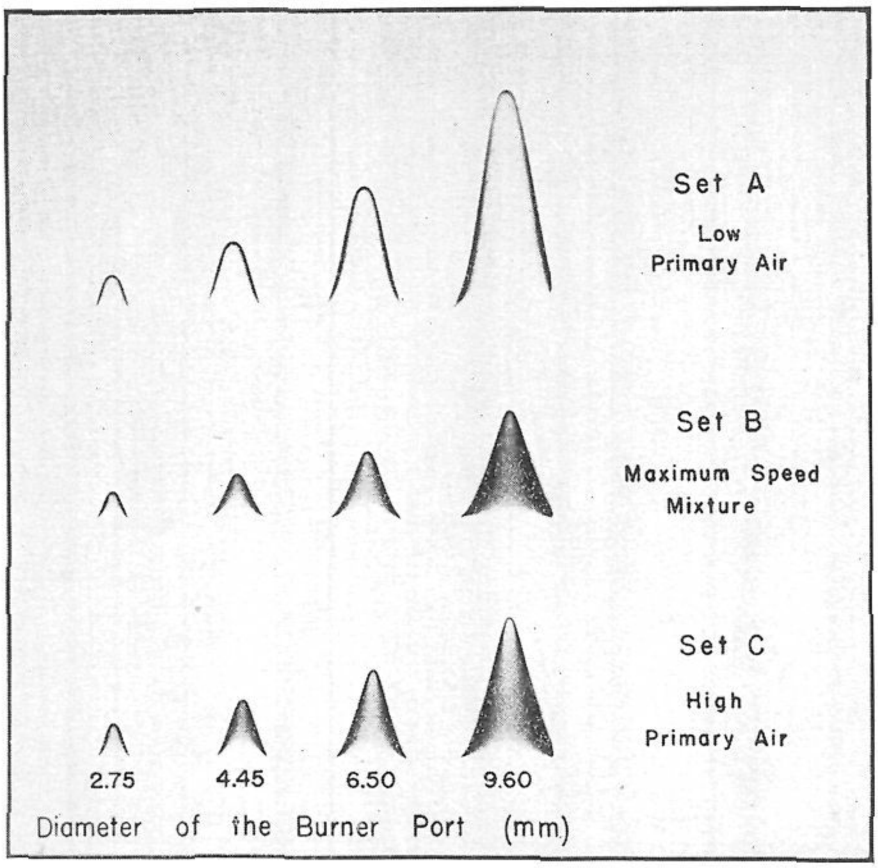

FIG. 4. Relative sizes and shapes of flames on four burners of different diameters when temperature, pressure, composition, and S_M were kept constant within each set.

Figure 5 shows the same flames with the four burners of each set enlarged by the proper amount to give each burner port the same apparent diameter. The position of the port with respect to the flame is indicated by the horizontal line under each flame. Since the composition and temperature of the mixture were kept constant, the product $S_M \sin \alpha$ is fixed within each set. In addition S_M was also kept constant, thus concentrating any differences between flames of different size in the angle α.

Table 2 shows that for the three larger burners in sets B and C the angle, and consequently the flame speed, is practically constant and independent of the size of the port.

Likewise, keeping all conditions constant except port size, any differences resulting from ports of different sizes are concentrated in the areas of the flame surfaces. Such differences are obvious in figure 5, especially in the case of set A and the smallest burner of all three sets.

Table 3 presents the enlarged areas,[3] measured by the method described by Corsiglia. These show clearly that the area is not independent of the size of the port. Consequently, the flame speed, computed from the volumetric rate and the actual area of the flame surface, is dependent on the size of the port.

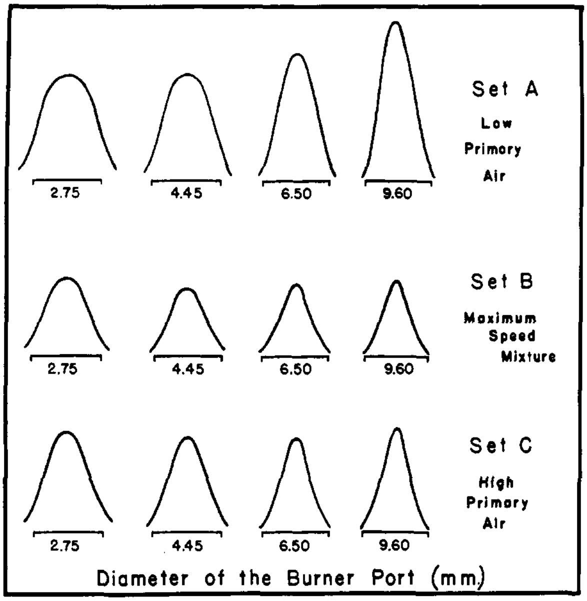

FIG. 5. Effect of burners of different sizes on the shape of the flame surface. Tracings of the flames of figure 4 with the four burners of each set enlarged by different amounts to give each burner port the same apparent diameter, the position of which with respect to the flame is indicated by the horizontal lines under the flames.

3. Computations of flame speed. Angle measurements versus area measurements

Table 4 shows the results of computing the flame speed, in these two ways, from measurements of the same flames. On the basis of our assumption of a definite fixed flame speed corresponding to a fixed composition and temperature of the combustible mixture, the results based on the angle appear to be a more reliable index to flame speed than those based on

[3] See footnote to table 3.

the area, for the case of burners larger than about 4 mm. in diameter and at or near the maximum-speed mixture. The values from the area are lower than, and appear to approach, those from the angle, and might reach coincidence if a burner of larger size were used. This is indicated in figure 3, which also shows that at about 67 per cent of the total air required the results based on the area are independent of port size, and agree with that from the angle with the 9.60-mm. burner. Whether any significance may be attached to this must await results by some such

TABLE 2

Effect of changes of port diameter upon the angle α, and consequently upon the numerical value of flame speed as calculated from measurements of the angle

PORT DIAMETER	COMPOSITION OF MIXTURE, PER CENT PRIMARY AIR	VELOCITY OF MIXTURE, S_M	ANGLE α	FLAME SPEED $S_M \sin \alpha$
Set A. Low primary air				
mm.	*per cent*	*cm. per second*		*cm. per second*
2.75	62.3	85.4	19° 5′	27.9
4.45	62.3	85.2	16° 32′	24.2
6.50	62.0	85.1	11° 48′	17.4
9.60	61.9	85.2	9° 43′	14.4
Set B. Maximum-speed mixture				
2.75	90.4	121.0	22° 58′	47.2
4.45	89.6	120.2	26° 27′	53.5
6.50	89.6	120.4	26° 19′	53.4
9.60	89.6	120.7	26° 36′	53.7
Set C. High primary air				
2.75	103.2	140.2	19° 4′	45.8
4.45	103.5	140.0	20° 8′	48.2
6.50	100.7	140.8	20° 13′	48.7
9.60	103.7	140.3	20° 3′	48.1

method as that described by Fiock and Marvin (6) in another part of this symposium.

Such differences as are significant in the shape of the flame surface when the same mixture is burned on burners of different size and when different mixtures are burned on the same burner have long been noted and are brought out in figure 4. Measurements indicate that the base of the flame is, in most cases, about 1.0 mm. larger in diameter than the port and somewhat above it. This, on a burner of 2.75-mm. diameter, amounts to 36 per cent of the port diameter.

The incongruity between the base of the flame and the port and the rounding off of the top of the flame lead to an area larger than that of a geometrical cone having the port as a base. Consequently, the numerical result for flame speed is lower as the distortion in shape becomes greater.

The angle is apparently affected much less than the area by the relative changes of shape and size which accompany changes in the size of the port.

TABLE 3

Effect of changes in port diameter upon the area of the flame surface, and consequently upon the numerical value of flame speed calculated from measurements of the area. Composition of S_M constant in a given set

PORT DIAMETER	ENLARGED AREA*	FLAME SPEED VOLUME RATE/ACTUAL AREA
	Set A. Low primary air	
mm.		*cm. per second*
2.75	654.0	18.5
4.45	729.3	16.8
6.50	801.9	15.1
9.60	869.9	13.8
	Set B. Maximum-speed mixture	
2.75	589.6	29.0
4.45	455.3	38.0
6.50	390.1	43.8
9.60	356.1	47.7
	Set C. High primary air	
2.75	644.4	30.7
4.45	560.9	35.9
6.50	483.7	41.3
9.60	453.8	43.6

* The enlarged area is the area of the flame surface, in arbitrary units, measured after the flames have been brought to a common basis for comparison, by enlargement of all ports to the same apparent diameter. If changing the size of the port had no effect upon the shape of the flame, and if the flame base was congruent with the port, all four areas within a given set would be equal.

4. Maximum-speed mixtures give minimum errors and are least objectionable for comparisons between fuel gases

It is clearly seen from figure 5 that the shape of the flames which yielded results least affected by changes in the size of the burner was that which departed least from the shape of a geometrical cone. This condition is found in or near maximum-speed mixtures and with the larger burners.

If the ability to measure the speed of flame relative to a combustible mixture is to be of any use whatever, one must be able to compare the speed in one mixture with that in another, and the speeds in mixtures of one fuel gas with those in mixtures of another. The limitations of the burner method of measuring flame speeds in regard to the former have just been considered.

A problem common to all methods is that of finding a suitable basis on which to make the comparison with respect to different fuel gases. For example, the data from the two gases may be obtained by the same method, with the same apparatus, and the comparison may be made (*a*) by substituting one combustible gas for the other in a gas–air mixture which is otherwise unchanged in composition and temperature. The two gases may be methane and propane, each constituting 7.5 per cent of its mixture with air. An examination of the curves plotted in figure 6 shows that all that can be elicited from such a comparison is that the flame velocity in a very lean mixture containing 7.5 per cent of methane is more than twice that in a very rich mixture containing 7.5 per cent of propane. The comparison may also be made (*b*) between mixtures, each of which contains the same percentage of the total air required for the complete combustion

TABLE 4

Effect on the numerical value for flame speed of computations based on measurements of the angle, as compared with those based on measurements of the area, with changes of port diameter. Composition and S_M constant in a given set

PORT DIAMETER	FLAME SPEED $S_M \sin \alpha$	FLAME SPEED VOLUME RATE/ACTUAL AREA
	Set A. Low primary air	
mm.	*cm. per second*	*cm. per second*
2.75	27.9	18.5
4.45	24.2	16.8
6.50	17.4	15.1
9.60	14.4	13.8
	Set B. Maximum-speed mixture	
2.75	47.2	29.0
4.45	53.5	38.0
6.50	53.4	43.8
9.60	53.6	47.7
	Set C. High primary air	
2.75	45.8	30.7
4.45	48.2	35.9
6.50	48.7	41.3
9.60	48.1	43.6

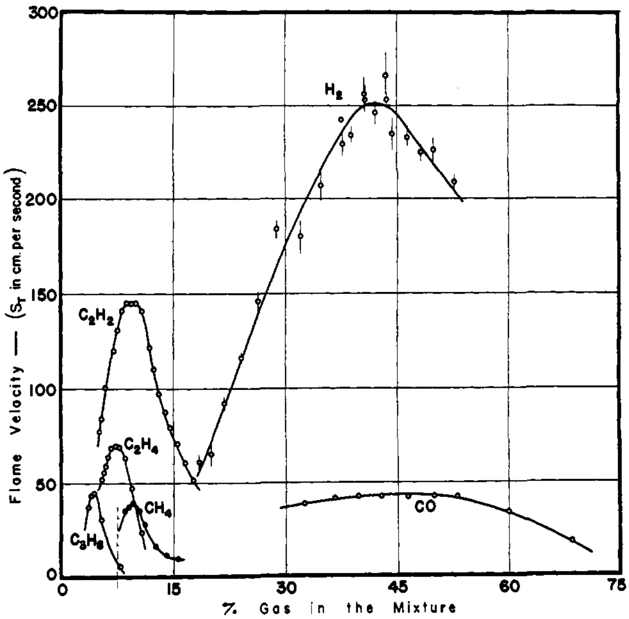

FIG. 6. Flame-speed curves plotted, in the customary manner, with "percentage of gas in the mixture" as abscissa

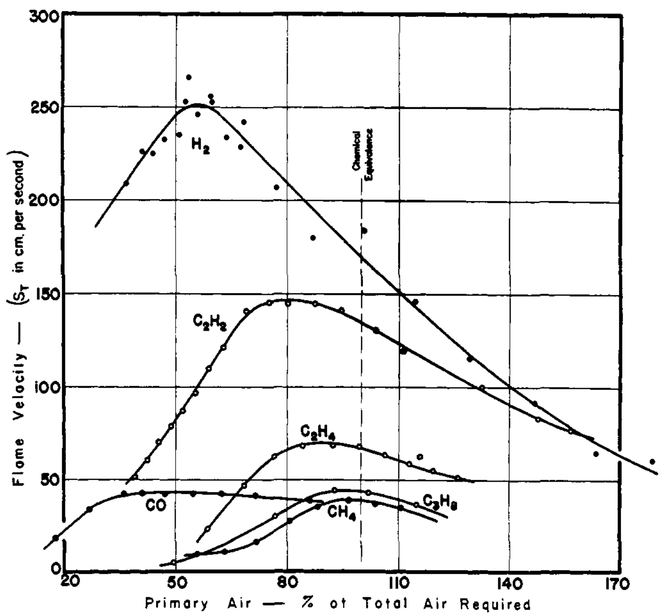

FIG. 7. Flame-speed curves plotted to place the gases on a common basis with respect to the air required for combustion, and nearly so with respect to heating value.

of the respective gases. The curves plotted in figure 7 show that such a comparison may be valid between methane and propane, but if either of the gases is compared with hydrogen in mixtures containing, for example, 80 per cent of the air required for complete combustion, the same difficulties are encountered as before but not to such an extreme degree. Such comparisons are obviously useless, and the alternative of choosing the maximum-speed mixtures as the only points on the curves which are much more than roughly comparable one with another must be accepted. Even with maximum-speed mixtures, the flame speeds in different mixtures, obtained by different methods, may be compared with validity only when the different methods have been shown to yield the same result with a given mixture, the composition, temperature, and pressure being the same in each case.

C. Changes in the distribution of velocities in a stream of mixture emerging from a burner tube

Among the factors which influence the shape of the flame surface is the velocity of flow of the mixture. The surface of the flame may be considered to be generated by the movement of a flame front radially from a point of ignition on the outer boundary of the moving stream of mixture. If the velocity of the stream were uniform throughout, the flame front would be the surface of a segment of a sphere, all parts of which were being carried away from the burner port by the stream of mixture. If flame front and mixture traveled at the same speed, a nearly flat flame surface across the port would soon result. The spherical flame front would remain in contact with the port rim, at the original position of the point of ignition, its radius of curvature continually increasing as its center (the point of ignition) receded in the moving stream. Such a situation would probably be not far from the original conception of Bunsen, who assumed that the flame speed just exceeded the mixture velocity when the flame traveled down through the port. Although it may be approached with ports about 4 mm. in diameter or less at low rates of flow, this condition is never found in practice.

Theoretically, the distribution of velocities in a fluid in laminar flow in a tube is parabolic. This means that the maximum velocity at the axis is twice the average velocity, and that the average velocity occurs in a cylindrical lamina having a diameter 0.707 that of the tube. Ordinarily, the distribution is probably only approximately parabolic and the average velocity of the mixture is several times as great as the flame speed.

Some early workers in the field attempted to compute the changes in velocity in the various parts of such a stream of gas when it emerged from the tube into the surrounding air, but without success. They, and most others, have assumed that the parabolic distribution persists, without significant modification, for a sufficient distance from the port to include the inner cone of the flame.

In the course of the study of flames and burners at the National Bureau of Standards, interest in this matter was revived late in 1935 in an attempt to account for the marked rounding off of the tops of some of the flames which have just been discussed. Other widely scattered workers have also become interested.

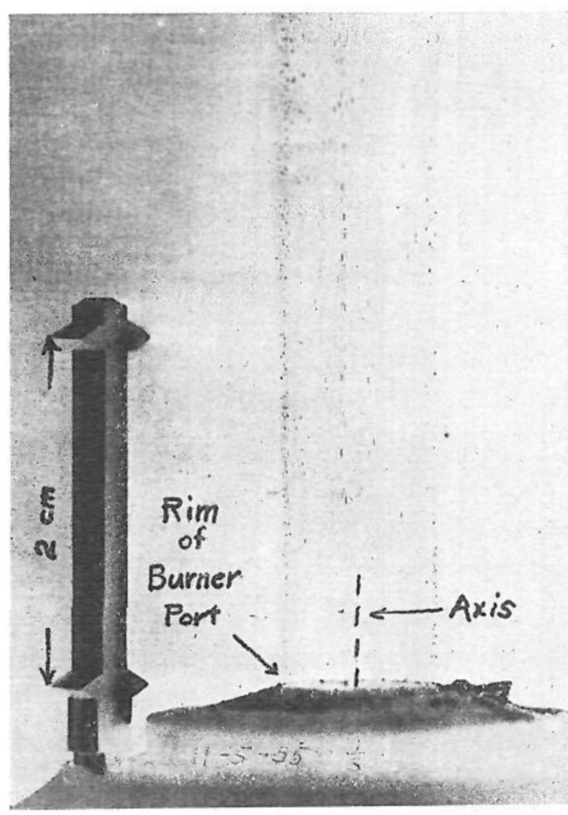

FIG. 8. Aluminum particles, suspended in a stream of air rising from a burner tube, photographed by reflected light, interrupted by a slotted disc rotating at known speed.

Some preliminary work has been done by the writer in an attempt to detect and measure such a redistribution of velocities in the stream of the mixture by photographing particles of aluminum suspended in the stream. Figure 8 shows a photograph, measurements of which indicate that there is a deceleration of particles near the axis and an acceleration of those near the boundaries of the stream. The velocity at points from 1 to 2.5 diameters above the port and near the axis was decreasing about 3.4 cm. per second in 1 cm. At the same time the velocity at points from $\frac{1}{3}$ to 2 diameters above the port and near the boundaries of the stream was increasing about 11 cm. per second in 1 cm. on one side and from 8 to 50 cm. per second in 1 cm. on the other. Of course, the velocity at the boundaries was still only a fraction of that near the axis at these short distances from the port, but the measurements indicate that changes of considerable magnitude in the distribution of velocity were taking place within a relatively short distance from the port.

Predvoditelev and Stupotshenko (11) have studied the problem of a decaying gas jet with pipes 100 mm. in diameter and larger by means of an anemometer. Predvoditelev (10) concludes that: "The inner cone of the Bunsen flame is a photograph of the hydrodynamic law of the distribution of velocities over the cross-section of the torch, nothing more." It seems certain that this is an overstatement of the case. Apparently he considers that the flame surface is farther from the port at the axis than it is at the boundaries of the stream, only because the velocity of flow of the mixture is greater at the axis than at the boundary. Smith and Pickering (12), as well as various other workers, have shown that the angle between flame surface and axis depends on the ratio of flame speed to mixture velocity, and not on mixture velocity alone.

III. PROBLEMS OF STATIONARY FLAMES AS RELATED TO BURNERS

A. Kinds of stationary flames

A stationary flame may be defined as one in which a stream of combustible material flows through a flame front maintained in a fixed position by some mechanical device usually called a burner.

Stationary flames may be classified in various ways, but for the purposes of this discussion the classification will be on the basis of whether or not part of the air required for combustion of the gas is mixed with it before it emerges from the port.

1. Diffusion flames

In this classification fall all those flames in which the fuel gas emerges from the burner and burns as and when it becomes mixed with a sufficient quantity of surrounding air. Such flames range from candle, wick lamp, gasoline flare, through the old gas light, the acetylene flashing beacon, some newer industrial equipment, to the old jewelers' blowpipe and modern blast lamp.

In all these the process of liberating heat is limited in speed by the rate at which mixing takes place between the gas and air. In some it is accomplished by diffusion alone. In some, mechanical mixing plays a relatively important part. In blowpipe and blast lamp mixing is accelerated by forcing a jet of air through the emerging gas. This not only increases the area of contact between gas and air, but produces considerable mixing by turbulence as well.

Such flames occupy a relatively large space compared to the rate at which they liberate heat, for the flame surface must extend itself until all the fuel gas has made contact with the air required to burn it.

2. Bunsen-type flames

To this class belong flames of almost all domestic gas appliances, many laboratory burners, many industrial and special-purpose burners, blow torches, welding torches, etc., in which the fuel gas is mixed with a part or all of the air it requires for combustion before it emerges from the port. Many of these burners use part of the energy of the gas supplied to them under pressure to inject or inspirate this primary air and assist in the mixing. Others have both gas and air supplied under pressure, and the mixture is controlled by means of valves.

In all these cases, however, the speed of the combustion process is limited by the speed at which flame travels relative to the particular mixture flowing from the port. It is with this class of flames that this discussion is primarily concerned.

B. Usefulness of flames as related to stability

A flame is useful only so long as it remains on the burner. One may use the burner as a handle with which to change the size, direction, or intensity of the flame. Since usefulness depends on the flame remaining stable, subject to control by means of a burner under a variety of changes, problems of stationary flames are involved inextricably with those of burners.

The limits of the stable range of operation of a flame are evidenced by the flame flashing back inside the port at one extreme and being blown off the port by the stream of mixture at the other. Whether the flame operates near one of these limits or the other depends on the relative magnitudes of the flame speed, S_T, and the velocity of flow of the mixture under the varied conditions of use.

1. Range of variation of velocity of mixture of constant flame speed

When the proportions of fuel and air must be kept constant while the rate of heat production is varied, as is sometimes the case, the range of stable operation with a given burner is greatest when the proportion of primary air is least. As may be seen from figure 9, for the case of a burner port 6.50 mm. in diameter burning city gas, mixtures containing less than 40 per cent of the air required for complete combustion of the gas are not likely to flash back until flow practically ceases. Likewise, a very rapid flow is required to blow the flame from the port. In the maximum-speed mixture, the range of stable operation between flash-back and blow-off is very much less, and, in mixtures containing as much as 150 per cent of the theoretically required air, one limit or the other is encountered if only a slight variation in the rate of heating is permitted. Furthermore, the rate of heating has become so low as to be of little use. If the conditions of operation are such that the products of combustion, in escaping, exclude secondary air, the curve representing the blow-off limit doubles back toward the flash-back limit. The range of stable operation is then greatest in the maximum-speed mixture and decreases rapidly as the proportion

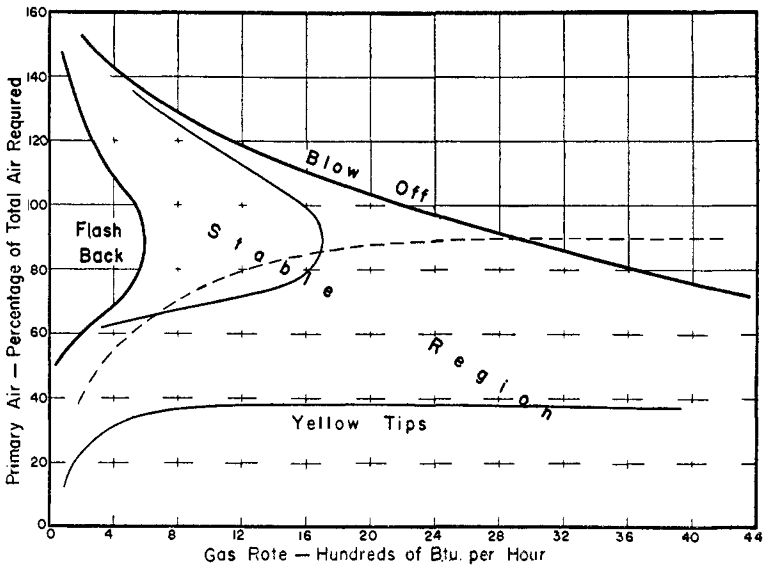

FIG. 9. Typical operation curves bounding the regions in which flash-back, blow-off, and yellow tips occur. The recurved blow-off curve results if secondary air is excluded. The dotted curve typifies the proportion of air injected by the gas. (6.50-mm. burner with city gas–air.)

of air is changed in either direction, with simultaneous reduction in the rate of heating.

2. Range of variations in composition

In most applications of gas flames the composition, as well as the velocity of the mixture, is subject to variation. Starting with a yellow flame, adding air to the mixture increases the flame speed and also the velocity of flow. Increasing flame speed tends toward flash-back. Increasing mixture velocity tends toward blow-off. With further addition of air stable operation continues with both limits rapidly approaching each other. If the velocity is high enough, no flash-back results, even with the maximum-speed mixture, and the tendency toward flash-back recedes with the decreasing flame speed as the addition of air continues. The increasing velocities of flow, however, soon blow the flame from the port.

If secondary air be excluded, the primary cone alone remains, as in the case of the Smithell's flame separator. The mantle flame around the port rim ordinarily seals the primary cone to the port, but when it is absent it is evident from figure 9 that mixtures near maximum flame speed are required to offset the tendency for the velocity of flow to carry the flame off the port.

For maximum usefulness it is obviously desirable to have as large as possible the range of stable operation in respect to rate of flow and composition of the mixture. The effect of the secondary combustion in keeping the flame on the port when the flame speed is low points to the mode of operation of the many "flame-retaining" devices, all of which operate on this principle.

A supplementary port (or ports) around the rim of the burner port is supplied with part of the same mixture at a lower rate of flow, or with a separately controlled mixture of constant composition and velocity, to supplement the mantle flame in maintaining a source of ignition at the port rim. Devices of the former type tested by the writer prevented the blowing off of the flame until the proportion of air in the mixture had reached around 200 per cent of that theoretically required to burn the gas. A device of the latter type will, of course, prevent blowing off entirely, and will burn at least a part of the mixture passing the main burner port even though it be well below the lower inflammable limit.

3. Effect of temperature of burner on stability

With many burners operating properly below 100° or 200°C. on a mixture of relatively low flame speed, the flame is blown off the port if the burner is heated to 300° or 400°C. The flame speed increases with increasing temperature, but the volume of the mixture, and consequently its velocity, are increased so much more than the flame speed that blow-off results. With burners operating properly in a higher range of temperature, or with mixtures of relatively high flame speed in the lower range of temperature (mixtures with oxygen instead of air), the temperature coefficient of the flame speed may be greater than that of the velocity of the mixture, and flash-back may result.

C. Utilization of heat from flames

The heat from stationary flames is usually utilized in one of two ways. Either the heat is absorbed and converted at relatively low temperatures, or it is required to raise the body to which heat is being transferred to a high temperature. The flow calorimeter affords an excellent example of the efficient absorption of heat on a large surface kept at a low temperature. An example of the second case is a thermocouple formerly used in attempts to determine the temperature of a flame; the temperature attained by the junction rises until the rate of heat loss from the junction equals the rate at which heat is being supplied to it.

A body receives heat from a flame partly by radiation but mainly by conduction from the hot gases. The rate at which heat is transferred, therefore, is affected by the thermal conductivity of the layer of gases at the surface of the body, and, consequently, depends on the relative proportions of hydrogen, carbon dioxide, water vapor, carbon monoxide, nitrogen, oxygen, and other gases present in the layer in which the transfer takes place. The gases are enumerated in the order in which their effect is of decreasing importance.

If the body is a thermojunction which is small as compared to that part of the flame where the gases are hottest, there is little if any heat carried away from the junction by gases of lower temperature. Heat is lost by conduction through the leads from the junction in relation to their size and temperature, and by radiation from the junction and adjacent leads at a rate depending on their surface area and temperature. Small size of the body to be heated is a prime requisite if its temperature is even to approach that of the gases of the flame.

It is obvious that, in any specific case, the temperature attained by a body of appreciable size in a flame has little or no relation to the "flame temperature" as determined by usual optical methods.

1. Matching the flame to the requirements of the application

In selecting a flame for a specific purpose and keeping in mind the points just mentioned, it is usually possible to come to some decision as to the rate at which heat is to be liberated, the fuel gas to be used, the proportion of air or oxygen with which it is to be mixed, the area over which the heat is to be distributed, whether the mixture is to be variable or fixed, and, if fixed, at what composition. Access of secondary air to the flame, the space in which combustion is to take place, and whether transfer of heat by radiation from flame or refractory, or by contact with hot gases alone, is suitable, are important in making some of these decisions. Some of the various compromises involved in the case of domestic gas appliances are discussed in a circular of the Bureau of Standards.[4]

[4] C 394, section VII.

2. Matching the burner to the flame

There is a somewhat more definite basis for the selection of a suitable burner for a given flame than there is for the selection of the flame for a special purpose. In the interest of stability one would attempt to select a burner with which normal operation is as remote as practicable from both flash-back and blow-off.

Having decided upon the identity of the fuel gas and whether it is to be burned with air or oxygen, the range of variation of composition of the mixture permits the estimation of the range of volumetric rate of flow and the range of flame speeds involved. Values of the latter should, of course, be relative to the mixture, and not taken from the literature indiscriminately.

The relationship between flame speed and average mixture velocity within the limits of stable operation has not been fully investigated as yet. There appears to be no general relation which holds for more than two or three fuel gases in a group, or for burners of different sizes. So far, however, S_M has always been found greater than S_T. With mixtures of city gas and air and a 9.6-mm. burner, for example, S_M/S_T = about 3 at flash-back. With mixtures of hydrogen and air and a 3.8-mm. burner $S_M/S_T = 1.8$. At blow-off, with city gas–, carbon monoxide–, and propane–air mixtures and the 9.6-mm. burner, S_M/S_T = about 10.

By taking a value for the flame speed and the ratio of S_M/S_T in the mid range (about 6 or 7), an approximate value of S_M can be obtained. From this value and the volumetric rate a tentative diameter for the burner tube may be selected. If a computation of the Reynolds number, R (see footnote 2), indicates that the flow is turbulent, the stable range between flash-back and blow-off will be less and the applicable ratios of S_M/S_T will be different.

Studies of the effect of the depth of the port, reported by Eiseman and Smith (5), indicate that maximum susceptibility to flash-back occurs when the length (or depth) of the cylindrical port is about one-half the diameter, and that increasing the depth decreases susceptibility to both flash-back and blow-off. Turbulent flow was found to produce a marked increase in susceptibility to flash-back, other conditions remaining constant.

Of course, appropriate modifications in the above computations would be necessary in the case of a burner having multiple ports or other characteristics significantly different from a single smooth cylindrical tube.

3. Intensity of combustion

It has been indicated in section III C of this paper that "flame temperature" is not a reliable guide to the relative ability of different fuel gases to heat an object to a high temperature. The maximum flame temperatures of the various gases do not differ very much, but only a few can be used for such operations as welding.

Similarly, the heating value of the fuel gas is no indication of its ability in this respect. For example, the comparison between hydrogen, carbon monoxide, and natural gas shows hydrogen and carbon monoxide to be similar with respect to the heat produced from a cubic foot, and carbon monoxide and natural gas to be about equally poor for use with torches to produce high local temperatures, while the heating value of natural gas is from three to five times that of carbon monoxide or hydrogen. Hydrogen, with the low heating value, is the only one of the three which is suitable for such uses.

TABLE 5

Relative combustion intensities of several fuel gases

FUEL GAS	NET HEATING VALUE	HEATING VALUE OF MAXIMUM S_T MIXTURE	MAXIMUM FLAME SPEED	COMBUSTION INTENSITY
	B.t.u. per cu. ft.	*B.t.u. per cu. ft.*	*ft. per sec.*	*B.t.u. per sec. per sq. ft.*
CH_4	895	89	1.1	98
C_2H_6	1607	95	1.4	133
C_2H_4	1473	106	2.5	265
C_2H_2	1414	135	4.7	634
CO	315	143	1.4	200
H_2	269	117	8.8	1030

Passauer (9) and Brückner and Jahn (2) have pointed out that the maximum intensity of combustion should be attained with the maximum-speed mixture, because under these conditions the maximum quantity of heat per second can be liberated in the smallest space. The advantage of this situation in producing high local temperatures is easily seen when one considers that the smaller the area through which the heat escapes, the higher is the temperature gradient required to maintain the flow of heat at a given rate, and, consequently, the higher the temperature attained within the space where the heat is liberated.

Table 5 compares the combustion intensities of five fuel gases. Heating value and flame temperature are poor criteria by which to compare fuel gases for torch work, because, as heating value increases, so also does the quantity of air or oxygen required for combustion. The heating value of the theoretical mixture of many gases is not far from 100 B.t.u. per cubic foot. The maximum-speed mixture differs from the theoretical by varying amounts for the different gases, and the heating value of the former is slightly the higher. The mixture with which maximum flame temperature is attained is not far from the maximum-speed mixture. The heating value for these mixtures is of the same order of magnitude for all the gases, thus accounting for the similarity of the "flame temperatures."

The maximum flame speed is thus left as the significant and controlling factor in determining the intensity of combustion. The means by which intensity can be controlled are those which affect flame speed. The substitution of premixed primary air for diffusion processes with secondary air, of ethylene, acetylene, or hydrogen for carbon monoxide or the paraffin hydrocarbons, of oxygen for air in the mixture, and preheating the mixture, all increase flame speed and intensity of combustion.

D. Turbulence, flame speed, and noise

Scattered through the literature are numerous statements, often conflicting, concerning the interrelationships between turbulent flow, flame speed, and noise. It seems very improbable that turbulence would have any effect on the speed of the flame relative to the mixture, but it does increase the mass rate of burning by increasing the area of the flame surface.

Probably the most exhaustive and careful study of these problems has been Project No. 13 of the Committee on Industrial Gas Research of the American Gas Association (1). This work shows without question that, in general, noise increases with the velocity of flow of the mixture and with the flame speed, and that no noise results when a homogeneous mixture emerges from the ports in laminar flow. (In the latter case the flame front is at rest.)

Of course, in excess of the critical velocity, turbulence increases as the velocity of the mixture increases. Thus, increasing noise may result from a simultaneous increase in turbulence and in flame speed, which might then be associated by the unwary as cause and effect. It is more probable that the flame speed is fixed by the properties of the mixture, regardless of the vagaries of motion of the medium in which the flame travels.

There is little doubt that the source of the sound is in the random disorganized changes of position of the flame front. The part of the flame which is most active depends on individual circumstances. It may be the flickering at the base, caused by intermittent blow-off, which can be remedied by the use of any means which keeps the flame seated on the port. It may be the entire flame surface in a jumble of random incipient flash-back and blow-off, in a multiplicity of explosions of small masses of mixture partially detached from the stream and ignited separately.

In some cases, like those reported by Eiseman and Smith (5), there might be some reason to suspect that the noise was the result of resonance in the burner. The sound, at times, approached a pure note, the pitch and loudness of which increased with flame speed and rate of flow. The flame surfaces could be observed in rapid alternation between two sharply defined positions. The sound was absent, however, when the mixture, otherwise unchanged in any way, was allowed to flow without ignition.

IV. SUMMARY AND CONCLUSIONS

Numerical values for flame speeds obtained with burners are affected by the various ways in which the measurements of the flames are made, by experimental conditions, and by the different ways in which the results are computed.

Measurements of the angle between flame surface and axis at a point $0.7r$ from the axis, on flames resulting from mixtures in laminar flow at or near the composition for maximum flame speed and on burners over 4 mm. in diameter, yield results least affected by variations in experimental conditions.

Maximum flame speeds alone are suitable for making comparisons between different fuel gases because of the lack of any common basis (in point of composition) for comparison.

An appreciable redistribution of velocities in the stream of the mixture takes place as the stream leaves the port. This takes the form of an acceleration near the boundaries of the stream and a deceleration near the axis, and affects the shape of the flame surface.

Although burner methods of measuring flame speed are relatively simple and the results directly applicable to a multitude of burner problems, the field of usefulness of the method appears at present to be considerably restricted by the limitations mentioned above.

The usefulness of flames is dependent on their stability and susceptibility to control. Laminar flow, favored by deep ports and small diameters of the port, increases the range of stable operation between the limits of flash-back and blow-off. Complete mixing and low proportions of air do likewise. Such conditions also tend to eliminate turbulence and noise.

In the absence of secondary air, the maximum range of stable operation is found with the maximum-speed mixture. The range is about half that in secondary air, and decreases rapidly as the composition of the mixture is changed in either direction.

In selecting a flame for a definite purpose one should keep in mind the fact that the temperature attained by the body being heated rises until the rate at which heat is lost becomes equal to the rate at which it is supplied.

In choosing the dimensions of a burner for a given flame, a likely value for the average velocity of flow of maximum-speed mixtures with air will be from six to seven times the maximum flame speed.

Where local high temperatures are required, they can be obtained by providing conditions which result in the liberation of heat at the highest rate in a given space. Maximum flame speed rather than flame temperature or heating value of the gas is the key to this. The heating value of the maximum-speed mixture, multiplied by the maximum flame speed, is an index to intensity of combustion (B.t.u. per second per unit area).

REFERENCES

(1) Am. Gas Assoc. Testing Lab. Repts. No. 692 (1932) and 724 (1933).
(2) Brückner, H., and Jahn: Gas- u. Wasserfach **74,** 1012 (1931).
(3) Bunsen, R.: Pogg. Ann. **131,** 161 (1866).
(4) Corsiglia, J.: Am. Gas Assoc. Monthly **13,** 437–42 (1931).
(5) Eiseman, J. H., and Smith, F. A.: J. Research Natl. Bur. Standards **18,** 485 (1937), RP 988.
(6) Fiock, E. F., and Marvin, C. F., Jr.: Chem. Rev. **21,** 367 (1937).
(7) Gouy, M.: Ann. chim. phys. [5] **18,** 27 (1879).
(8) Michelson, W.: Ann. Physik [3] **37,** 1–24 (1889).
(9) Passauer, H.: Gas- u. Wasserfach **73,** 392 (1930).
(10) Predvoditelev, A.: Tech. Phys. U. S. S. R. **2,** 364 (1935).
(11) Predvoditelev, A., and Stupotshenko, E.: Tech. Phys. U. S. S. R. **2,** 357 (1935).
(12) Smith, F. A., and Pickering, S. F.: J. Research Natl. Bur. Standards **17,** 7 (1936), RP 900.
(13) Stevens, F. W.: Natl. Advisory Comm. Aeronaut., Rept. 305 (1929).
(14) Ubbelohde, L., and Hofsäss, M.: J. Gasbeleucht. **56,** 1225–32 (1913).
(15) Ubbelohde, L., and Koelliker, E.: J. Gasbeleucht. **59,** 49–57 (1916).