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COMPARISON OF METHODS USED IN CALCULATING BURNING VELOCITIES OF FLAMES IN LAMINAR FLOW

Thesis for degree of M. S.
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DEAN E. BLUMAN
1956

THESIS

This is to certify that the

thesis entitled

COMPARISON OF METHODS USED IN CALCULATING
DOWNWASH VELOCITIES OF FLAPPED AIRFOILS

presented by

Bruce E. Blumen

has been accepted towards fulfillment
of the requirements for

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COMPARISON OF METHODS USED IN CALCULATING BURNING VELOCITIES OF FLAMES IN LAMINAR FLOW

By

Dean E. Bluman

AN ABSTRACT

Submitted to the College of Engineering of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

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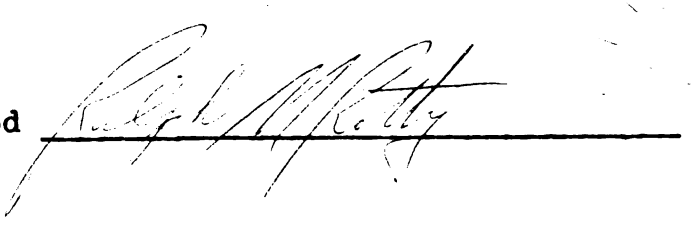
Approved 

THESIS

One of the areas in the field of combustion theory and application which has been extensively investigated is the measurement of burning velocities of combustible mixtures. The burning velocity is the velocity with which a flame front moves normal to its surface through the adjacent unburned gas. It is a fundamental constant of the combustible mixture, and is important both practically, in the stabilization of flames, and theoretically, for theories of flame propogation.

This discussion is limited to flames which appear above gases in non-turbulent flow, such as the familiar bunsen burner flame. Elementary considerations of continuum physics are applied in order to examine certain flame characteristics. It is shown that the overhang of the flame at its base and the rounding off of the flame tip effect the local burning velocities. Thus a distinction is drawn between apparent flame velocities and standard burning velocities. The more important of the many methods which have been used to measure flame speeds, such as the soap bubble, right cone, flame angle, total flame area, Dery's, and the particle track methods, are discussed. From a photograph of an actual flame, calculations were made by as many of these methods as was possible, in order to compare the results. It was found that a wide varience of the results occured, which is not always recognized in the literature.

The methods which give apparent flame speeds that most closely approximate the standard burning velocities are those which circumvent the effects of the flame base and tip.

Also discussed were the various methods by which the flame front can be located. The direct photograph gives a reasonable approximation by considering the inside boundary of the visable flame, but for more accurate results the schlieren method is recommended. The schlieren method gives the location of the maximum rate of change of density of the mixture as it moves through the flame. This is considered to be the true beginning of the combustion process.

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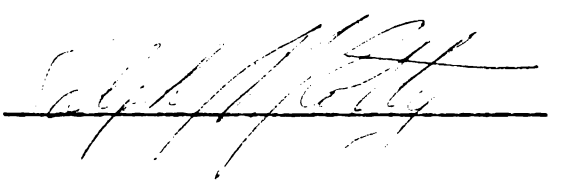
Approved 

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TABLE OF CONTENTS

I.	INTRODUCTION	1
II.	THE SOAP BUBBLE TECHNIQUE	8
III.	ELEMENTARY THEORY OF FLAME STRUCTURE	12
IV.	GEOMETRIC ANALYSIS OF FLAME SHAPE	23
V.	LOCATING THE FLAME FRONT	27
VI.	THE CALCULATION OF APPARENT FLAME SPEEDS	30
VII.	EXPERIMENTAL EQUIPMENT AND PROCEDURE	36
VIII.	DATA AND CALCULATIONS	38
IX.	CONCLUSION	43
X.	LIST OF REFERENCES	48

INTRODUCTION

In our present highly mechanized society, our main source of power comes from the release of heat energy by the oxidation of hydrocarbon fuels. While it is true that water power is important in some parts of the country, and that the heat released by atomic fission and possibly even fusion promises to provide more and more energy in the future, the mainstay of our power is the combustion of fossil fuels.

Two basic types of heat engines, used to convert heat energy into mechanical power, are recognized by the engineer. The first is the familiar internal combustion engine in which the fuel is burned inside the power-producing machine and the products of combustion are expanded directly to produce mechanical power. In the second type, the heat released by combustion is transferred by means of a heat exchanger into the working fluid of a cyclic heat engine, as in a steam power plant. Because of this difference, the problems of combustion chamber design are considerably different, but the broad principles of combustion are in many respects the same.

In this connection, it is obvious from a survey of the literature that the average practicing engineer has little or no conception of the true nature of combustion processes.

From chemistry and physics it is learned that combustion is a process of rapid oxidation, that carbon dioxyde and water vapor are formed, and that heat quantities released can be found in appropriate tables. Beyond this point, American engineering practice dictates the trial and error method of design rather than the application of theoretical principles. In all fairness to the engineers, it should be noted that only a very small portion of flame characteristics can be explained by theory, but in recent years the accent in industry has been toward research on a fundamental level. It is hoped that this trend will carry from the laboratory to the design and development engineering departments.

Much information is available in the literature on both theoretical and experimental aspects of combustion, but in every case the reader will encounter repeated reference to major areas as yet unexplored or just barely touched upon. In recent years there have been several organized attempts to further our general fund of knowledge in this field. AGARD, The Advisory Group on Aeronautical Research and Development, North Atlantic Treaty Organization, annually publishes a book entitled "Combustion Researches and Reviews." The Combustion Institute has held (as of 1954) five international symposia on the subject, and the list of contributors and members composes an outstanding cross section of prominent names in the field. Other private and governmental organizations, such as the U.S. Bureau of Mines, are also making outstanding contributions.

As is the general practice in the field of combustion, this paper will use the definitions of terms and symbols as they are used by Lewis and von Elbe[1], except where they are different from common engineering practice.

It is obvious that general problems in combustion are both physical and chemical in nature. Of necessity, the chemistry of combustion is omitted except for very general statements which are required for an understanding of the physical aspects. (The reader is referred to Lewis and von Elbe, Chapters I through V, for a comprehensive discussion on the chemistry of combustion.)

The general term "combustion" is defined by the layman to refer to a chemical reaction between a "fuel" and oxygen which produces heat and light. Although this definition does not hold in a few minor cases, it will suffice for our purposes here. Some compounds, such as ozone, acetylene, etc., are explosive by themselves, as they possess large negative heats of formation. However, there is no fundamental difference between a combustion wave in a single-component explosive gas and a mixture of gases.

This paper will be concerned primarily with combustion waves or flame fronts under non-turbulent conditions in hydrocarbon and air (or oxygen) mixtures. The difference between turbulent and laminar flow with respect to Reynolds number is well known, and only flames in laminar flow will be discussed.

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[1]B. Lewis and G. von Elbe. Combustion, Flames, and Explosion of Gases. New York: Academic Press Inc., 1951.

There seems to be some disagreement among scientists as to the actual mechanism of flame propagation, and many theories have been advanced on the subject. There seems to be general agreement, however, that the reaction proceeds via free radicals. For example, in the n-paraffin group, it is thought that a free radical is formed by the removal of an H atom from the molecule, which is then subject to attack by the addition of O_2 to the free C valence[2]. Thus it is seen that "heat" is only a part of the story in flame propagation.

An ignition source is generally a source of heat. However, it is known that ignition sources, such as an electric spark, also create atoms and free radicals which can perpetrate the reaction. Therefore, a combustion wave is propagated by the transfer of heat from the wave to the surrounding gases, and also by molecular diffusion of free radicals. In this way, heat and diffusion are interrelated since the molecular activity is increased by a higher temperature level.

The combustion process occurs as follows: A chemical reaction in the fuel and air mixture is initiated by the flow of heat and/or chain carriers from an ignition source. This reaction zone acts as an ignition source for the adjoining layer of mixture. Thus, if the proper physical conditions are present, the reaction is a continuous one, and a combustion wave is formed.

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[2] Ibid, Page 172

It is necessary to distinguish between a combustion wave and a detonation wave. This can be done by noting that the speed of the combustion wave is small compared with the speed of sound in the explosive medium, while the speed of the detonation wave exceeds that of sound. This is the result of a different type of process which causes the chemical reaction in the highly compressed shock wave region. That is, the mixture is compressed to a high temperature by the shock wave so that the detonation wave can proceed faster than in the normal combustion wave where the increase in temperature of the unburned gases is due only to heat transfer and diffusion. Most combustible mixtures will support either type of wave, depending on the physical conditions of the situation, especially confinement and composition. For example, the familiar oxygen-acetylene welding torch maintains a steady combustion wave when the constituents are in the right proportions, but if the flow is cut back, the flame reaches the "flash-back" point and a detonation wave is formed, as evidenced by the sharp sound produced. However, if the percentage of one or the other of the constituents is increased, or an inert gas is introduced, a dilution point is found where a detonation wave can no longer form. This is called <u>limit of detonability</u>. Usually a combustion wave can be maintained after this limit is past until further dilution causes the <u>limit of inflammability</u> to be reached. Generally, a detonation wave is an undesirable phenomenon, and most humanly controlled combustion processes are of the

combustion wave variety. Therefore, we will confine our definition of flame velocity to that of combustion waves.

At this point it is advisable to make a distinction between true burning velocity and apparent flame velocity. Much confusion exists in the literature due to the varied usuage of terms pertaining to flame velocity. Obviously, flame speed depends primarily on the chemical composition and characteristics of the combustible mixture. However, the same mixture will burn with varying velocities in different physical surroundings. This is due to several things, which will be discussed later. It is thus desirable to select and define a "standard" burning velocity which is dependent only on the pressure, temperature and chemical composition of the combustible mixture. (Obviously, these should be defined for a numerical value of burning velocity to have any significance, and this has not been done in many cases.)

It is this phase of combustion, that is, the determination of burning velocities of a wide variety of fuels, that a large percentage of the research in the field of combustion has been done. The need for such basic information is readily apparent. It is the purpose of this paper to review the various methods by which flame velocities in laminar flow have been measured and to discuss the advantages and disadvantages of each.

As yet, no truly direct method of measuring standard burning velocity has been found. This is due partly to the

fact that the combustion wave itself gives rise to complex physical manifestations, such as the motion of the unburned gas as it approaches the flame front, and the pressure drop, large or small, which always occurs across the wave front, and partly due to our inability to devise a method whereby the physical surroundings will not affect in any way the reaction process. Therefore, any physical measurement of this type should properly be called an apparent flame speed. Our criterion for judging a particular method of measuring flame velocity will be the degree to which we feel the result approaches the standard burning velocity.

THE SOAP BUBBLE TECHNIQUE

A large variety of experiments has been tried in an attempt to measure the burning velocities of combustible mixtures. One of the most unique, and in many respects the most direct approach to the problem, is the soap bubble method. This method was devised by F. W. Stevens at the laboratories of the National Advisory Committee on Aeronautics. A ring of gold wire is suspended from above, as is a tiny electric spark gap located in the center of the ring. A combustible mixture is then enclosed inside a soap bubble, the bubble being attached to the gold ring. When a spark is created at the gap, the mixture ignites and expands as a

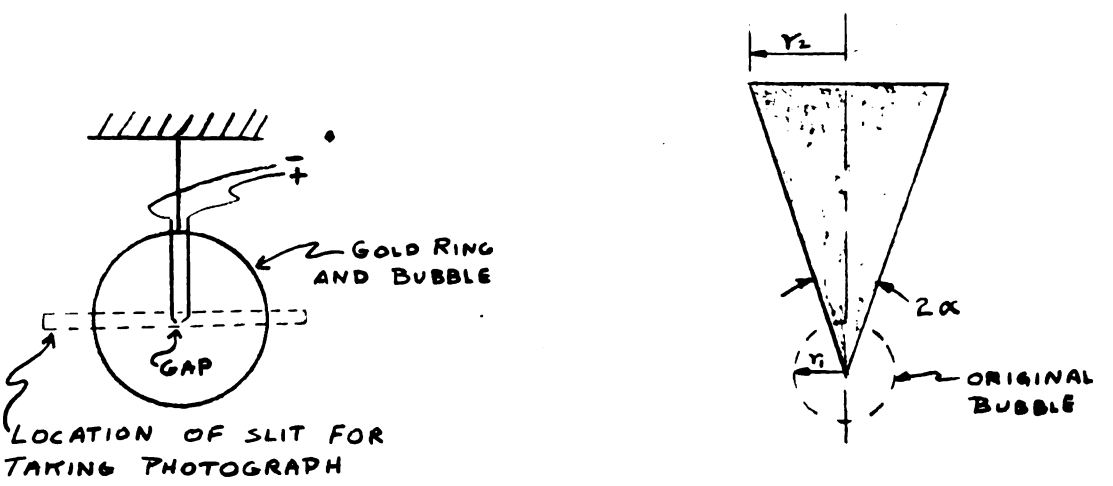


Fig. 1. Schematic of soap bubble experiment and expanding flame picture

spherical combustion wave. The soap bubble offers practically

no resistance to the enclosed gas, and so the combustion process is virtually one of constant pressure. The presence of the wire and the electrodes at the center of the flame causes some deformation at the top and bottom due to the heat sink effect. Also, in slow burning mixtures, there will be some convective rise. However, from high-speed pictures of the actual combustion process it was observed that a narrow horizontal midsection of the flame appeared to be unaffected. Therefore, all but this portion was blacked out and a piece of film was drawn with uniform velocity over the remaining slit and at a right angle to the horizontal. Thus a record of flame expansion with time was recorded. The perfect linearity of this variation is most impressive, as shown in Fig. 1. It gives convincing proof that the velocity of flame propagation is indeed perfectly steady and uniform. As will be discussed later, this is of prime importance in other methods of determining burning velocity.

While the most important result of this experiment is the positive proof of constant and uniform flame propagation, it has also been used by Stevens and others to measure flame velocities directly. The image left by the advancing flame front on the moving film starts as a point at the spark gap and expands linearly until the gas is consumed. Thus the side of the picture makes an angle α with the image of the spark gap. The magnification factor (m) and the linear film velocity (S_f) are known, and the final radius (r_2) of the flame and the angle α can be read from the photograph.

The subscripts u and b refer to the unburned and burned gases, respectively. The burning velocity of the gas will be hereafter referred to as S_u. From simple geometry, the speed of the flame in space (S_s) is given by

$$S_s = m\, S_f \tan \alpha$$

We can define an expansion ratio (E) at constant pressure in terms of the radii or the densities.

$$E = \left(\frac{r_2}{r_1}\right)^3 = \frac{\rho_u}{\rho_b}$$

where (r_1) is the radius of the spherical bubble before ignition. The conservation of mass principle can be utilized to equate the mass of gas entering the wave with the mass leaving.

$$S_u \rho_u = S_s \rho_b$$

Combining and solving for the burning velocity,

$$S_u = \frac{S_s \rho_b}{\rho_u} = \frac{S_s}{E} = \frac{m S_f \tan \alpha}{E}$$

Thus the burning velocity may be calculated directly from the results of the bubble experiment.

The soap bubble method would appear to give an accurate value of the true burning velocity, but there are some complications which can arise. As was mentioned previously, convection effects will cause some error in slow-burning mixtures, and the bubble-supporting ring and electrodes will absorb some heat from the reaction. This technique obviously involves some delicate and sensitive instruments to provide reasonable accuracy, but probably the most serious objection is the effect of the aqueous soap film on the combustible mixture.

It was found by subsequent investigators that the partial pressure of H_2O vapor rapidly increased in the originally dry combustion gases until it equaled the partial vapor pressure of the atmosphere. This occurred with the use of a mixture of water, glycerine, and soap as the bubble substance. Another serious difficulty under the same conditions is the fact that the method is not suitable for use with hydrocarbon fuels, since they rapidly diffuse into and perhaps through the film causing a change in the measured chemical composition of the mixture. Some work is now being done using certain detergents in other solutes than water, but the results are not yet available.

ELEMENTARY THEORY OF FLAME STRUCTURE

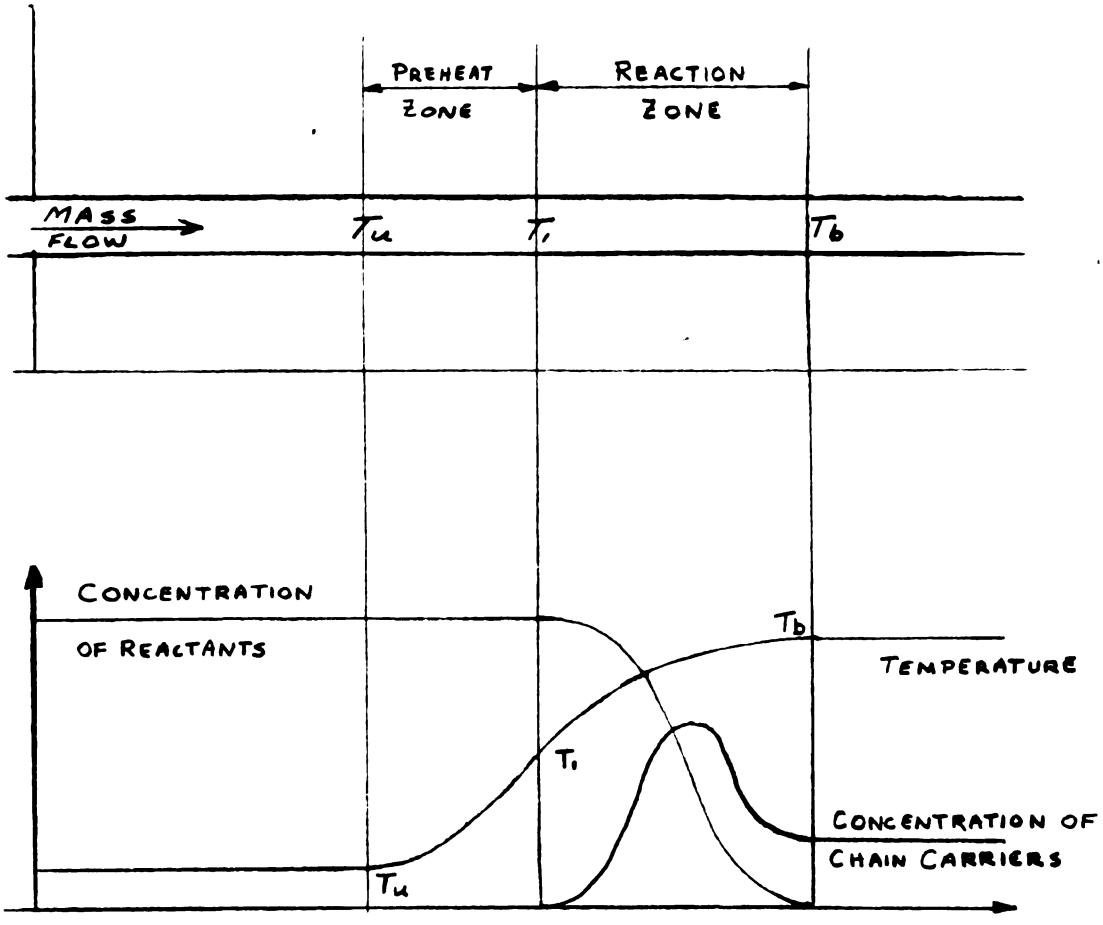
It has been tacitly assumed and then shown by the soap bubble technique that a combustible mixture does have a unique and constant burning velocity. It follows that if the proper amount of gas is flowing toward the flame front there will be a condition, or range of conditions, where the normal velocity of the unburned gas will be equal to the apparent flame velocity and a so-called "standing" combustion wave will result. This is a familiar phenomenon to the layman in such devices as gas stoves and furnaces, welding torches, and the like, although in these cases the gas is usually moving with turbulent flow. (The combustion process in turbulent flow must be analyzed separately and will not be included here.) Probably the standing combustion wave most familiar to the science student is the bunsen burner flame. This type flame has been used more than any other method for determining flame speeds. It is most used above a cylindrical tube where the velocity distribution of the gas is parabolic, but it is also used above nozzles, where the velocity distribution is uniform over the exit section. The other important measuring technique is the flat flame, but this sometimes requires special burners, and will be dealt with separately.

In any non-turbulent flame the general theory of the structure and stability of combustion waves in gas streams applies. This section of the paper is devoted to a description of this theory as it applies to laminar flames.

The combustion wave in laminar flow is examined by the use of continuum physics theory; thus the principles of conservation of mass, momentum, and energy which govern the processes within the wave are expressed by the three hydrodynamic equations of change: the equation of continuity, the equation of motion, and the equation of conservation of energy. These equations, in conjunction with equations for diffusion and chemical reaction, determine the distribution of various molecules, as well as the changes in mass velocity, pressure and enthalpy throughout the wave. As was mentioned previously, a combustion wave differs from a detonation wave in that its velocity is very much less than the speed of sound in the mixture. As shown in hydrodynamics, this implies that there is essentially no pressure change across the wave front from the mass acceleration. Thus it is usually assumed permissible to neglect the small effect of the pressure gradient across the wave, and therefore the equation of motion, which determines the pressure change, may be ignored in low Mach number combustion processes. In a somewhat similar manner, other flame phenomena or characteristics can be largely understood from elementary considerations of heat conduction and diffusion, or conservation of mass and momentum principles. This will be apparent from the remainder of this section.

Since the analysis of the inner wave structure is the most difficult part of combustion theory, this treatise will deal only with those problems which are essential to an understanding of burning velocity measurement theory and which can be explained qualitatively by simple continuum theory.

A combustion wave can be thought of as a series of elemental layers of infinitesimal width. The surfaces of such layers may be chosen so that the temperature, or the concentration of some molecular species, or the rate of some process associated with chemical reaction is constant along the surface. If the wave does not change its curvature with time, and the gradients across the wave do not vary with time, the wave is said to be in steady state. A fixed reference axis can then be defined, so that the unburned gas flows across the layers. The waves may then be assumed plane-parallel to each other, so that the direction of the mass flow is known, say in the x-direction, and a stream tube is considered through the layers. Molecular flow in these stream tubes is due not only to a pressure gradient, but also by diffusion due to a concentration gradient of various molecular species. Referring to Fig. 2, the subscripts u and b again refer to the unburned and burned gases respectively, and the subscript (1) refers to the point of inflection in the temperature-versus-distance curve. This inflection point is generally considered to be the boundary between the preheat and reaction zones. If an element of unburned gas is followed through the tube, it is found that the temperature rises as shown in Fig. 2. In the



[3] Fig. 2. Scheme of the Propagation and Structure of a combustion wave

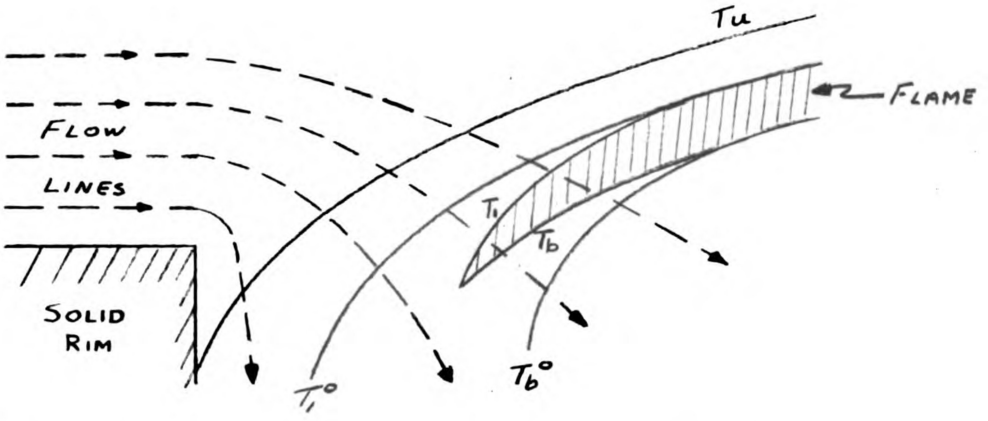
theory of heat conduction, it is shown that the rate of temperature rise for one dimensional heat flow is given by $\propto \frac{\partial^2 T}{\partial x^2}$, where $\propto$ is the coefficient of thermal diffusivity. When this quantity is positive, as from (u) to (1), the element is receiving more heat from the (b) direction than it can reject toward the (u) direction. After it has passed through point (1), the quantity is negative, that is, it is losing more heat than it is getting. The temperature does continue to

[3] Ibid. Page 231.

rise, however, because the chemical reaction is still releasing heat. Similar arguments can be made for the other two quantities plotted above; in particular, the diffusion of intermediate products such as atoms and free radicals which may serve as chain carriers in the reaction. However, while the temperature rises asymtotically to a maximum, the chain-carrier concentration may pass through a maximum and decrease toward a value corresponding to the thermal equilibrium between atoms, free radicals, and neutral molecules at the boundary b. This value at temperature b is determined partly by the dissociation of the products of combustion and partly by the diffusion which is taking place along the flow lines.

There are two physical aspects of a conical flame which effect the measurement of the burning velocity. One is the so-called "overhang," or deformation of the flame around the rim of the burner tube, and the other is the rounding off of the flame tip when theoretically, by simple geometrical considerations, the tip should be a sharp point. (This will be proven in the following section.) An analysis of these phenomena are now given in the light of their effect on burning velocity.

Consider the diagram, Fig. 3, which shows a section of the flame and the burner rim (not to scale) and a series of flow lines and isotherms. Heat being transferred from the flame front to the unburned gas causes an expansion and therefore a divergence of the flow lines as they leave the



[4]Fig. 3. Flow lines and isotherms of a combustion wave near a burner rim

burner tube. The solid rim acts as a heat sink for the flame and as a heat source for the entering gas, but these effects decrease rapidly toward the center of the tube so that for stream tubes toward the middle of the burner the heat evolution of combustion is essentially adiabatic. Adiabatic combustion values are properties of those stream tubes which reach the flame front without a gain or loss of heat, and are differentiated by use of the superscript °. It is seen that $T_1°$ and $T_b°$ coincide with T_1 and T_b, respectively, at some distance away from the burner rim, but as the effects of the rim come into play they separate and eventually T_1 and T_b merge to form the edge of the flame. T_1 and T_b are the same temperatures referred to in the one-dimensional flow analysis, except that now the conduction equation should be written as

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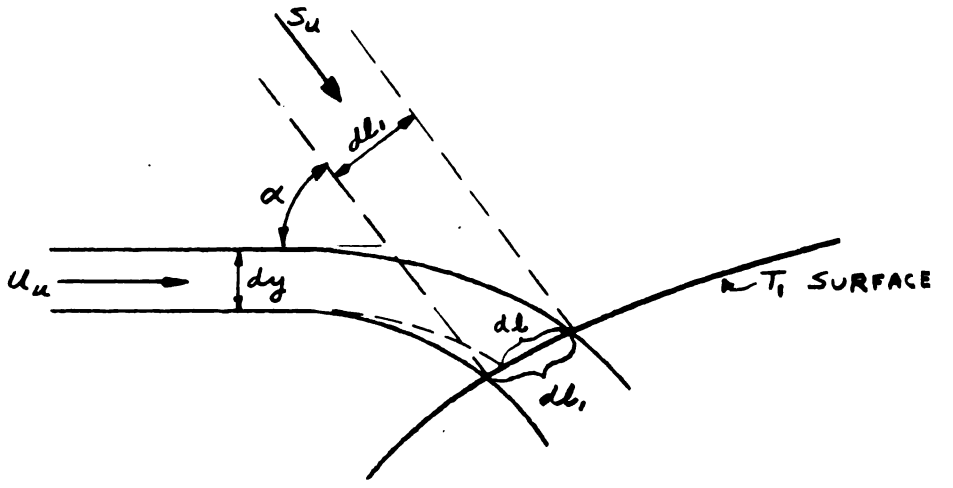
[4]Ibid. Page 233.

$\nabla^2 T$ instead of $\frac{\partial^2 T}{\partial x}$ since we are dealing with three-dimensional flow.

The surface defined by the T_1 isotherm is considered to be the front of the combustion wave, and is used as the reference surface whose movement relative to the gas stream determines the direction and velocity of the combustion wave. Thus, the direction of the wave coincides with the normal to the surface, and the wave velocity is the normal component of the fluid velocity relative to the wave front. ρ and S are introduced to denote the density and the normal component of the mass velocity relative to the wave front. In Fig. 4, a stream tube is shown across the wave front which encloses the elemental area dl_1.



[5]Fig. 4. Relation between mass velocity and burning velocity

[5]Ibid. Page 236.

The mass transferred across dy is $\rho_u u_u dy$.
By the continuity equation, this is equal to $\rho_1 S_1 dl_1$.
To define the wave velocity, we consider an imaginary tube of constant cross-section dl_1, and assume that the axial component of mass velocity along this tube is constant, so that $\rho_1 S_1 dl_1$ equals $\rho_u S_u dl_1$. The velocity so defined, S_u, is called the burning velocity. If the flow lines remained parallel in the wave the subtended area would be $dl \leq dl_1$.
Substituting and solving for S_u,

$$S_u = u_u \frac{dy}{dl_1} = u_u \frac{dl}{dl_1} \cos\alpha$$

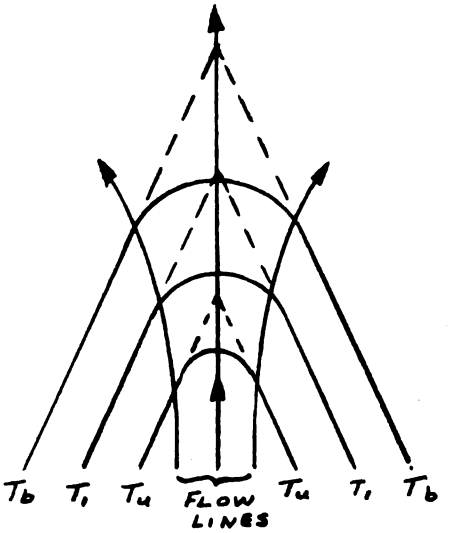
If we consider the tube to be extended to the b surface, the tube encloses a volume of the combustion zone equal to dl_1 times zone thickness. Thus if $\bar{q}$ is the average rate of heat evolution per unit volume, and if we assume dl_1 to be unit area, the heat released in the volume is $\bar{q}$ times thickness. This must equal the rate of supply of heat of combustion, or $Q\rho_u S_u$, where Q is defined as the heat of combustion per unit mass of fresh gas.

$$\bar{q} \text{ times zone thickness} = Q\rho_u S_u$$

The quantity $\bar{q}$ and the zone thickness will both decrease near the burner rim as was shown previously. Since Q and ρ_u are constant, it follows that the flame velocity must decrease, and ultimately vanish at the point where the T_1 and T_b isotherms merge. This is proof of the statement made earlier in this paper that burning velocity is affected by the physical surroundings, and points up the distinction between "standard" burning velocity, which is a constant, and apparent flame speed.

The region between the flame fringe and the burner rim is usually called the "dead space." Evidently, as two sinks, such as opposite sides of a burner, are brought together, the dead spaces will merge and a "zone of quenching" is formed past which the flame cannot prop gate. The concept of a quenching distance is of practical importance in the design of such things as gas stoves, where the ports are smaller than the critical quenching distance so that the flame cannot flash back to the point of air entrainment. As would be expected, the critical quenching distance is a property of the combustible mixture.

Consider now the tip of a conical flame. As shown in Fig. 5, when two plane waves intersect, there is a rounding off of the intersection. Converging heat from both waves causes T_1 to be reached in the central stream before the extensions of the T_1 lines of each flame meet.



[6]Fig. 5. Curvature of wave layers at the intersection of two combustion waves

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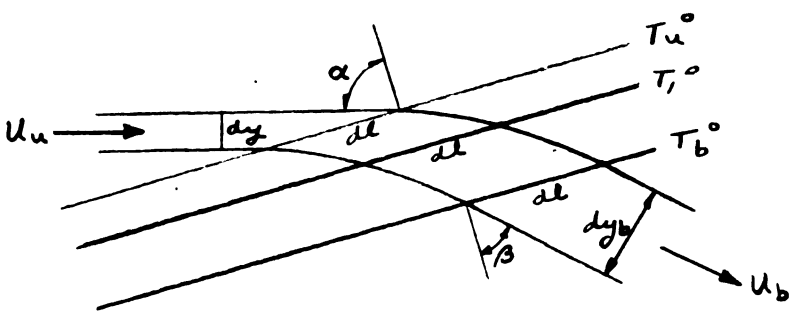
[6]Ibid. Page 237

Thus the T_1 line and all the other isotherms curve to form a tip approximately as shown. Just as the flame velocity decreased at the burner rim, so it must increase at a point of sharp concave curvature such as the cone tip.

In order to define "standard" burning velocity, a section of a plane wave at a distance from wave intersection or wave edge effects is now examined. The release of the heat of combustion in the wave causes a thermal expansion of the gas which exerts a force on the surrounding gases. However, since all surrounding stream tubes are exerting equal and opposite forces, the only direction the gas can expand is in the normal direction. Thus if the stream tube is inclined against the wave, the normal component of the velocity will increase while the tangential component remains a constant. This is shown in Fig. 6 (a).



[7]Fig. 6a. Plane combustion wave inclined against the gas flow. Stream tube and wave layers

[7]Ibid. Page 239.

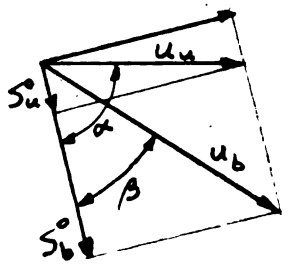


Fig. 6b. Plane combustion wave inclined against the gas flow. Velocity vector diagram.

Note that the enclosed segments of the wave layers have equal areas. Since the mass flow through any stream tube is a constant, and dl is a constant, it follows that

$$\rho_b S_b^\circ = \rho S^\circ = \rho_u S_u^\circ$$

where the superscript $^\circ$ now applies specifically to a plane wave remote from a heat sink. S_u° is called the "standard" burning velocity. If β is the angle between the exit velocity vector and the normal to the surface, $\frac{dy_b}{dl} = \cos\alpha$ and

$$\rho_u u_u \cos\alpha = \rho_b u_b \cos\beta$$

The tangential components remain constant across the wave and are denoted by $U_u \sin\alpha$ and $U_b \sin\beta$. Combining,

$$\frac{\rho_u}{\rho_b} = \frac{\operatorname{ctn}\beta}{\operatorname{ctn}\alpha}$$

which relates the refraction of the stream to the expansion of the gases.

GEOMETRIC ANALYSIS OF FLAME SHAPES

In general, there is only one shape a laminar flow flame can assume above a cylindrical burner. Consider the segment of a wave as shown in Fig. 7. It is assumed that the combustion wave is represented by a single surface, that the burning velocity is constant over the surface, and that the flow lines retain their velocity and direction from the burner opening up to the flame surface.

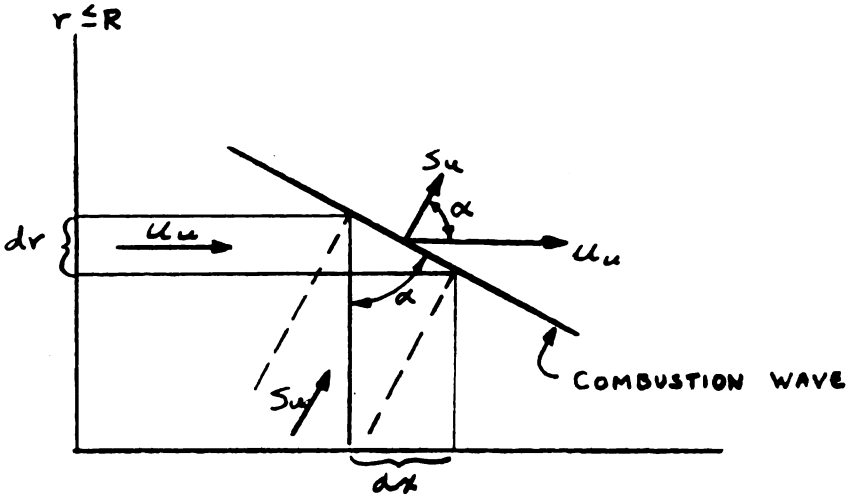


Fig. 7. Combustion wave above laminar flow

The expression for the velocity distribution across a tube in laminar flow is the well-known Poiseuille equation,

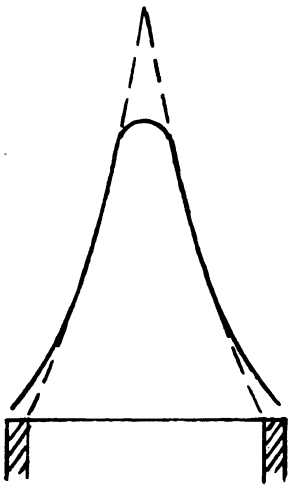
$$u_u = \frac{\Delta P}{4\mu \Delta x}\left(R^2 - r^2\right)$$

where R is the tube radius, r is the distance from the center to the point in question, ΔP is the pressure drop in distance Δx, and μ is the viscosity of the fluid.

In fully developed laminar flow, $\frac{\Delta P}{4\mu \Delta x}$ is a constant, and can be represented by the letter n. From geometrical considerations

$$\frac{dx}{dr} = \tan \alpha = \frac{(u_u^2 - S_u^2)^{1/2}}{S_u} = \frac{[n^2(R^2-r^2)^2 - S_u^2]^{1/2}}{S_u}$$

When the expression for U_u of Poiseulle's equation is substituted as shown, the equation assumes a form involving both the first and second orders of elliptic integrals. The solution to this equation is presented by H. Mache in "Die Physik der Verbrennungserscheinungen." Veit and Co., Leipzig, 1918. The solution, when plotted, gives an outline similar to that shown in Fig. 8. The solid line is the actual flame shape while the dotted line is the calculated shape.



[8]Fig. 8. Comparison of actual and ideal flame shapes above parabolic velocity distribution

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[8]A. G. Gaydon and H. G. Wolfhard: Flames: Their Structure, Radiation and Temperature. London, England: Chapman and Hall Ltd., 1953, Page 52.

The flow through a properly designed nozzle gives essentially a constant velocity distribution across the exit area. Thus, in the differential equation above, U_u, and therefore the entire right side of the equation is a constant. This integrates directly into a linear function, so that ideally the flame front is a right cone. The deviation of the actual from the ideal shape at the tip and base is very similar to that in Fig. 8, for the reasons discussed in the previous section.

Two special aspects of the above discussion are of interest. First, the mathematics of the situation produces a plus-or-minus solution to the differential equation. This shows up in the physical picture in that the flame may be anchored at the base in the normal way, or may be inverted by being anchored to a point sink in the center of the stream. The inverted flame has been used only rarely in the measurement of flame velocities, but its possibilities have not been fully explored. The other interesting aspect is the flat flame phenomenon. Referring again to our differential equation, it is obvious that when the stream velocity is equal at every point to the flame velocity, the equation reduces to $\frac{dx}{dr} = 0$, which defines the flat flame. Note that this can appear only when the gas velocity profile is a constant, since the flame velocity was assumed a constant over the entire surface. The flat flame method has the advantage that the flame velocity is equal to the gas velocity, which can be measured or calculated directly. Powling built special burners which use

grids in a regular burner tube and which result in a uniform velocity profile. This technique for measuring flame velocities seems very well adapted for extremely slow-burning mixtures, and unsatisfactory for fast burning mixtures.

LOCATING THE FLAME FRONT

The development of the theory of burning velocity as discussed in Section III defines the burning velocity to be normal to the T_1 surface, which is called the flame front. The question immediately arises as to how this surface can be located or identified in an actual flame. There are three methods in use at the present time: the direct photograph, the schlieren photograph, and the interferometer photograph.

The direct photograph is obviously the easiest and cheapest to use, and gives fairly accurate results. It is, therefore, used most often. It is generally agreed that the flame front lies on the inner surface of luminescence, but this is somewhat hard to define with the human eye. The eye can recognize, however, the region of maximum rate of change in intensity, so this is assumed to be the flame front location.

"Schliere" is a German word meaning an inhomogeneous region in an otherwise homogeneous matter. Generally, in a transparent body, schlieren are anything which cause an irregular deflection of light which emmanates from a relatively small area. They may be caused either by a change in the refractive index of the medium or a change in thickness. A simple example is a plate of poor quality glass. When a light is passed through it on to a screen, light and dark regions

are observed. It is important to realize that only the dark regions are in a straight line from the glass, since the light refracted away from them is scattered randomly.

Toepler's schlieren arrangement is the most basic, although several variations are used. Suppose that a small source of light, such as a carbon arc, is half covered by a knife edge. The remaining light passes through a convex-convex lens and is focused on the lens of a recording camera. Another knife edge is placed across half of the camera lens so that when the light is undeformed by the absence of a test object, no light can enter the camera. The insertion of a test object, in this case a flame, between the lens and the camera lens causes certain light rays to deflect and enter the camera. If the two knife edges are rotated through 90°, a complete record of the schliere is obtained. The literature is full of more complete discussions of schlieren techniques, so it will be omitted here. The important consideration is that the rate of change of density of the gases across a combustion wave is a maximum at the T_1 surface so it is generally agreed upon by observers that the darkest schliere in the flame represents the true flame front as nearly as we can observe it. It has been shown that this schliere lies just inside the surface as defined by the direct photograph. Thus only a small error is introduced by use of the direct photograph, but for extremely accurate results, a schlieren apparatus should be used.

The one other important method is the interferometer, a device familiar to the science student. It is more expensive and more complicated than a schlieren set-up, but enables more quantitative results to be obtained. It enables the refractive index to be determined, whereas the schlieren method gives primarily the gradient of the refractive index. The refractive index can be related by theory to the temperature of the flame, but has no more significance in the determination of burning velocities than does the schlieren, so further discussion of it is omitted here.

THE CALCULATION OF APPARENT FLAME SPEEDS

A. Flames Above a Gas Stream with Parabolic Velocity Distribution

Consider a flame front as shown in Fig. 9.

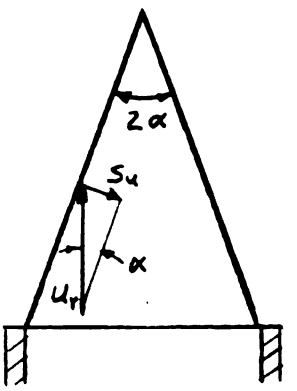


Fig. 9. Flame shape and velocity vector diagram

It is assumed that the flame speed is a constant over the surface, that the density is constant until it reaches the flame front, and that the flow lines are undeflected. The basic premise in the area (or Gouy's) method is the conservation of mass flow. Thus if A_o is the area of the burner mouth and U_o is the average gas velocity across the mouth, their product must be equal to the area of the flame front, A_f, multiplied by the normal component of the velocity which we have previously defined as S_u.

The A_o and U_o terms are readily measurable, and the area of the flame front can be calculated in several different manners, as discussed below.

1. Right Cone

Assume the flame is in the shape of a right cone, of base-radius equal to the radius, R, of the burner, and of height equal to the measured height, h, of the actual cone. Thus, from geometry, $A_f = \pi R \sqrt{R^2 + h^2}$.

2. Angle Method

Referring again to Fig. 9, it can be shown that under the assumptions used in number 1, the following relation can be developed.

$$\sin \alpha = \frac{S_u}{U_o}$$

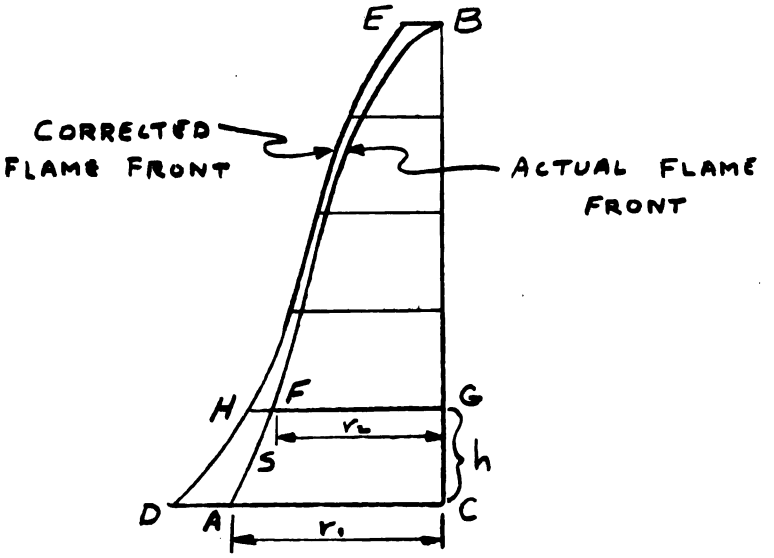
$$S_u = U_o \sin \alpha$$

Thus the cone half-angle can be measured instead of the cone height. This should give the same results as the calculation by method number 1 if the same cone is used. More accurate results will be obtained if the angle between the two relatively straight sides of the actual cone is used.

3. Actual Area Method

The actual area of the flame may be closely approximated by a planimeter measurement. Consider Fig. 10. The flame is divided into sections of equal height as shown. The surface area of the section AF is $\pi s(r_1 + r_2)$ where s is the distance AF, assumed to be a straight line. The area AFGC $= \frac{1}{2} h (r_1 + r_2)$. If α is the cone half-angle at this point, $s = h/\cos\alpha$,

and therefore area AFGC = $\frac{1}{2} s \cos\alpha (r_1 + r_2)$. Assume that the section is taken small enough so that α is constant from r_1 to r_2. Then a new area, DHGC, can be defined where $HG = \frac{r_2}{\cos\alpha}$ and $DC = \frac{r_1}{\cos\alpha}$. The area DHGC equals $\frac{1}{2} h (r_1/\cos\alpha + r_2/\cos\alpha)$ equals $\frac{1}{2} s (r_1 + r_2)$. Thus multiplying the plane area DHGC by 2π gives the flame area around AF. If we determine the area DEBC with a planimeter, we obtain the sum $\Sigma \frac{1}{2} S_n (r_n + r_{n+1})$.



[9]Fig. 10. Calculation of flame front area

If this is multiplied by 2π we have the surface area of the flame front, A_f. This method is more accurate than number one because it takes into account the true shape of the flame. However, the velocity is still assumed constant over the area, which, as has been shown, will introduce some error.

[9]Ibid. Page 56.

4. Dery's Method

Dery's method neglects the base and the tip and assumes that there is a frustrum of a right cone between these two locations. The lateral surface area is given by

$$A_f' = \pi s (r_1 + r_2)$$

where r_1 and r_2 represent the radii at the bottom and top surfaces of the frustrum, respectively, and s represents the lateral height. The volume rate of flow is now $\pi (r_1^2 - r_2^2) \bar{u}_{avg.}$ combining,

$$S_u A_f' = \pi (r_1^2 - r_2^2) \bar{u}$$

$$\text{or } S_u = \frac{\pi (r_1 + r_2)(r_1 - r_2) \bar{u}}{\pi s (r_1 + r_2)}$$

$$S_u = (r_1 - r_2) \bar{u} / s$$

The radii and the lateral height can easily be measured from a photograph. Since the effects of the tip and the base are bypassed, this method would appear to give an apparent flame velocity closer to the standard burning velocity than the first three methods mentioned. It is also probable that the effects of the curvature of the flow lines are cancelled out between the two radii.

5. Particle Track Method

The particle track method was utilized by Lewis and von Elbe to measure burning velocities and also the paths of flow lines through the flame. They used a rectangular burner, and introduced MgO particles into the combustible mixture. By illuminating the particles intermittently from the side, the particle tracks could be followed, and the velocity could be measured at any point as a function of lengths of the path recorded while the light was on (or off) for a known length

of time. Figure 11 shows a plot from their data of velocity versus distance r from the center of the burner. The important result here is the verification of the theory that the

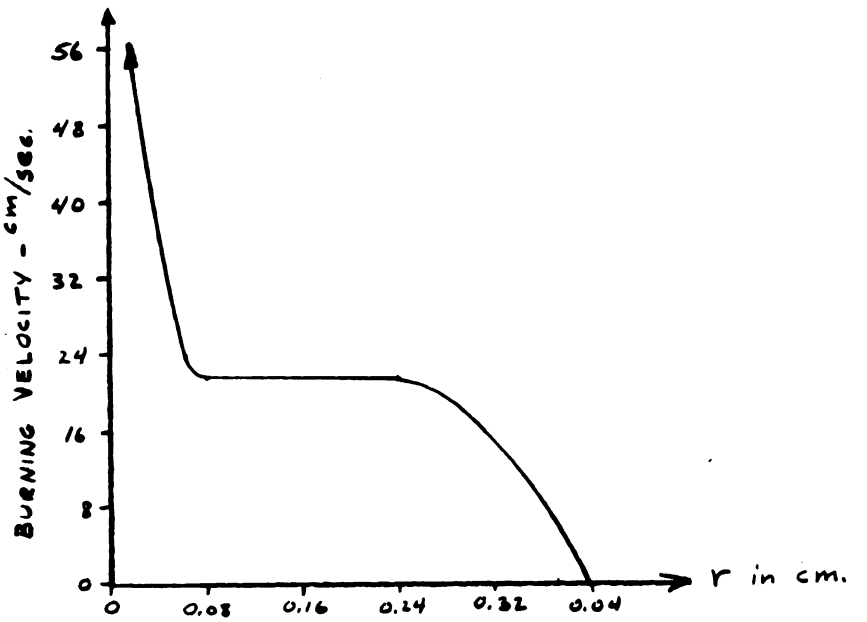


Fig. 11. Relation between flame velocity and distance from center of burner

flame speed increases at the flame tip, decreases at the base to zero, and is virtually constant over the rest of the flame front. Their burner had a width of only 0.755 cm, and this, no doubt, explains the small ratio of constant burning velocity area to the total area. A possible weakness of the method is the effect of the M_gO particles on the velocity. Lewis and von Elbe report an S_u of 21 $\frac{cm}{sec.}$ by the particle track method and of 23.4 $\frac{cm}{sec.}$ [10] by the area method which is not a large difference considering the inherent inaccuracies of both methods.

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[10] High Speed Aerodynamics and Jet Propulsion Institute. Physical Measurements in Gas Dynamics and Combustion. Princeton, New Jersey: Princeton University Press. 1954. pages 419,420

B. Flame Above a Gas Stream with Uniform Velocity Distribution

The methods described in the previous section can all be applied to flames above a nozzle. It is expected that the results will be more accurate since a uniform velocity distribution was assumed but not realized. The one additional method which can be used is to adjust the flow so that a flat flame is formed. In this case U_u equals S_u directly.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

An experiment was set up in the laboratory as is shown in Plate 1. Air from a 15 psig line and natural gas from a commercial line were metered separately in Precision Wet Test Meters after passing through pressure regulating tanks. The two flows were then mixed in a small cylindrical can and passed up a cylindrical brass burner tube of 9/16 inches inside diameter and 5/8 inches outside diameter. The tube length was about twenty inches which is more than sufficient to insure fully developed laminar flow at Reynolds numbers below the critical value of 2000. To completely eliminate diffusion burning, which is evidenced by the outer cone of faint luninescence, the burning should have taken place in an evacuated container, but this was not feasible considering the time available. An Exacta camera with bellows extension attached was used to make a photograph of the stable flame. (See Plate 2). It was found that a slightly rich mixture was required in order to obtain a stable flame. (Stoichiometric mixture for natural gas is approximately 10% by volume.) This was probably due to the diffusion burning mentioned above in which oxygen from the surrounding air diffuses toward the flame and reacts with the unburned gas. The following data were taken: volume rates of flow of air and gas, the pressure and temperature of the air and gas, and a picture of the stable flame (f2, 1/25 sec.).

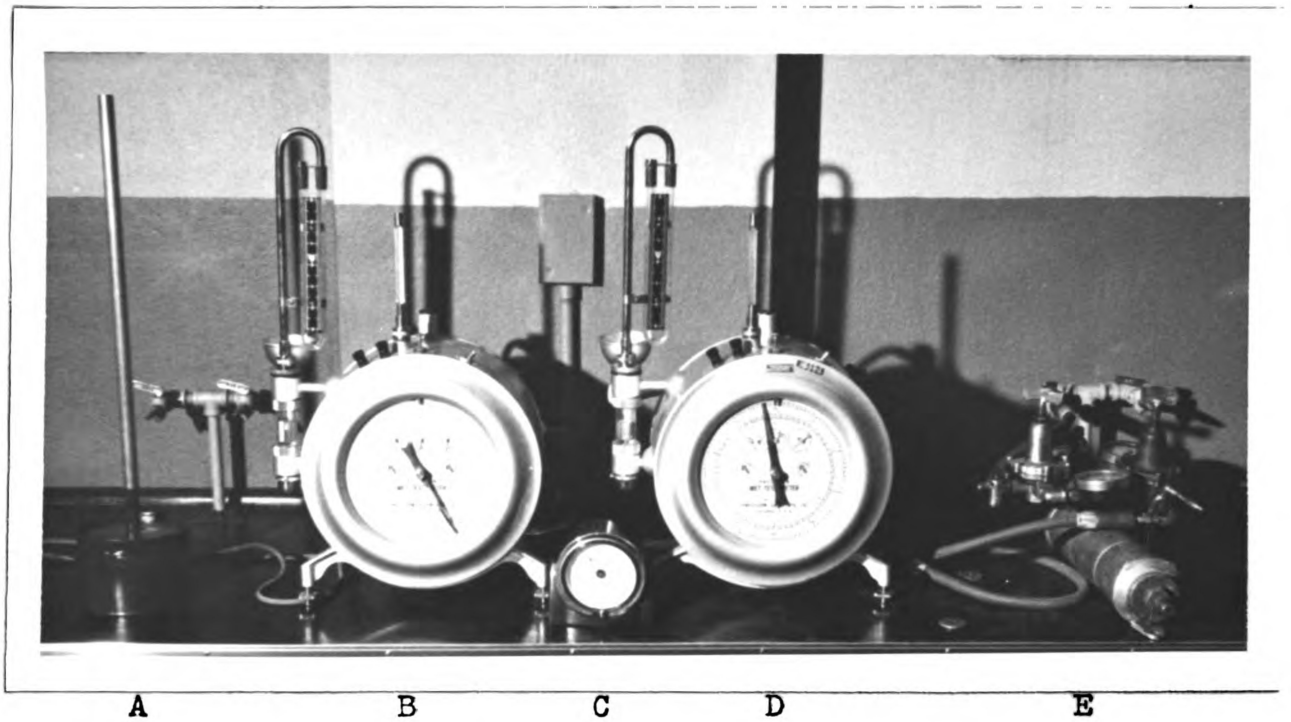

Plate 1. Laboratory Equipment for Premixed Laminar Flow

A. Gas mixing tank with vertical burner tube.

B. Precision Wet Test Meter for natural gas.

C. Stop watch

D. Precision Wet Test Meter for air.

E. Gas and air flow-control valves.

DATA AND CALCULATIONS

Rate of Flow of Air - 2.13×10^{-3} ft^3/sec

Pressure of Air - 1.2 in.H_2O

Temperature of Air - 82°F

Rate of Flow of Gas - 0.33×10^{-3} ft^3/sec

Pressure of Gas - 0.1 in.H_2O

Temperature of Gas - 83°F

The first step in the calculation is to find the average velocity, $\bar{U}_o$, of the gas as it leaves the burner rim. The volume rate of flow divided by the area of the burner exit gives the average velocity. The volume of a gas is inversely proportional to its absolute pressure. Thus the volume of the air and gas will not change appreciably in flowing from meter to the flame, and can be assumed constant.

$$V_{total} = V_{air} + V_{gas}$$

$$= (2.13 + 0.33) \times 10^{-3} \text{ ft}^3/\text{sec}$$

$$= 2.46 \times 10^{-3} \text{ ft}^3/\text{sec}$$

and

$$\bar{u}_o = \frac{V_{TOTAL}}{A} = \frac{2.46 \text{ ft}^3/\text{sec} \times 10^{-3}}{\pi (0.047)^2/4} = 1.425 \text{ ft/sec}$$

As a check on the value of Reynolds number, assumed that the kinematic viscosity $\bar{\nu}$ is that of air at 80°F.

$$R_e = \frac{\bar{u}_o D}{\bar{\nu}} = \frac{1.425 \text{ ft/sec} \times 0.047 \text{ ft}}{1.7 \times 10^{-3} \text{ ft}^2/\text{sec}} = 393$$

which is much less than the critical value of 2000, and laminar flow is thus assured.

The picture of the flame shown on Plate 2 was printed with a magnification factor of five, so that all dimensions taken from the picture must be divided by that amount. Naturally, area measurements will be divided by 25.

In order to calculate the flame speed by method number one outlined in the previous section, it is necessary to obtain the cone height and diameter from Plate 2. The height of the cone is found to be 4.5/5 inches and the base diameter is 3/5 inches. Thus the lateral cone area is

$$A_f = \pi R \sqrt{R^2+h^2} = \pi (.3)\sqrt{(.3)^2+(.6)^2}$$

$$= \pi (.3)\sqrt{.45}$$

$$= 0.585 \text{ in}^2$$

And the apparent flame speed is

$$S_u = \frac{A_o \bar{u}_o}{A_f} = \frac{V_{total}}{A_f}$$

$$= \frac{2.46 \times 10^{-3} \text{ ft}^3/\text{sec}}{0.585 \text{ in}^2 \times \frac{1 \text{ ft}}{144 \text{ in}^2}}$$

$$= 0.605 \text{ ft/sec.}$$

By method number two, the <u>actual</u> cone half-angle measures 14.5° considering the long and relatively straight portion of the cone.

$$S_u = \bar{u}_o \sin \alpha = 1.425\ (0.242) = 0.345 \text{ ft/sec.}$$

By method number three the planimetered area was 3.4 inches, so the actual flame area would be $\frac{2\pi \times 3.4}{25} = 0.855 \text{ in}^2$. See Fig. 12.

$$S_u = \frac{V_{total}}{A_f} = \frac{2.46 \times 10^{-3} \times 144}{0.855} = 0.414 \text{ ft/sec.}$$

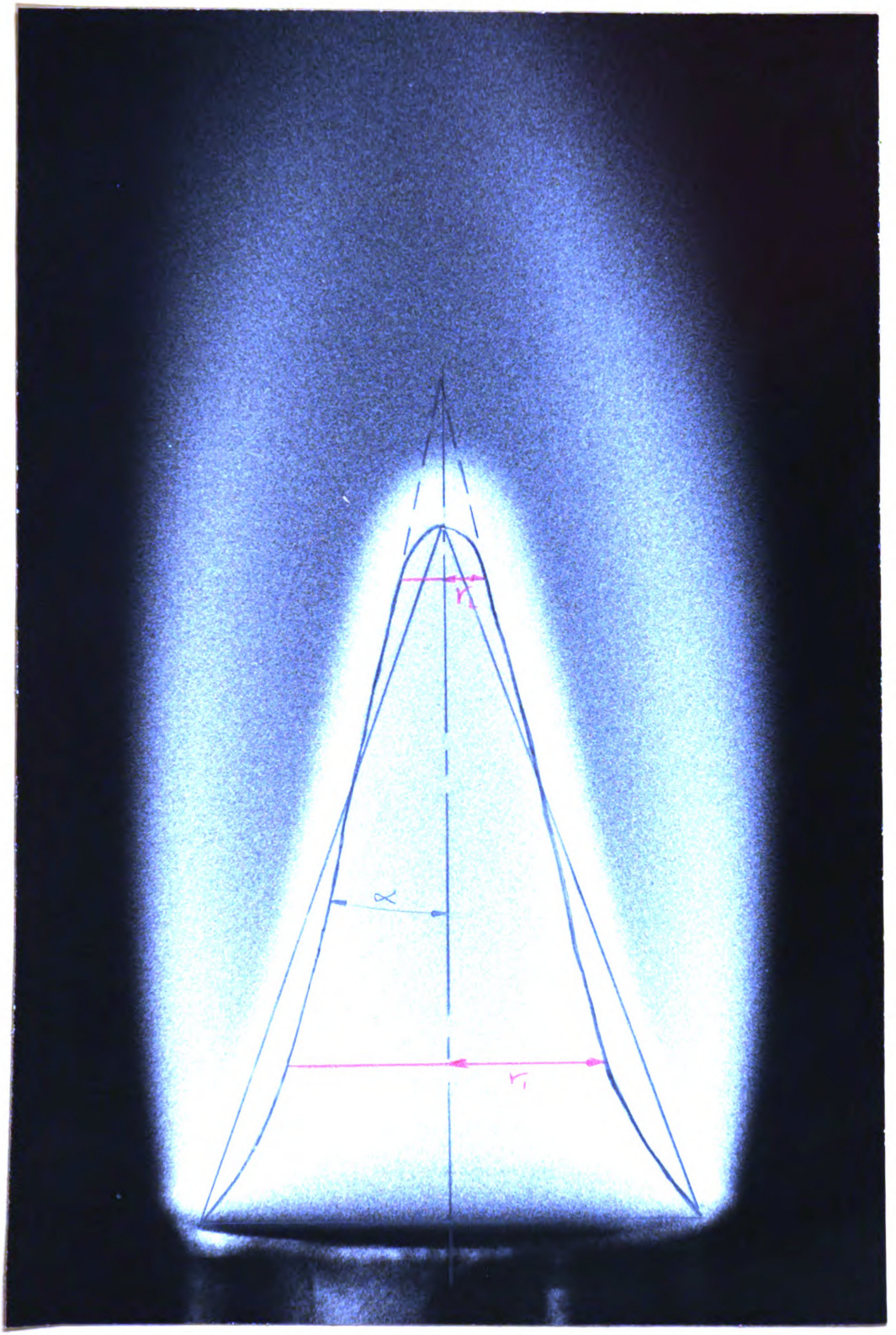

Plate 2. Enlarged Photograph of Bunsen Flame with Superimposed Calculation Lines

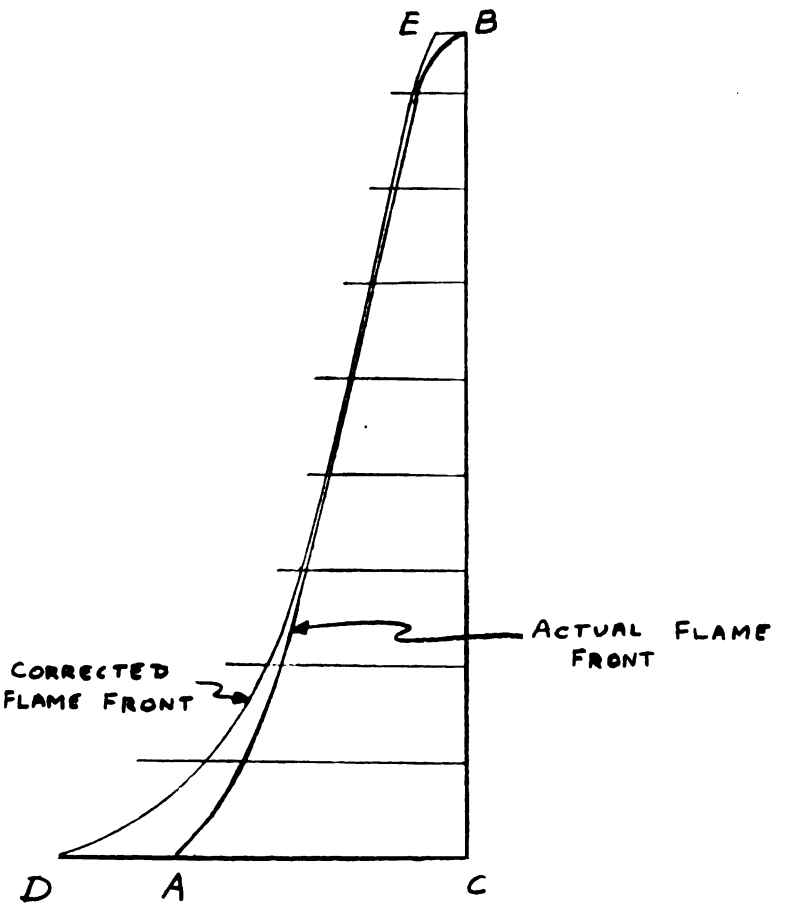

Fig.12. Actual flame front taken from Plate 2, showing flame front corrected by method described in Sec. VI, A-3

Actual area DEBC = 3.4 inches, by planimeter.

By method number four, the sector of the cone was chosen as indicated in red on Plate 2, such that $r_1 = 1/5$ inch, $r_2 = .25/5$ inches, and $s = 3.1/5$ inches. Thus

$$S_u = \frac{(r_1 - r_2)\bar{u}_o}{s} = \frac{(\frac{1}{5} - \frac{.25}{5})(1.425)}{3.1/5} = 0.345 \text{ ft/sec.}$$

Since the particle track method requires considerable special equipment which was unavailable, this method of measuring flame velocity could not be used experimentally to compare with the others.

CONCLUSION

The experiment described in this paper was designed primarily to point out the differences in calculated flame velocity values using the different methods commonly encountered in the literature, and not specifically to determine an actual flame velocity for the mixture involved. The discrepencies obtained above are exactly what one encounters in a survey of the literature. For example, one investigator might measure flame velocity by the right-cone method and describe his answer as "burning velocity." Another investigator, using the same mixture, might calculate his answer by Dery's method and conscientiously label it an "apparent" flame velocity. The latter method probably gives an answer which is closer to the "standard" burning velocity, and yet the reader is led to believe that just the opposite is true. This is particularly true of the literature published in the pre-war years, when the present terminology had not been universally agreed upon.

From the considerations discussed in the section on the theory of flame structure, it is apparent that Dery's method should yield an apparent flame velocity almost equal to the standard burning velocity, with the actual cone angle method running a close second. From the calculations shown here, it would appear that both methods are equally accurate. In

fact, when the equation of Dery's method, $S_u = \frac{(r_1 - r_2)}{s} \bar{u}_o$, is examined, it is seen that $\frac{(r_1 - r_2)}{s}$ is nothing more than $\sin \alpha$ of the angle method. However, it is more accurate to measure the three lengths of Dery's method than α. For example, a one degree error in measuring α produces a 7% error in S_u. The right cone method should be used only for a comparison of relative burning velocities of different compositions, and even then its use seems hard to justify considering the ease of calculation of Dery's method. The actual flame area method is probably more reliable than the right cone method, but the plotting of the corrected flame front is certainly more laborious than Dery's method, and the results are not as meaningful. The inaccuracies of the right cone and total area methods result primarily from the inclusion of the tip and the base areas, in which the flame velocity varies as indicated previously in Fig. 11.

The assumption made for all of the above calculations that an average velocity could be assumed across the burner port will introduce some error in the results. This assumption can be realized in practice by the use of a nozzle instead of a cylindrical tube as a burner. The only difficulty encountered is the increased danger of an explosion due to flash-back, but with a reasonable amount of care this danger can be minimized. The nozzle is therefore recommended over the straight burner tube for the most accurate results.

A general consideration pertaining to conical flames is the burner diameter. The larger the diameter, the smaller

will be the percentage effect of the tip and the base. The size of the burner is limited by the change from laminar to turbulent flow. Here again the nozzle has the advantage in that larger flows can be obtained without turbulence.

The particle track method could not be compared directly with flame speeds as calculated here. Experience of a variety of investigators indicates, however, that the method is an accurate one. The results are probably on the small side of the standard burning velocity because the mass of the particles is large compared to the mass of the molecules of the reacting gases. Thus an inertia lag of the particles is to be expected across the flame front. This reemphasizes the need for care in selecting the particles to be used. They should be as small as possible and still be visible, but not small enough to have random motion.

In stating the measured burning velocity of a mixture, special care should be taken to state the fuel-air or fuel-oxygen ratio, since the burning velocity is very much a function of this parameter. Thus for natural gas the maximum burning velocity occurs in a mixture very close to the stoichiometric mixture which is about 10% gas by volume, and falls to zero at the upper and lower limits of inflammability, which are about 15% and 5% gas by volume, respectively. The maximum flame velocity for natural gas is about 1 ft/sec. In the experiment recorded in this paper, the fuel-air ratio was 13.5% by volume, so the orders of magnitude of the reported results seem reasonable.

It was stated early in the paper that the pressure and temperature of the unburned gas should be reported along with a value of burning velocity. The reason for this will now be discussed. Without exception, the burning velocity of a given mixture will increase with the temperature of the entering reactants, but not nearly as rapidly as the well-known exponential relation between chemical reaction rate and temperature. This points out that while the rate of chemical reaction has some effect on the burning velocity, it is not the only effect. Rather, the effect of the initial temperature in producing a moderate increase in S_u indicates the importance of the transfer of matter and energy from the flame to the adjacent unburned gas by virtue of molecular motion. The effect of the pressure on burning velocity is not nearly as well understood. In fact, a decrease in pressure will increase S_u in some substances and decrease it in others. One important consideration is the effect of pressure on flame thickness. Low pressures tend to increase the thickness of the flame, which has been assumed a surface in space. Thus some experimental error is introduced.

One final consideration is the flat flame technique. An inverted flame can be stabilized above a nozzle by a small wire located above and in the axis of the nozzle. A decrease in the flow rate will cause the cone angle to increase until the flame is flat. Further decrease in the flow rate can cause the flame to move downstream and stabilize itself somewhere between the nozzle and the wire. Such

a flame will often remain stable in this position even if the wire is removed. This points out the importance of extremely small forces which may be thought of in terms of pressure, thrust, or change in momentum which have been assumed negligible throughout this paper and throughout most of the literature. (See Section III.)

In conclusion, most authorities agree that with the best of the methods described here (that is, the Dery's and cone methods) standard burning velocities can be measured within 10% of their true value. The need at present in this field of combustion is not for a new and more accurate measuring technique, but for a more complete understanding of the true nature of the combustion process, particularly in the quantitative sense.

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