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ON THE DETERMINATION OF LAMINAR FLAME SPEEDS FROM STRETCHED FLAMES

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The effects of stretch on the determination of the laminar flame speed are experimentally studied by using the positively-stretched stagnation flame and negatively-stretched bunsen flame, and by using lean and rich mixtures of methane, propane, butane, and hydrogen with air whose effective Lewis numbers are either greater or less than unity. Results demonstrate that flame speed determination can be influenced by stretch through two factors: (1) Preferential diffusion which tends to increase or decrease the flame temperature and burning rate depending on the effective Lewis number, and (2) Flow divergence which causes the flame speed to assume higher values when evaluated at the upstream boundary of the preheat zone instead of the reaction zone. Recent data on flame speed including the present ones are then examined from the unified viewpoint of flame stretch, leading to satisfactory resolution of the discrepancies between them. The present study also proposes a methodology of determining the laminar flame speeds by using the stagnation flame and linearly extrapolating the data to zero stretch rate.

Introduction

The laminar flame speed S_L^o, defined as the velocity of steady, one-dimensional, laminar propagation of a planar, adiabatic combustion wave into a uniform fuel-air mixture at rest (Fig. 1a), is an important combustion parameter because it indicates the reactivity and exothermicity of the given mixture. Consequently extensive efforts have been expended to experimentally determine its value for different mixtures. Despite such efforts, however, irreconcilable differences still exist between the experimental data determined by different researchers using different techniques, even for such a common mixture as hydrogen-air. Thus the primary motive of the present study is to examine the various factors which can influence the determination of S_L^o, and thereby provide a unifying explanation for the experimental differences.

To facilitate the following discussions, we shall replace S_L by the mass flux F_L (Fig. 1b), hereafter called the laminar buring rate, as the primary parameter of interest. It is well established that because of thermal expansion, the determination of S_L depends on the specific location where it is evaluated. On the other hand F_L remains a constant in the planar one-dimensional situation of Figs. 1a and 1b, and therefore is a more fundamental parameter indicating the consumption rate of the mixture. We further differentiate F_{L1} and F_{L2} to be the values of F_L evaluated at the upstream boundaries of the preheat and the reaction zones respectively. For one-dimensional flame propagation $F_{L1} = F_{L2} = F_L^o$. Note that S_L and F_L designate any laminar flame while S_L^o and F_L^o are used only for the one-dimensional planar case.. Furthermore, except for Fig. 1a, these quantities are positive when directed downstream.

While F_L^o is defined for the strictly one-dimensional situation, most realistic flames are subjected to stretch due to either flow nonuniformity, flame curvature, or flame acceleration.[1–3] It is then of interest to examine the extent F_L can be affected by

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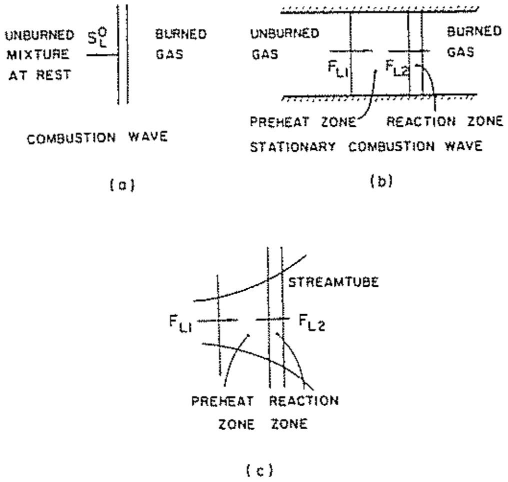

FIG. 1. Schematic of various flame-flow configurations: a. One-dimensional planar flame propagation in laboratory frame; b. One-dimensional planar flame propagation in flame-stationary frame; c. Planar flame in divergent flow, $F_{L1} > F_{L2}$.

stretch, and whether the F^o_L corresponding to the one-dimensional situation can be determined from measurements carried out on stretched flames.

For stationary flames, there are three factors that could influence the determination of F_L. Take the flat flame stabilized in a divergent flow as an example.

The first effect is due to pure stretch as represented by the divergence of the flow when it traverses the reaction region. That is, an increase in the (negative) velocity gradient $\Gamma = -du/dx$ increases the reaction volume and thereby reduces the burning intensity represented by F_{L2}. This effect, however, is expected to be significant only for states close to extinction and therefore will not be further considered. Note that Γ is simply the flame stretch factor[1,2] defined as $D(\ell nA)/Dt$, where D/Dt is the material derivative and A the flame surface area.

A stronger effect on F_{L2} in the presence of stretch is that caused by preferential diffusion.[4–8] Figure 1c shows that since diffusion of heat and mass occurs normal to the flame while convective transport is along the (divergent) streamline, then for mixtures whose effective Lewis number is Le > 1, an increase in the stretch rate would reduce the flame temperature T_f and consequently F_{L2}. The converse holds for a Le < 1 mixture; Le is defined herein as the ratio of thermal diffusivity to mass diffusivity. Note that for a Le = 1 mixture or if the flow has no stretch, T_f is simply the adiabatic flame temperature. Typical values of Le can be found in Ref. 7.

The third effect is due to the fact that the area of the streamtube can change appreciably in a nonuniform flow field. Thus if we consider the flow in the preheat zone to be quasi-one-dimensional, then since $\rho uA = F_L A$ is constant where A is now the area of the streamtube, we would expect $F_{L1} > F_{L2}$ in a divergent flow. Therefore unlike the strictly one-dimensional case, in a stretched flame the plane for the definition of F_L is important, as pointed out by Dixon-Lewis and Islam[9] through computer simulation. In particular, their results show that, in the absence of preferential diffusion which they did not consider, F_{L2} instead of F_{L1} is to be identified as the laminar burning rate F^o_L. This is an important result because experimentally the laminar flame speed is usually determined at the upstream boundary of the preheat zone. This results in F_{L1} which is not F^o_L.

The above discussions show that for a flat flame in a nonuniform flow, $F_{L2} \approx F^o_L$ if Le = 1. When Le ≠ 1, not only $F_{L2} \neq F^o_L$, F_{L1} is also affected by preferential diffusion through the change in F_{L2}. However, in the limit of vanishing stretch rate, then both preferential diffusion and flow divergence effects should also vanish such that

$$F_{L1} \to F_{L2} \to F^o_L \text{ as } \Gamma \to 0. \qquad (1)$$

Relation (1) provides the basic methodology for the determination of F^o_L in the present investigation, to be discussed later.

In the above example the flame is subjected to positive stretch. However, if the flame possesses a sufficiently strong concave curvature towards the approach flow, as in the case of the bunsen flame which is a recommended configuration for flame speed determination, then the flame suffers negative stretch such that the preferential diffusion effects just discussed are completely reversed.[10, 11] That is the flame intensity is enhanced for a Le > 1 mixture and reduced for a Le < 1 mixture. For this curved flame the flow divergence effect is also greatly enhanced when the radii of curvature becomes comparable to the preheat zone thickness.

In view of the above discussions, it is clear that care needs to be exercised in attempts to determine F^o_L from stretched flames. Not only one should measure F_{L2} instead of F_{L1}, but the effect of preferential diffusion also needs to be "subtracted out" from F_{L1}. Without these corrections, discrepancies exceeding the experimental error would result. One such example is the spread of 3.1 to 3.6 m/s in the maximum burning velocity of hydrogen-air mixtures determined from well-executed experiments.[12–14]

In the present experimental investigation we have systematically substantiated the above concepts by studying the dynamic structure of flames with different extents of stretch and preferential diffusion. The model systems adopted are the stagnation flow

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and the bunsen flame, which respectively manifest stretch effects due to flow nonuniformity and flame curvature. Consequently we are able to explain the discrepancies in the existing data from the unified viewpoint of flames under stretch. Furthermore, from the stagnation flow results we also propose a new methodology for the determination of the laminar flame speed from stretched flames.

The experimental methodology is presented in the next section, which is followed by discussion of the results.

Experimental Methodology

The Stagnation Flow Experiment

This apparatus mainly consists of a uniform flow nozzle and a stagnation plate positioned about one nozzle diameter above the exit. The plenum chamber was 100 mm diameter and reduced to interchangeable nozzles with exit diameters of 40, 30, 20, 10, 7 and 5 mm. Variation of flow rate through the burner at constant fuel-air ratio was accomplished with bypassing part of the mixture without changing the rotameter settings. Flow velocity was measured by a TSI LDV system in the back-scattering mode, with 1 μm MgO particle seeding and a measuring volume of 0.1 mm dia. × 0.9 mm length.

Figures 2a and 2b respectively show typical measurements in the stagnation flow setup without and with combustion; the coordinate system is also defined in the figure. The presence of the stagnation plate modifies the pressure field and the velocity profile, producing a slightly dish-shaped flame when it is not close to the stagnation plate. The center portion of the flame, however, can be considered planar and perpendicular to the central streamtube. Typical flame photographs can be found in Refs. 6 and 15. Velocity profiles were mapped at down to 0.1 mm intervals. To ensure that the experimental results were not affected by the specific nature of the stagnation surface, the cooled brass plate was replaced by the counterflow of either cold air, cold nitrogen, or an opposed flame. In all these cases the minimum velocity at the flame and the burned gas temperature immediately after the flame were not changed. Boundary layer effects were also found to be negligible as long as the flame is not too close to the stagnation surface, as reported previously.[15]

The velocity profile along the centerline can be considered the superposition of the effects of the flame and the stagnation flow field, shown in Fig. 3 with an actual profile of a CH_4-air flame. The velocity at the point of initial temperature rise is the point where the curve starts to depart from the descending line of unburned gas velocity. It was determined that this velocity is very close to the minimum velocity in the entire traverse, especially when the velocity gradient Γ is low. Thus for all practical purposes the measured minimum velocity can be used to represent the velocity at the beginning of the preheat zone to a good degree of approximation. We thus define this to be the propagation velocity S_{L1} of the flame with the stretch rate Γ. We also note that this definition appears to be a somewhat more rational choice than that adopted in Ref. 16.

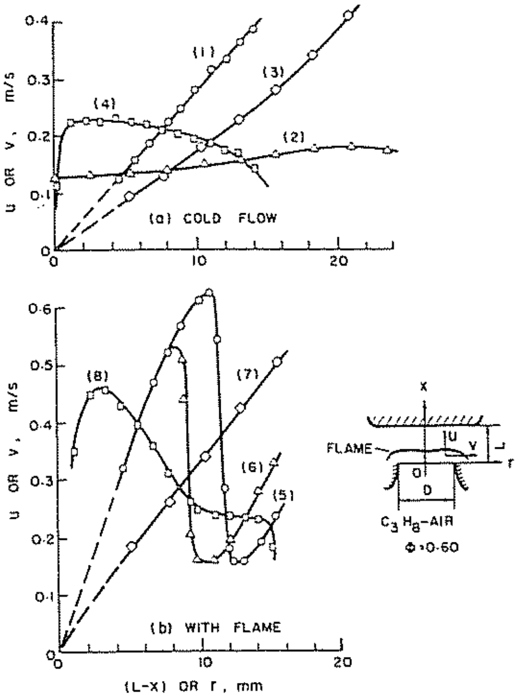


FIG. 2. Velocity profiles in stagnation flow (D = 40 mm, L = 24 mm): a. Cold flow, (1) u vs (L-x), centerline, (2) u vs r at (L-x) = 4.5 mm, (3) v vs r at (L-x) = 4.5 mm, (4) v vs (L-x) at r = 12.7 mm; b. With flame, (5) u vs (L-x), centerline (6) u vs (L-x) at r = 12.7 mm (7) v vs r at (L-x) = 4.5 mm (8) v vs (L-x) at r = 12.7 mm.

The experiment then involved the determination of S_{L1} as functions of Γ as well as the nature and extent of preferential diffusion; the latter effect was manifested by using different fuels (H_2, CH_4, C_3H_8, C_4H_{10}) and inerts (N_2, He, Ar).

Finally, it is important to recognize that our experimental measurements depend only on the *local* velocity distribution across the flame. Therefore as long as the flame is locally flat, the bulk structures of the flame and the flow field are relatively unimportant. The experiment can thus be set up with relative ease.

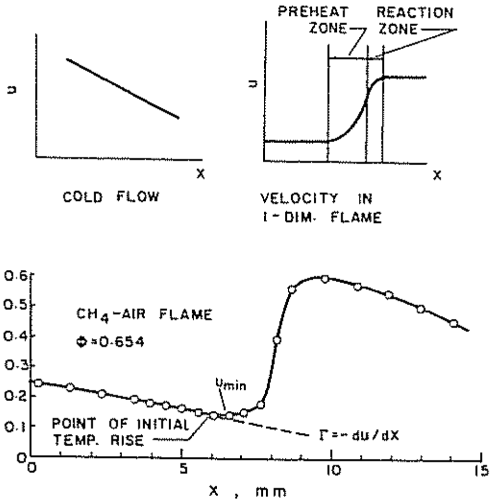


FIG. 3. Velocity across flame in stagnation flow illustrating the definition of the flame speed.

Bunsen Flame Experiment

The laminar flame speed of H_2-air and other hydrocarbon-air mixtures were also determined by the schlieren cone angle-approach gas velocity method, using the same stagnation flow apparatus but without the stagnation plate. Only the smaller nozzles of 5, 7 and 10 mm dia. were used for the fast burning mixtures because of the difficulty of maintaining a stable, laminar flame at the higher velocities with large nozzles. The flame speeds S_{L1} were determined in the middle portion of the flame cone.

Results and Discussions

Effects of Stretch on Flame Speed and Temperature

Figures 4 to 6 show the effects of Γ on S_{L1} and T_f, obtained in the stagnation flow apparatus; where T_f is the maximum temperature in the flame. Temperatures for the lean mixtures were measured by using uncoated 50 μm Pt/Pt-10%Rh thermocouples, and hence were obtained only for the purpose of relative comparison. Furthermore, even though we conducted our introductory discussions on the basis of F_L, the data are now presented as S_L because ρ_1 is fixed in the experiments and because the extent of thermal expansion for the same mixture equivalence ratio are about the same for flows with different Γ.

Figure 4 shows the variation of S_{L1} with Γ for lean mixtures of methane, propane, and butane with air. For the methane mixtures, the increase in S_{L1} with Γ is consistent with the influence of preferential diffusion in that $Le < 1$ in these cases such that an increase in stretch should enhance the burning intensity. Also, the flow divergence causes F_{L1} to be larger than F_{L2}. Both these factors will make the measured S_{L1} increase with increasing Γ.

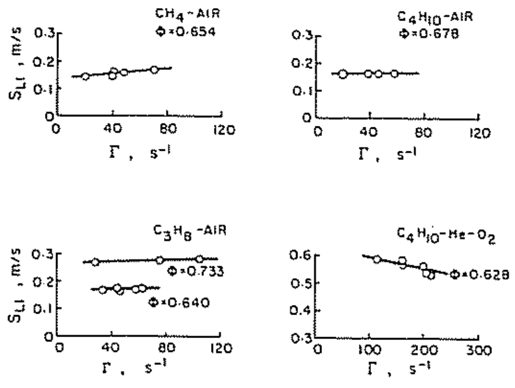


FIG. 4. Effect of Γ on S_{L1}, various mixtures.

The lean mixtures of propane and butane with air have $Le > 1$, so preferential diffusion should decrease the burning rate with increasing stretch. Yet the measured S_{L1} either increases slightly or stays nearly constant. This can be caused by the cancelling of the opposite effects of flow divergence which makes $F_{L1} > F_{L2}$, and preferential diffusion which reduces F_{L2}. To substantiate this possibility, Fig. 5 shows that the flame temperature T_f, and thereby the burning intensity represented by F_{L2}, indeed decreases with increasing Γ.

To further demonstrate the relative nature of the

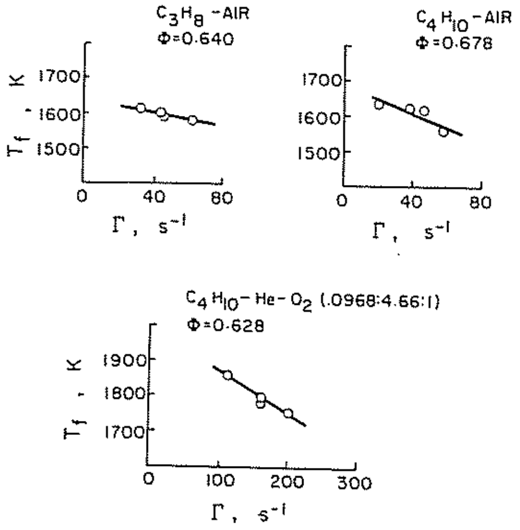


FIG. 5. Effect of Γ on T_f, various mixtures.

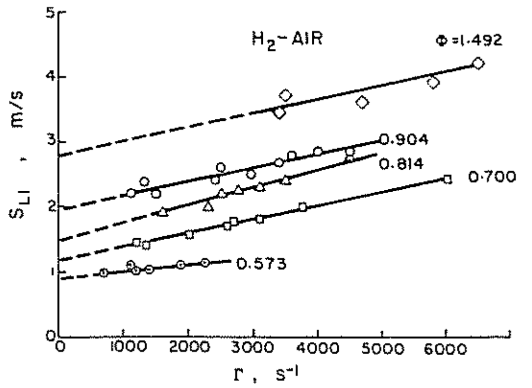


FIG. 6. Effect of Γ on S_{L1}, H_2-air mixtures.

influence of preferential diffusion versus flow divergence, preferential diffusion is boosted by substituting N_2 by He in the butane mixtures. Figures 4 and 5 show that preferential diffusion is now so strong that it overcomes the flow divergence effect to yield a decreasing S_{L1} with Γ. The flame temperature also decreases with Γ as should be.

Figure 6 shows the corresponding plot for the H_2-air system. It is seen that S_{L1} increases with Γ for both the lean as well as the rich mixtures. Note, however, that the richest concentration of $\phi = 1.492$ is still on the lean side of $\phi = 1.8$, at which the maximum laminar flame speed occurs.

Methodology for Determination of Laminar Flame Speed, S_L^o

Figures 4 and 6 show that S_{L1} varies linearly with the stretch rate Γ. Theoretical results[17] also reveal such a linear relation in the limit of small values of stretch. Thus by linearly extrapolating the values of S_{L1} determined for stretched flames to vanishing stretch rate ($\Gamma = 0$), the intercept on the ordinate, S_{L1} ($\Gamma = 0$), should then by definition be the laminar flame propagation velocity S_L^o defined for the one-dimensional unstretched flame.

It is significant to note that except for the flat flame burner method for the determination of slow to moderate flame speeds, most other experimental techniques developed for flame speed measurements involve flames with stretch manifested through either flow nonuniformity, flame curvature, or flame acceleration. The present technique then provides a rational methodology at determining S_L^o, especially for fast burning flames which cannot be easily stabilized by the method of flat flame burner with heat loss.[18]

CH_4-*Air Flame Speeds*

The results of S_{L1} measurements from the stagnation flame at low velocity gradients are presented in Fig. 7 for CH_4-air mixtures. Since the values at such low velocity gradients differ from the zero velocity gradient values by only a small amount not larger than the uncertainties of measurement, these values were not corrected to zero velocity gradient. Some data from recent measurements and numerical computation[13,19,20] are also shown. It can be seen that the comparison is very favorable. It is also of interest to note that the behavior of our data at the rich end qualitatively agrees with that of the numerical solutions of Tsatsaronis.[20]

Hydrogen-Air Flame Speeds

Because of the highly-diffusive nature of hydrogen, the influence of stretch is more pronounced here. Measurements were made with both conical and stagnation flames. Results with conical flames on nozzles of 5 mm and 7 mm dia. are shown in Fig. 8, together with the data of Takahashi et al.,[12] and Liu and MacFarlane.[14] It is clear that there is an effect of nozzle size on S_{L1} determined by the schlieren cone angle method. Data of Liu and MacFarlane, which were taken with the 3 mm nozzle and therefore suffer the highest stretch, are the highest. Our 5 mm nozzle data falls between the 3 mm and 7 mm nozzle data, while the 7 mm nozzle data also checks those of Takahashi et al. very well, especially on the lean side; lean being relative to the fuel concentration at maximum flame speed ($\phi \approx 1.8$). On the rich side there seem to be a little more uncertainty, but the rather unexpected turn in the curve at $\phi \approx 2.6$ probably does exist because it can also be seen both in the data of Takahashi et al.[12] and some other curves quoted in their paper.

As discussed previously, effects of stretch are due to flow divergence and preferential diffusion. While flow divergence increases the measured S_{L1}, preferential diffusion tends to reduce (increase) the burning rate on the lean (rich) side of the present negatively-stretched hydrogen-air flames. Thus the data of Liu and MacFarlane[14] show that flow divergence overwhelms the effect of preferential diffusion on the lean side. Flow divergence appears to have a somewhat weaker influence on the rich side because otherwise the flame speed would be very high here due to the simultaneous enhancement induced by preferential diffusion. We also note that the excessively small nozzle used here[14] can produce flames whose preheat zone thickness is of the same order as the radius of curvature.

For the 7 mm nozzle the effect of stretch appears to be quite small in that the data agree well with those obtained by extrapolating our stagnation flame data to zero velocity gradient. Of course it is also possible that the flow divergence and preferential diffusion effects approximately cancel out on the lean side for these 7 mm data.

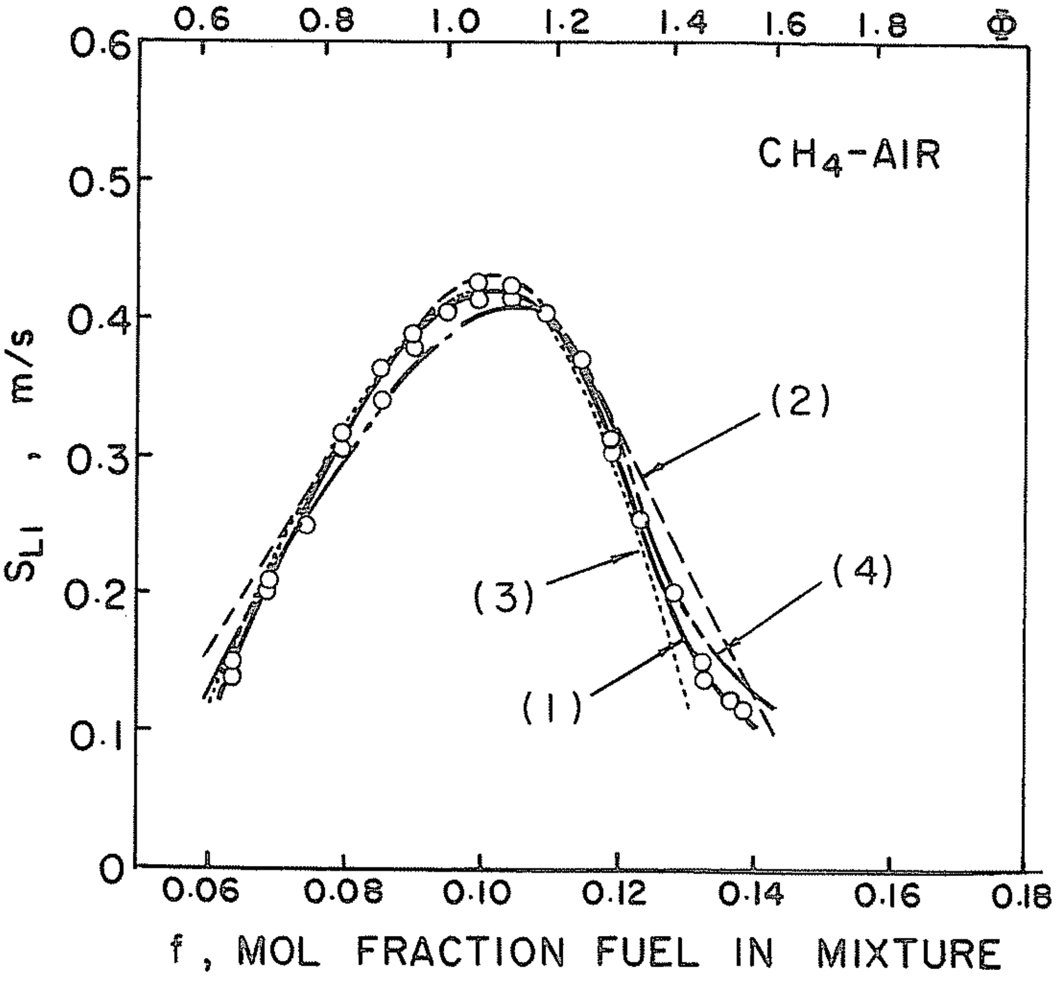
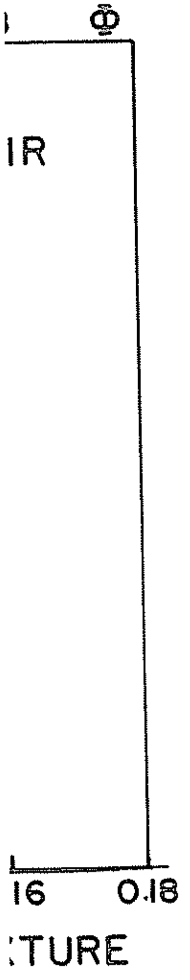


FIG. 7. Laminar flame speeds of CH_4-air mixtures (1) Present work, stagnation flow, LDV (2) Andrews-Bradley,[19] double kernel (3) Günther-Janisch,[13] button flame, particle track (4) Tsatsaronis,[20] computer modelling.

Next we discuss the button flame data of Günther and Janisch[13] obtained from a 4 mm nozzle, recognizing that the flame now suffers positive stretch. Thus on the lean side the simultaneous enhancement effects of flow divergence and preferential diffusion significantly elevates the measured burning velocity. It is worth mentioning again that by extrapolating to $\Gamma = 0$, our stagnation flame data basically eliminates the stretch effects in the button flame and thereby assume lower values as shown. On the rich side it is seen that preferential diffusion lowers the burning velocities to be less than those of the 7 mm nozzle conical flames which do not suffer much stretch. Thus all data appear to be explanable within the coherent viewpoint of flame stretch.

Concluding Remarks

In the present investigation we have first emphasized the importance of stretch on the determination of the laminar flame speed. In stationary flames stretch is manifested through two factors, namely preferential diffusion and flow divergence. Effects due to perferential diffusion are physically real, and can cause the flame temperature and mass burning rate to either increase or decrease, depending on the mixture effective Lewis number and whether the flame is positively or negatively stretched. The flow divergence factor is definitional.[9] That is, because of the increase in the streamtube area, the mass flux at the upstream boundary of the preheat zone is larger than that of



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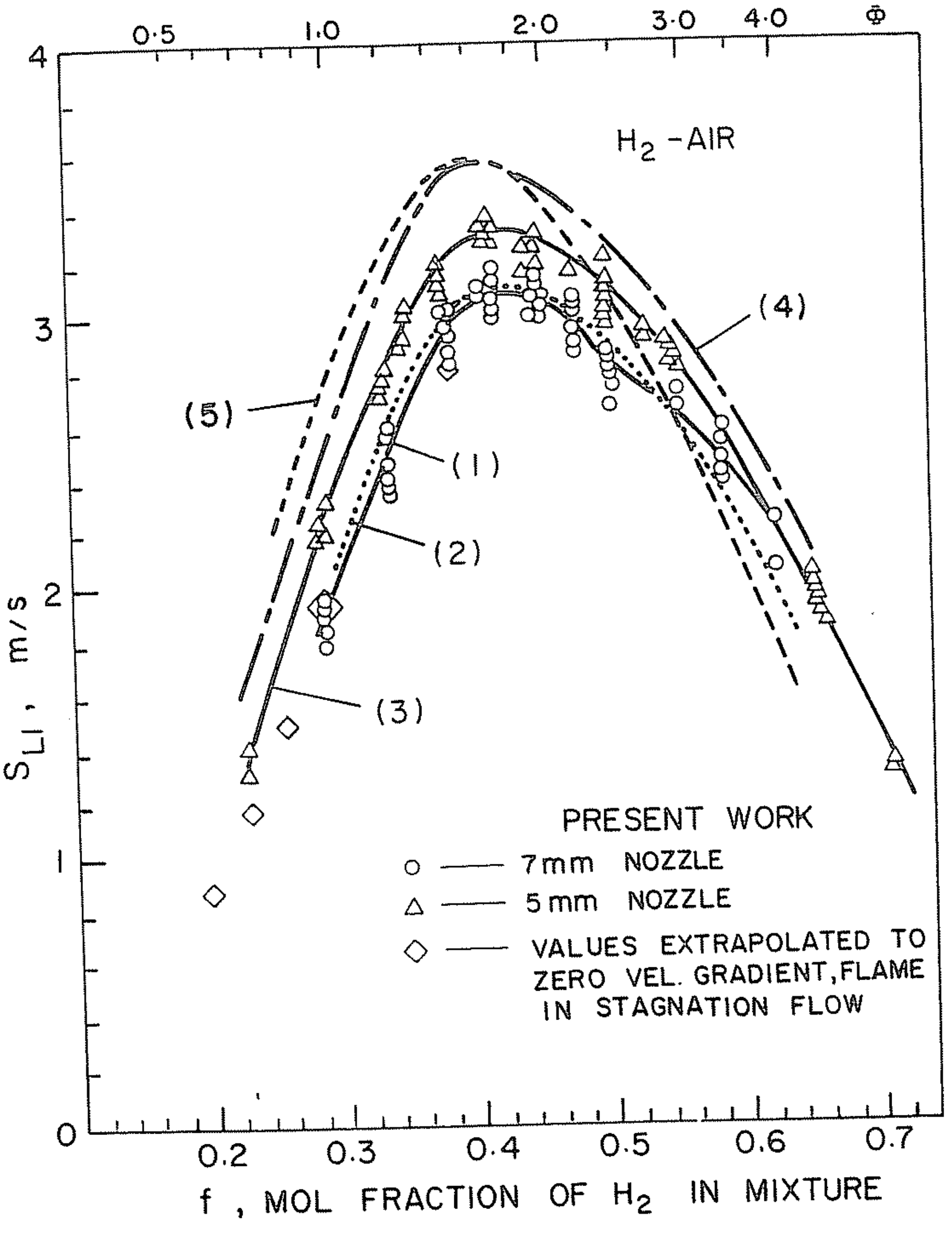

FIG. 8. Laminar flame speeds of H_2-air mixtures by various methods: (1) Present work, bunsen flame, 7 mm nozzle (2) Takahashi, et al.,[12] bunsen flame, 7 mm nozzle (3) Present work, bunsen flame, 5 mm nozzle (4) Liu and MacFarlane,[14] bunsen flame, 3 mm nozzle (5) Günther and Janisch,[13] button flame, 4 mm nozzle.

the reaction zone. Thus while the burning velocity should be evaluated at the reaction zone, practically all existing techniques define the flame speed at the upstream boundary of the preheat zone, and thereby introduce a source of inconsistency into the data. This practice, however, need not be discouraged because the preheat zone boundary is experimentally well defined as compared with that of the reaction zone. The important point, then, is to be aware of this factor and account for it in actual comparisons.

We have also conducted extensive experimentation on flow and fuel-inert-oxidizer systems which exhibit both positive and negative stretch as well as Le $>$ 1 and Le $<$ 1 behavior. The results conclusively substantiate the above concept. By further examining recent flame speed data including the present ones, the discrepancies can be satisfactorily resolved within the coherent explanation of flame stretch.

As corollaries of the present investigation, we are able to propose a rational methodology for the determination of the laminar flame speed from stretched flames. Furthermore, the present results also emphasize the need to use the proper laminar flame speeds in fundamental flame structure studies. An important example is the extraction of the dominant kinetic mechanisms of given fuel-air mixtures through computer simulation[21,22] by comparing the predicted dynamic and structural properties of one-dimensional flames with those of the measured values. Thus if the experimental data contain systematic non-kinetic influences as a result of convective-diffusive transport, especially those of preferential diffusion which can have opposite effects in lean and rich mixtures, then care needs to be exercised in drawing conclusions regarding the dominant, system-independent kinetic mechanisms.

Acknowledgment

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COMMENTS

G. Dixon-Lewis, University of Leeds, England. By means of detailed laminar premixed flame computations, I have recently[1] used flame speeds measured by Andrews and Bradley[2] for spherically-expanding hydrogen-air flames as benchmarks for calibration of the hydrogen-air flame mechanism. These flame speed measurements are entirely objective in character. The calibrated mechanism was then used in turn to calculate the normal burning velocities across the whole flammable range. The maximum predicted burning velocity was 300 cm/s, for a mixture containing 41% hydrogen. How does this value compare with your measurements?

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Authors' Reply. The maximum flame speed, S_{L1}, measured on the 7 mm diameter nozzle for hydrogen-air mixtures was 3.1 m/s at a hydrogen content of ~41%, which agrees with the data of Takahashi, et al. However, there is still a flow divergence effect at this diameter. By extrapolating the data of the 3 mm, 5 mm and 7 mm nozzles down to zero curvature, the value of planar flame speed is roughly 2.8 m/s. In order to obtain a flame speed which can be considered truly one-dimensional and adiabatic, more refined experiments need to be performed and the effects of flame stretch and other possible effects such as radiative heat loss taken into account. For the present, we would say that agreement with the 3.0 m/s value predicted by Dixon-Lewis is fair.