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Measurement of Normal Burning Velocities of Propane-Air Flames from Shadow Photographs*

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The limitation placed upon the stroboscopically illuminated particle method of measuring the normal burning velocity by the heat capacity of the particles is discussed. A supplementary method of measuring the normal burning velocity using a modified Gouy procedure is presented. The line between the dark and light spaces on shadow photographs, taken at different distances from the flame to the film, is used in this method to define the flame area. This area is then extrapolated to the diametral plane of the flame. This procedure gives results that are consistent with the particle method of determining the normal burning velocity and its use is justified empirically. Burning velocities of propane-air flames are given.

Nomenclature

α = Angle between flame front and vertical
u_f = Gas filament velocity in vertical direction
u = Burning velocity
A = Area of flame surface
V = Volumetric flow rate

INTRODUCTION

IN order to obtain a knowledge of the mechanism of flame propagation it is necessary to measure accurately parameters that are characteristic of the burning mixture. One parameter that is commonly measured is the "burning" or "transformation" velocity. This is defined as the rate of propagation of a flame through gas in a direction normal to the flame surface. However, this is not a quantity that is readily defined unless the velocity is measured relative to the cold unburned gas. When this velocity is measured relative to the cold gas, it is known as the "normal burning velocity."

Measurement of the burning velocity has been accomplished by three general methods. First, the propagation of a flame in a tube or a spherical bomb has been used to measure this quantity.[1] Second, the propagation of a flame in a soap bubble has been used.[2,3] These two methods are inaccurate because they perturb the burning mixture with changing pressures, water vapor, cold walls quenching the flame, or an irregularly shaped flame front. For these reasons the third method, which consists of measurements made on stationary Bunsen flames, has been most commonly used. The use of a laminar Bunsen flame has the advantage of steady-state determinations which are easier to make than measurements of transients.

Generally, Bunsen burner methods of obtaining burning velocities are either a modification of the Michelson method[1]

$$u = u_f \sin\alpha, \tag{1}$$

or of the Gouy method[1]

$$u = V/A. \tag{2}$$

The Michelson method will yield the normal burning velocity if the angle and gas filament velocity can be determined. The angle can be measured fairly accurately, but measurement of the filament velocity offers some difficulties.

Smith and Pickering,[4] in using the Michelson method, assumed that with laminar flow the parabolic velocity distribution across the tube continued for some distance above the mouth of the burner tube. They then used this assumption to determine the filament velocity. This process introduces systematic errors because the velocity distribution is not parabolic due to the back pressure of the flame; and the visible flame cone from which the angle is determined lies in the hot gas region and therefore the streamlines have diverged.[5] Since the streamlines diverge, burning velocities measured near the center portion of the cone are low.

Lewis and von Elbe[6] introduced small particles into the flowing gas and stroboscopically illuminated them to obtain the filament velocity. The addition of a constant-velocity profile nozzle to give straight-sided flame cones and an improved method of feeding particles into the gas stream[5] has made this an accurate and simple method of obtaining normal burning velocities for a limited range of fuel-air mixtures.

Further work at this laboratory has indicated that the development of a method of measuring normal burning velocity other than the stroboscopically illuminated particle method is necessary. For the propane-air system, it has been observed that the addition of particles to mixtures leaner than 3.8 percent propane causes a significant decrease in the burning velocity. This is evidenced by an increase in the height of the

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[1] Jost-Croft, *Explosion and Combustion Processes in Gases*, (McGraw-Hill Book Company, Inc., New York, 1946), Chap. III.
[2] Fiock and Marvin, Chem. Rev. **21**, 367 (1937).
[3] Stevens, NACA, T.M. 305 (1929); NACA, T.M. 372 (1930).
[4] Smith and Pickering, J. Research Nat. Bur. Stand. **17**, 7 (1936).
[5] J. W. Andersen and R. S. Fein, J. Chem. Phys. **17**, 1268 (1949).
[6] B. Lewis and G. von Elbe, J. Chem. Phys. **11**, 75 (1943).

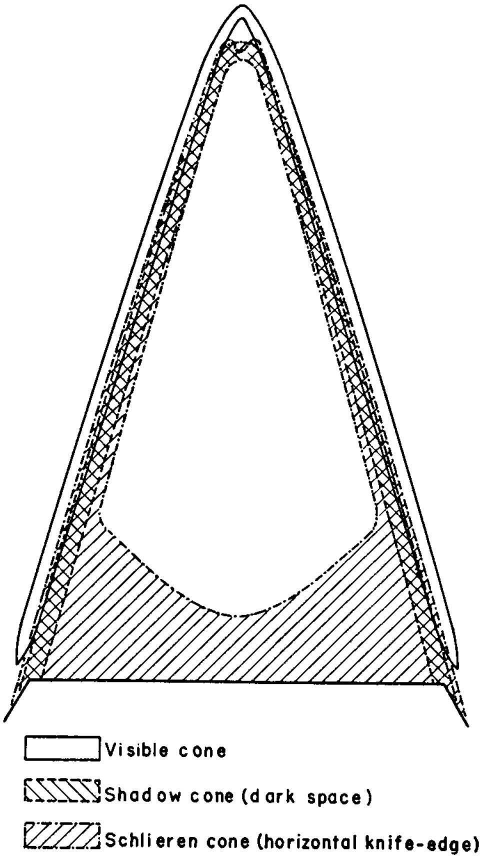


FIG. 1. Propane-air flame cones.

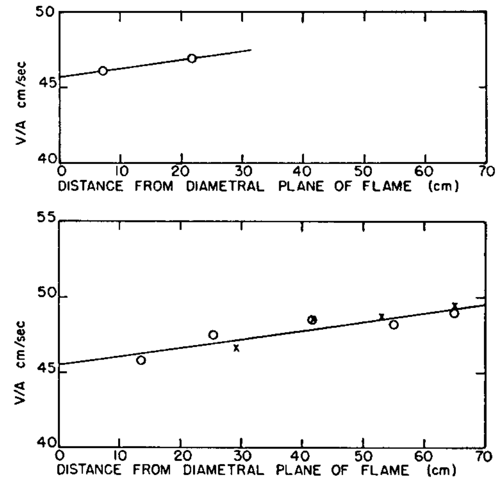
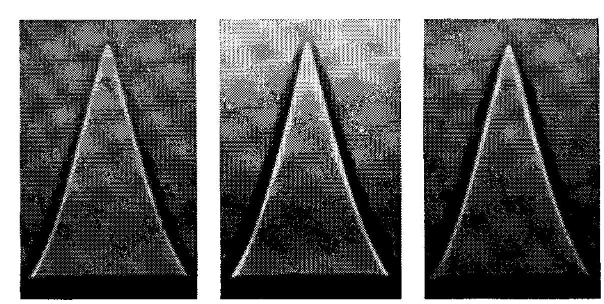


FIG. 3. Determination of normal burning velocity of a 4.12 percent propane-air flame from the flame area defined by line between dark and light spaces on shadow photograph. Top: $\frac{1}{2}$-inch constant velocity profile nozzle. Bottom: $\frac{1}{2}$-inch straight tube. ○, flow rate=119 cc/sec.; ×, flow rate=237 cc/sec.

flame cone upon the addition of the particles. The decrease in the burning velocity is probably the result of the large heat capacity of the magnesium oxide particles. As leaner mixtures are approached, the residence time of the particles in the flame zone increases and, as a result, the particles take up enough heat to appreciably disturb the flame. The increased residence time is caused by the decreased burning velocity and the increased thickness of the flame zone. To circumvent this difficulty, it is necessary to develop a method of measuring the normal burning velocity that will not disturb the flame.



(a) (b) (c)

FIG. 2. Shadow photographs of 2.87 percent propane-air flame; flow rate 108 cc/sec., $\frac{5}{8}''$ I.D. burner tube. Distance from diametral plane of flame to film (a) 23.8 cm, (b) 33.0 cm, (c) 43.3 cm.

The Gouy method of measuring the burning velocity will give the normal burning velocity provided the following conditions are true: (1) the flame area that is measured is at the base of the temperature gradient through the flame zone; and (2) if the quenching of the flame at the base of the cone and the increased burning velocity at the tip of the cone caused by preheating of the unburnt gases and/or diffusion of active centers into the unburnt gases are negligible or compensate for each other. It is apparent that to obtain results consistent with the definition of normal burning velocity, an experimental procedure for the detection of the base of the temperature gradient is necessary.

Flame areas for the Gouy method of measuring burning velocities have been determined by direct, schlieren, and shadow photographs.

The flame cones obtained by these three types of photographs for a 4.12 percent propane-air flame on a constant-velocity profile nozzle are illustrated in Fig. 1. It should be observed that the three cones do not coincide. Since it can readily be shown that the outer edge of the dark shadow cone must correspond to the top of the temperature gradient,[7] it is apparent from Fig. 1 that the visible cone lies in the hot gas region. This is in agreement with the results of the determination of the temperature gradient through the flame front from stroboscopically illuminated particle tracks[5] and rules out the use of the visible cone for the determination of normal burning velocity. The use of the Schlieren cone is not practical because the Schlieren method is too sensitive to give a well-defined flame cone. Thus, the shadow cone remains as a possible source of flame area data that is consistent with the definition of the normal burning velocity.

[7] Sherratt and Linnett, Trans. Faraday Soc. 44, 596 (1948).

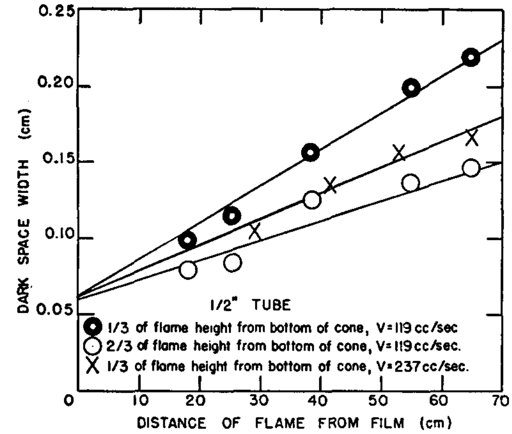


FIG. 4. Extrapolation of dark space width to the flame.

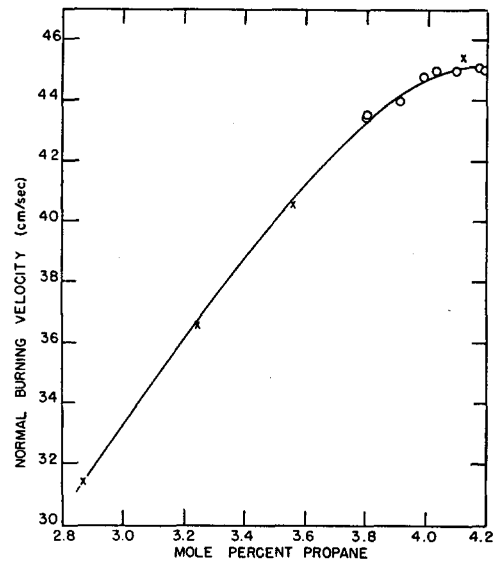


FIG. 5. Normal burning velocities of propane-air mixtures. ○—measured by stroboscopically illuminated particle tracks. ×—measured by shadow photographs.

EXPERIMENTAL METHOD AND JUSTIFICATION

Sherratt and Linnett[7] have used the line between the dark and the light space (inside line of dark space in Fig. 1) to measure the burning velocity. This gives a burning velocity that is too large because the width of the dark space increases with increasing radius of curvature and with distance from the diametral plane of the flame to the photographic plate.[8] This is illustrated in Fig. 2.

Since the width of the dark space decreases as the film is brought close to the flame, the velocity, V/A, determined from numerical integration of the area defined by the line between the dark and light spaces and from the flow rate, also decreases. It is found that if V/A, determined in this manner, is extrapolated back to zero distance between the flame and the film, the velocity obtained agrees with the normal burning velocity obtained with stroboscopically illuminated particles.[5] This is shown in Fig. 3, which illustrates the extrapolation for 4.12 percent propane-air flames under widely varying flow conditions. It is apparent that 45.5 cm/sec. is obtained from the extrapolation of V/A. This value agrees well with 45.0 cm/sec. from the particle method.[5]

On the presumption that this method of determining the flame area is correct, the width of the dark space at zero distance should correspond to the length of the temperature gradient through the flame (since the outer edge of the dark space indicates the top of the temperature gradient). Figure 4 shows the extrapolation of dark space widths determined with a pair of dividers, for the 4.12 percent propane-air flame. The extrapolated width of 0.6 mm is in good agreement with the length of the steep portion of the temperature gradient.[5,9]

From the preceding evidence, it is concluded that this is an accurate technique for the determination of the normal burning velocity. The method has been used to supplement the data obtained by the particle method for lean propane-air flames and the results are presented in Fig. 5.

[8] Keenan and Polachek, Nav. Ord. Report No. 86–46.

[9] St. John and Olsen, UW/APL, CM Report No. 549 (1949).