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Measurements of Normal Burning Velocities and Flame Temperatures of Bunsen Flames*

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Stroboscopically illuminated particle tracks are used to accurately measure normal burning velocities of laminar flames. The precision of the measurements is increased by the use of a constant-velocity profile nozzle which gives a straight-sided Bunsen cone. Normal burning velocity data are presented for 3.7 to 5.3 percent propane-air mixtures. The value for the stoichiometric flame was determined to be 44.8 cm/sec.

From stroboscopic and streak photographs of particle tracks it is possible to obtain the maximum flame temperature and temperature distribution in the flame front. Measurements from the two types of photographs are combined with the equation of continuity and the equation of state to obtain the flame temperature. The flame temperature for a stoichiometric propane-air flame was determined to be 2220°K. An extension of this method is used to obtain an approximation of the temperature distribution in the flame front.

TABLE OF NOMENCLATURE

u = velocity of gas.
b = distance between streamlines measured parallel to the flame front.
A = cross-sectional area of the stream tube.
r = radius from axis of flame to stream line.
α = angle between flame front and the vertical.
β = angle between flame front and emergent streamline on the hot side of the flame.
ρ = density of gas.
M = mean molecular weight of gas.
M_i = molecular weight of ith component of gas.
n_i = number of moles of ith component of gas.
V = molar volume of gas.
R = gas constant.
P = total pressure.
T = absolute temperature.
Subscript 1 refers to initial gas.
Subscript 2 refers to exit gas.
Subscript n refers to velocity component normal to flame front.

PART I. NORMAL BURNING VELOCITIES FROM STROBOSCOPICALLY ILLUMINATED PARTICLE TRACKS

Introduction

SEVERAL different experimental procedures have been proposed for the determination of the normal burning velocities of Bunsen flames. All of these methods involve the measurement of flame areas or cone angles. These quantities are difficult to define accurately because of the thickness of the flame front and the curvature of the flame. Additional errors are introduced by the pre-heating of the unburned gas at the top of the cone; the quenching of the burning gas at the base of the flame; and divergence of the streamlines in the unburned gas. The stroboscopically illuminated particle method of Lewis and von Elbe[1] allows measurements to be made at any point in the flame, thus eliminating most of the above mentioned uncertainties. Therefore, in this work, a modified version of their procedure is used. The straight tube is replaced with a constant-velocity profile nozzle producing a straight-sided flame cone.

The normal burning velocity of a laminar flame is defined as the rate of flame propagation normal to the surface of combustion and relative to the cold gas. Figure 1 illustrates the application of the above definition to a Bunsen type flame.

To obtain the necessary data for the determination of u_{n1} particles of magnesium oxide are introduced into the base of the burner tube. When the particles appear in the flame, they are illuminated by a periodically intermittent sheet of light in the plane of the diameter. A photograph of the particles at right angles to the beam of light records the tracks. From the length of the particle tracks and the time interval of illumination the filament velocity may be calculated.

Thus, measurements of normal burning velocity may be made at any point along the Bunsen cone. This property is constant in the central portion of the side of the cone, where pre-heating at the tip and quenching at the base have negligible effect.

Apparatus

The equipment used in this study is illustrated in Fig. 2. Heavy construction was utilized to give maximum rigidity. To eliminate the effects of vibrations, the motor driven stroboscopic disk is mounted independently of the burner housing. As a further precaution, the entire burner housing is mounted on soft rubber.

The burner tube is 54 inches long, 2.00 inches in diameter, and topped by a copper nozzle made by an electroforming process.[2] This nozzle has a smooth internal surface, a wall thickness at the top of 0.040 inch, and an exit diameter of 0.500 inch. Magnesium oxide particles are introduced at the bottom of the burner from a particle-feeding chamber containing steel wool pads at top and bottom. A charge of particles is placed between these pads; the lower pad serves to support

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[1] B. Lewis and G. von Elbe, J. Chem. Phys. 11, 75 (1943).
[2] J. W. Andersen, Rev. Sci. Inst. 19, 822 (1948).

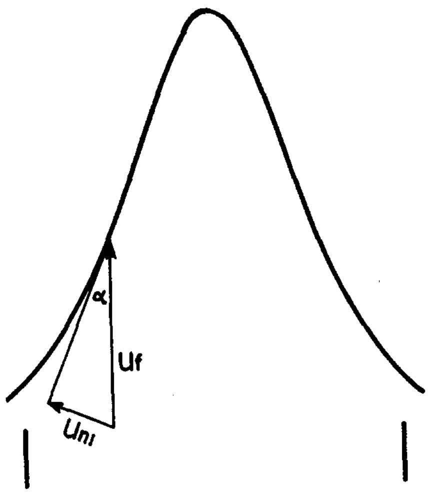

FIG. 1. Definition of normal burning velocity. u_f = filament velocity, u_{n1} = normal burning velocity = $u_f \sin\alpha$.

the charge, and the upper breaks up agglomerates. By diverting the gas flow through the feeder, particles are obtained in the flame. Their presence is detected by the yellow light produced by the small amount of sodium in the particles.

A standard type high peak, long-duration flash bulb provides illumination which is rendered intermittent by a sectored wheel driven by a synchronous motor. This light passes through a pair of slits arranged so that the thickness of the sheet of light along the plane of the diameter of the burner tube never exceeds 0.02 inch.

Photographs are taken on 4×5 inch film, and an extension bellows on the camera provides images on the negative with up to a threefold magnification. For convenience in making measurements, the negatives are enlarged tenfold. Because small quantities of sodium in the particles produce strong *D*-lines in the flame, orthochromatic film is used to avoid masking of the particle tracks. Increased emulsion speeds are obtained by heating the film to 70°C just prior to exposure. To obtain definition of particle tracks, it is necessary to keep the background on the negative low by use of short exposures.

Gas mixtures are provided by a critical velocity orifice metering system.[3] This system accurately meters three separate gas streams and then mixes them.

Particles

The size range of particles delivered by the particle feeder was determined by catching samples on a microscope slide at the top of the burner tube. This test was run on samples of magnesium oxide supplied by two different manufacturers. In one sample the largest size observable was 20 microns and it was 40 microns in the other sample.

[3] J. W. Andersen and R. Friedman, Rev. Sci. Inst. **20**, 61 (1949).

The success of the stroboscopically illuminated particle method depends upon the ability of the particle to accurately indicate the filament velocity. A sample of particles from the larger size range mentioned above was added to the gas stream and a photograph of the non-ignited jet taken. It was found that the total flow measured from particle tracks agreed to within 1 percent of the metered value. Across the flat portion of the velocity profile (90 percent of the diameter for the 0.500-inch exit diameter nozzle) individual particle tracks were within 0.3 percent of the average value.

Results

Figure 3 illustrates the photographs obtained. The central portion of the flame front, indicated in Fig. 3 between the short lines ruled perpendicular to the flame front, is the zone over which the normal burning velocity can be accurately measured. This section is not subject to the pre-heating effect which occurs at the tip of the flame, or to the divergence of streamlines that occurs near the base of the cone. The divergence of the streamlines in the unburned gas is caused by the pressure drop across the flame and by the lower gas velocities near the edge of the nozzle.

The propane used in the following experiments was stated by the manufacturer to have a purity of 99 percent. Precautions were taken to keep the water in the fuel-air mixture below 0.07 percent.

The use of the nozzle simplifies the measurement of the angle of the flame front because a straight-sided

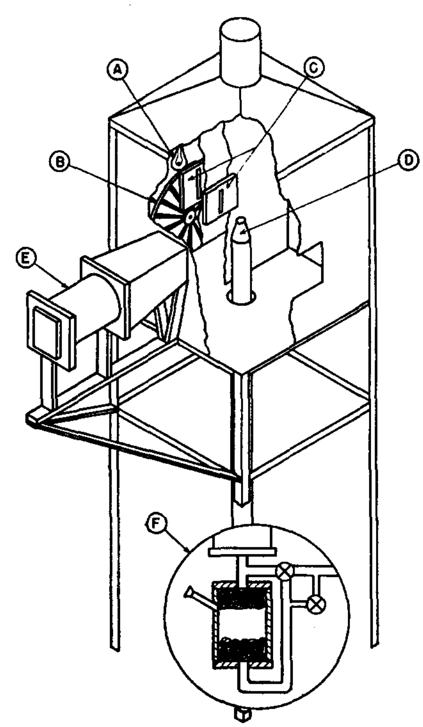

FIG. 2. Burner housing. *A*, Flash bulb; *B*, Stroboscopic disk; *C*, Slits; *D*, Nozzle; *E*, Camera; *F*, Particle feeder.

TABLE I.

Film number	Flow conditions	Filament velocity	Angle	Normal burning velocity
54	Nozzle	147 cm/sec	17° 30′	45.1 cm/sec
57e	Nozzle	92.0	22° 0′	44.6
58e	Nozzle	100.5	28° 30′	43.9
59a	Nozzle	159	16° 40′	45.6
61b	Straight tube	247	10° 40′	45.7
61b	Straight tube	289	9° 30′	45.0
			Average:	45.0 cm/sec

Bunsen cone is formed. The normal burning velocities that were measured are presented in Fig. 4.

The values of u_{n1} for a 4.12 percent propane-air mixture, obtained with the nozzle and a straight tube of the same exit diameter, are given in Table I and illustrate the agreement under the two different flow conditions.

Filament velocities were calculated from the measured lengths of particle tracks and the time of the light cycle. Nozzle flame angles were measured in the zone previously described. For the straight tube flames, the best tangent to the flame front (as indicated by the luminous zone) at the intersection of the filament whose velocity was measured, determined the flame angle. The spread in the data presented represents the maximum deviation which has been observed.

The range of composition, for which the normal burning velocity has been determined, is limited by the size of the nozzle. Outside of this composition range, the flow rate required to maintain a flame on the nozzle is too low to produce a straight-sided cone.

PART II. FLAME TEMPERATURES FROM STROBOSCOPICALLY ILLUMINATED PARTICLE TRACKS

Introduction

The measurement of the temperature of laminar flames has generally been accomplished by the use of line-reversal techniques. These methods can be applied most readily to the zone outside the Bunsen cone. It is felt that much information may be gained by the determination of the temperature gradient in the cone itself. However, optical methods are not feasible in this study because of the relatively large area which must be observed. The insertion of wires for the application of thermoelectric techniques would disturb the flow lines.

The procedure presented here may be used for the study of temperature gradients in the Bunsen cone. With the aid of stroboscopic and streak photographs, the gas particle velocities on both sides of the flame front are determined. These velocity measurements are then combined with the equation of continuity and the equation of state to yield the flame temperature.

Method

Figure 5 illustrates the cross section of a stream tube through a Bunsen cone as indicated by particle tracks. In the case of laminar flow, the equation of continuity for a stream tube is given by

$$u_1\rho_1A_1=u_2\rho_2A_2, \qquad (1)$$

where the velocities are perpendicular to the areas considered.

With a pair of dividers, it can be readily demonstrated from Fig. 6 that the distance between streamlines is constant when measured parallel to the flame front. That is to say:

$$b_1=b_2.$$

For ease of application, consider an infinitely thin stream tube, for which

$$db_1=db_2.$$

Since there is cylindrical symmetry, Eq. (1) may be written as follows:

$$u_{n1}\rho_1 2\pi r_1 db_1=u_{n2}\rho_2 2\pi r_2 db_2,$$

hence

$$u_{n1}\rho_1 r_1=u_{n2}\rho_2 r_2. \qquad (2)$$

The density terms from the equation of state are:

$$\rho_1=\frac{M_1}{V_1}=\frac{(\Sigma n_iM_i)_1}{(\Sigma n_i)_1RT_1}P_1,$$

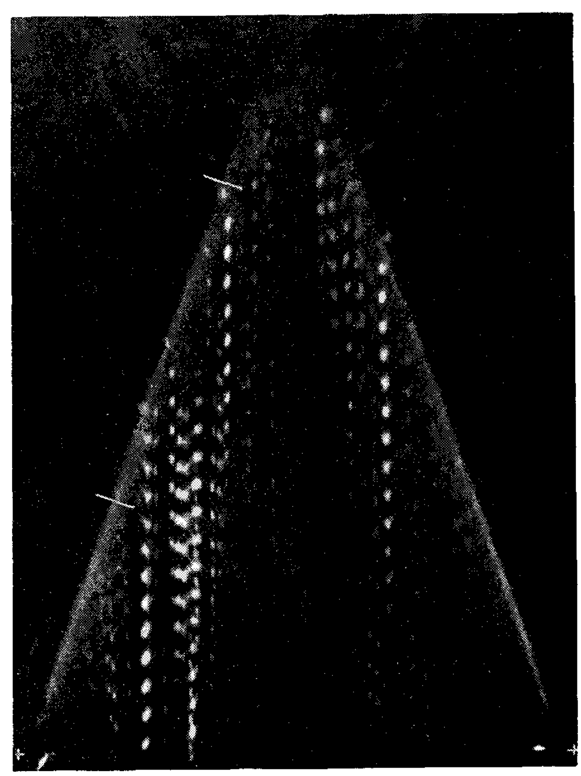

FIG. 3. Stroboscopically illuminated particle track photograph. 3.87 percent propane-air, total flow 175.2 cc/sec., exit diameter of nozzle 0.500 in., initial gas temperature 298°K barometer 731 mm Hg, light cycle 1/1800 sec.

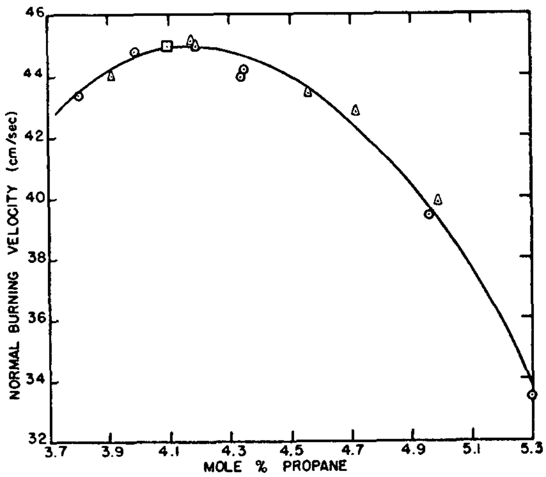

FIG. 4. Propane-air normal burning velocities. The different symbols represent data taken at various dates.

and

$$\rho_2 = \frac{M_2}{V_2} = \frac{(\Sigma n_i M_i)_2}{(\Sigma n_i)_2 R T_2} P_2.$$

Since the pressure drop across the flame is very low, P_1 may be taken as equal to P_2. Substituting for the density in Eq. (2) and observing that $(\Sigma n_i M_i)_1 = (\Sigma n_i M_i)_2$, the following relationship is obtained:

$$T_2 = T_1 \frac{(\Sigma n_i)_1}{(\Sigma n_i)_2} \frac{r_2}{r_1} \frac{u_{n2}}{u_{n1}}, \quad (3)$$

wherein $u_{n2} = u_r \sin\beta$, where u_r is the resultant exit velocity of the particle.

Experimental Procedure

To demonstrate the application of the above method, a 3.87 percent propane-air flame will be considered. This flame was established on a constant-velocity profile nozzle and particles were introduced into it by the method outlined in Part I. Stroboscopic photographs were taken of the particles for determination of emergent velocities (u_r) and streak photographs were taken for the determination of emergent angle β.

A study of Figs. 3 and 6 will reveal that some of the particles do not appear to follow the streamlines as well as others. Those particles which show this deviation are either too large or do not lie in the plane of the diameter. If the particles lie in this plane and are the same size, the paths of particles close together should be parallel. It is to be observed from the figures that those particles which appear to be small exhibit parallel paths. Also, they have the largest emergent angles, which indicates a more faithful representation of the streamline. Thus, correct results will be obtained if measurements are confined only to those tracks which appear to be from small particles. Unfortunately, these tracks are not the easiest to work with and need for an alternate method arises.

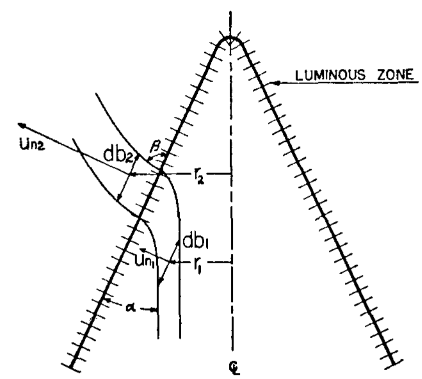

FIG. 5. Cross section of a stream tube through a Bunsen cone.

It will be observed from the photographs that many of the tracks of apparently larger particles become parallel to tracks of the smaller particles a short distance from the cone. These tracks may be extrapolated back to the luminous zone as indicated in Fig. 6, and are then equivalent to those made by the smaller particles.

To eliminate incidental errors, sines of the emergent angles and particle velocities are plotted against an arbitrary abscissa as indicated in Fig. 7. In this case, the abscissa chosen is the distance along the outside of

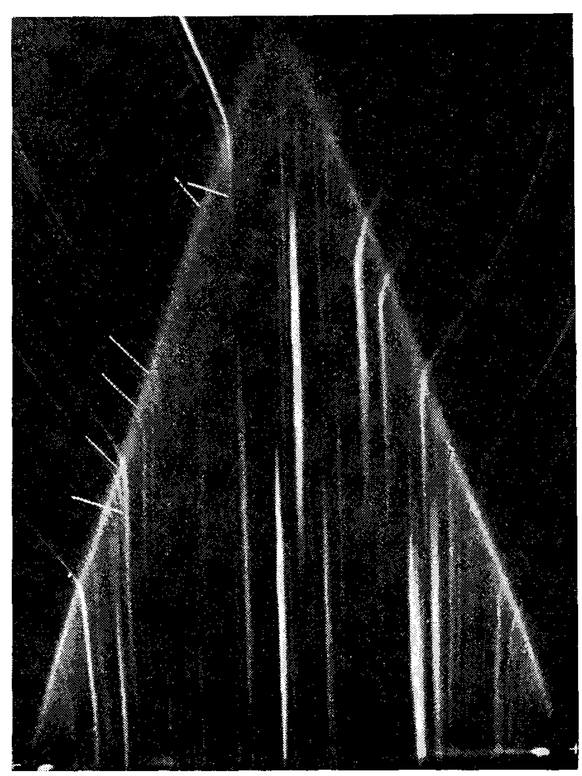

FIG. 6. Streak photograph. 3.87 percent propane-air, total flow 175.2 cc/sec., exit diameter of nozzle 0.500 in., initial gas temperature 298°K, barometer 731 mm Hg.

TABLE II.

Percent propane	Measured temperature	Theoretical temperature
4.03% (Stoichiometric)	2220°K	2280°K
3.87%	2240	2250
3.81%	2230	2240

the luminous zone from the point of intersection of the particle track to the reference point denoted by the white cross on Fig. 3 and Fig. 6. The above method makes possible the use of separate streak and stroboscopic particle photographs.

Since $u_{n2}(r_2/r_1)=u_r(r_2/r_1)\sin\beta$, consistent values for $u_{n2}(r_2/r_1)$ are obtained by multiplying the two ordinate values for a given abscissa in Fig. 7. If the best straight lines are drawn through the points, it is seen that $u_{n2}(r_2/r_1)$ is constant within 1 percent over the zone considered. The maximum deviation of any point from the straight line is $2\frac{1}{2}$ percent.

To determine the factor $(\Sigma n_i)_1/(\Sigma n_i)_2$, the necessary data for $(\Sigma n_i)_2$ was obtained from equilibrium considerations by the method described by Wenner[4] and $(\Sigma n_i)_1$ from the equation

$$C_3H_8+5.21\ O_2+19.6\ N_2 \\ =3\ CO_2+4\ H_2O+19.6\ N_2+0.21\ O_2.$$

This represents the combustion of one mole of propane in the 3.87 percent propane-air mixture. At the temperature 2250°K, the dissociation products of CO_2 and H_2O increase the total number of moles of reaction products from 26.8 to 27.0.

The following substitution may be made in Eq. (3) to obtain the flame temperature:

$$T_1=298°\mathrm{K},$$
$$(\Sigma n_i)_1/(\Sigma n_i)_2=25.8/27.0,$$
$$(r_2/r_1)u_{n2}=(r_2/r_1)u_r\sin\beta=0.795,$$
$$u_{n1}=u_f\sin\alpha=0.296\sin 20.0°=0.1012.$$

Then $T_2=(298)(25.8/27.0)(0.795/0.1012)=2240°\mathrm{K}$.

In this manner the data in Table II has been obtained.

It is worthwhile to note that Lewis and von Elbe[5] list a value of 2198°K for a 4.15 percent propane-air mixture. In the present work, flame temperatures were not determined for rich mixtures because of the difficult equilibrium calculation of the number of moles of burned gas.

Approximate Temperature Distribution in the Flame Front

After careful study of many photographs, several particle tracks were located which appeared to follow closely the very high acceleration which occurs in the flame zone. This was shown by an angle β, in the luminous zone, that agreed with the extrapolated values. By use of these tracks, it was possible to obtain the temperature gradient in the flame.

To determine the temperature gradient in the flame, it was necessary to assume the manner in which the velocity parallel to the flame front varies; the manner in which the change in number of moles occurs; and, of almost negligible consequence, that radial expansion through the flame front can be neglected. With no

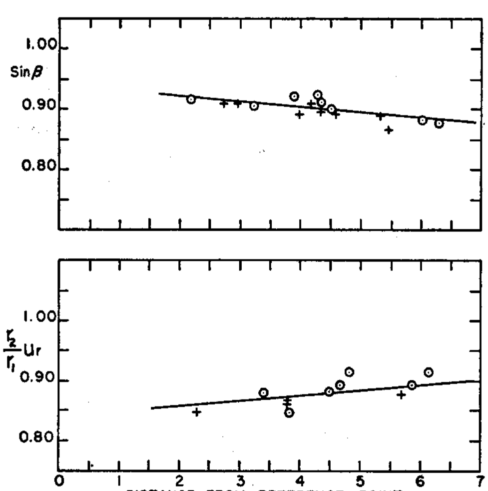

FIG. 7. Plot of sinβ and $(r_2/r_1)u_r$ for determination of u_{n2}. Two runs are represented in this figure.

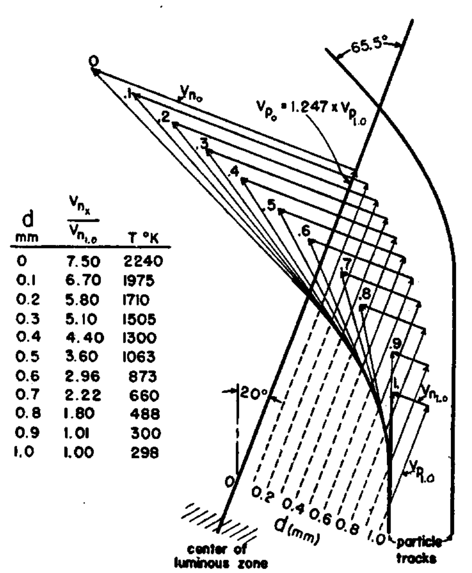

FIG. 8. Determination of temperature distribution in flame front.

[4] R. Wenner, *Thermochemical Calculations* (McGraw-Hill Book Company, Inc., New York, 1941), pp. 236–242.

[5] B. Lewis and G. von Elbe, *Combustion, Flames, and Explosions of Gases* (The Macmillan Company, New York, 1938), p. 399.

reliable information, the simplest assumption is that the change in moles and the change of velocity parallel to the flame front are linear with the distance normal to the flame front. The velocity assumption is most subject to criticism, but it should be pointed out that the increase in this component of velocity is only 25 percent.

The procedure in the determination of the temperature gradient in the flame front is shown in Fig. 8. The illustrated particle tracks are direct tracings of enlarged streak photographs. Actual distances are indicated: 1.0 mm is the point of first deflection of the streaks and 0.0 mm is the center of the visible zone. In brief, the analysis of these tracks is as follows:

a. The parallel velocity vector is drawn in as shown. This vector was assumed to vary in a linear manner as indicated previously. Its magnitude at the 0.0 mm distance was determined trigonometrically from the resultant velocity and emergent angle; and at 1.0 mm from the cone angle and filament velocity.

b. The tangent to the curve is drawn. This represents the direction of the resultant velocity.

c. The perpendicular to the flame front from the tip of the parallel vector is drawn. This is u_n and its length is determined by the intersection with the resultant vector.

d. Insertion of the values of u_n into Eq. (3) yields the temperature distribution in the flame front. The gradient is indicated in Fig. 9.

Discussion of Temperature Gradient

The thickness of the flame front determined here is approximately 10^{-1} cm. This may be compared with 10^{-3} to 10^{-4} cm for the decomposition of ozone obtained by Lewis and von Elbe[6] and 10^{-2} cm for carbon monoxide and 10^{-3} cm for hydrogen obtained by Tanford.[7]

It is of interest to calculate the temperature gradient of a hypothetical one-dimensional propane-air flame in which all of the heat release occurs at a plane. The steady-state heat transfer can be represented by:

$$(d^2T/dx^2)-(u_nc_p\rho/k)(dT/dx)=0, \tag{4}$$

where $k/c_p\rho=$ thermal diffusivity. The solution of this

[6] B. Lewis and G. von Elbe, J. Chem. Phys. 2, 537 (1934).

[7] C. Tanford, J. Chem. Phys. 15, 433 (1947).

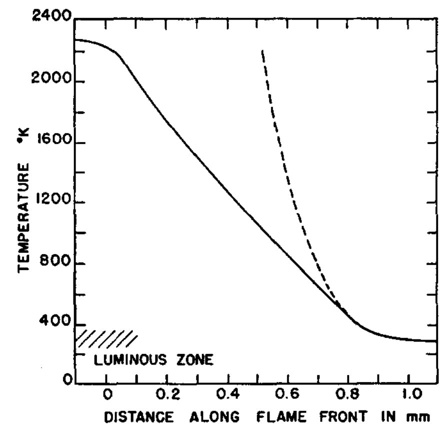

FIG. 9. Temperature gradient through a 3.87 percent propane-air flame.
——— Experimental curve.
- - - - Theoretical curve with heat release at a plane.

equation is

$$\frac{T-T_1}{T_2-T_1}=\exp\left(-\frac{u_nc_p\rho}{k}x\right). \tag{5}$$

Since the propane has a negligible effect on the properties of the fuel-air mixture at the lower temperature, the physical properties of dry air[8] were averaged over 100°K intervals. These were substituted into Eq. (5) and the resulting temperature distribution is plotted in Fig. 9.

The temperature at which heat release becomes important is indicated by the place where the two curves of Fig. 9 begin to diverge. Evaluation of the rate of heat release through the flame would seem possible from the experimental curve, however, the errors involved in doing this graphically are too great to yield results.

ACKNOWLEDGMENT

The authors wish to thank Dr. J. O. Hirschfelder and Dr. H. Lowell Olsen for their helpful criticism of this work and the Navy Bureau of Ordnance for their financial support under Contract NOrd 9938.

[8] Thermal conductivity evaluated from viscosity data of Hirschfelder, Bird, and Spotz, J. Chem. Phys. 16, 968 (1948) by the equation: $k=(\eta/28.966)(c_v+9/4)$.