The Application of the Turbulent Burning Speed Concept to Laboratory Flames

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THE APPLICATION OF THE TURBULENT BURNING SPEED CONCEPT TO LABORATORY FLAMES

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INTRODUCTION

The turbulent burning speed, S_T, is often used as a convenient means to characterize the propagation of premixed turbulent flames e.g. [1-13]. This parameter encapsulates the global effects of turbulence on combustion rate and has been the subject of numerous experimental and theoretical investigations. Its basic concept is quite straightforward when presented in one-dimensional form. The majority of the earlier experimental investigations and many current works have focussed on determining S_T in laboratory flames and correlating the results with the incident turbulence intensities. One of the main objectives is that the results and correlations can be used to support the development of combustion theories and are applicable to engineering designs. Also guided by this concept, many 1-D theoretical models have been developed e.g. [14-16] for investigating the flame structures, the local reaction rates and other characteristics of flame-turbulence interactions. Prediction of the turbulent burning speed is one of the necessary validations for the models.

These theoretical and experimental efforts have improved the general understanding of various aspects of flame propagation. There are, however, still many unresolved problems associated with the interpretation and correlation of turbulent burning speed. The most significant one is the large scatter shown by the S_T data. Although they all indicate an increasing trend with turbulence intensity, correlating the data with turbulence intensities, turbulence length scales and other parameter have not been totally successful. In addition, very little is know about relationships between S_T and other local flame properties such as the mean reaction rate to guide the development of predictive models. At present, the application to engineering had yet to be attained. This situation has lead to some questions about the uniqueness of S_T in complex systems and whether or not this concept is useful to basic and engineering research. Suggestions have been made that other parameters may be more suitable to express the propagation rate of premixed turbulent flame.

This current status can be attributed to many different factors. First of all, the flame propagation processes in most systems may be too complex to be described by a burning speed correlated only with the properties of the incident turbulent flow. Another reason is related to the experimental approach. Many different diagnostics methods have been used for determining the burning speed in a wide variety of burners. Yet the analysis methods are mostly guided by 1-D or 2-D models. Perhaps the more important one is that in the past, the turbulent burning speed has been considered as a "universal" global property. This seem to be an over simplification for describing complex turbulent flames, and may have contributed to some of the current problems and misconceptions. It is, however, important to recognize that the turbulent burning speed can be very useful to characterize flame propagation and continuing works in this area will be more fruitful when some of the problems encountered in prior works are identified and resolved.

The purpose of this paper is to review and critique previous and current practices of applying the turbulent burning speed concept to different laboratory flames. Also evaluated and discussed are the suitability and limitations of the flame configurations, and conventional and novel experimental methods for determining S_T. The survey shows that most of the currently available S_T data obtained by flame geometry methods tend to be high and need to be corrected for the effects of flow divergence. This emphasizes the significant of the flowfield on flame propagation.

BASIC CONCEPT

There are only two 1-D flame configurations in which the turbulent burning speed are defined unambiguously (Fig. 1). For a stationary infinite planar flame normal to the approaching turbulent flow (Fig. 1(a)), S_T is simply the mean velocity U_∞ of the reactants. A more general definition derived from the 1-D model for inclines 2-D flame is that S_T is equal to **the incident flow velocity component normal to the local orientation of the flame brush.** For an unsteady spherical flames (Fig. 1(b)), assuming that the reactants remain stationary, S_T is proportional to the rate of change of the mean radius R and the expansion ratio, ρ_u/ρ_p.

$$\frac{dR}{dt} = S_T \left(\frac{\rho_u}{\rho_p}\right) \qquad (1)$$

Unfortunately, neither one of the 1-D configurations can be easily exploited by laboratory experiments. The normal infinite planar flame is an theoretical idealization and stabilizing a normal turbulent flame in laboratories is possible only for conditions with large scale low turbulence intensity. The unsteady spherical flames are much easier to produced in laboratory but the typical size of the laboratory experiments limits the useful time for observing flame propagation to less than several microseconds.

The wrinkled laminar flame model introduced by Damköhler in 1940 [17] provides a useful link between S_T and turbulent flame structures. This concept can also be exploited for the determination of S_T. The underlying assumption is that for conditions where the chemical time scale is small compared to the turbulence scale, (i.e. Damköhler number, $Da >> 1$) the most significant effect of turbulence is to wrinkled the laminar flame sheet without altering its internal structure. By further assuming that the local reaction rate is constant, the ratio of the turbulent/laminar burning speed is equal to the ratio of the flame sheet area A_L to the cross sectional area of the stream-tube A_T. For the planar normal flame, S_T is defined by the mass flow rate $\dot{m}$ through the stream tube

$$\dot{m} = \rho_r S_L A_L = \rho_r S_T A_T \tag{2}$$

and the ratio of the turbulent/laminar burning speed $\overline{W}$ is

$$\overline{W} = \frac{\rho_r S_T}{\rho_r S_L} = \frac{A_L}{A_T} \tag{3}$$

Similar argument also applies to the unsteady spherical flame and shows that the area ratio is directly proportional to S_T.

RELATIONSHIP TO OTHER FLAME PROPERTIES

Fig. 2 presents schematically the relationships among the global burning rate parameters such as S_T, the statistical mean, and the local reaction rates. The purpose is to illustrate the dimensions of the scales relevant to these parameters and the relative significance of flowfield, turbulence and chemistry. It can be seem that the turbulence characteristics and the interaction with combustion chemistry are significant to the local reaction rate and the mean reaction rate while the turbulence and flowfield characteristics have a greater effect on the global burning rate. At present, many theoretical models have been formulated for the global, mean and local reaction rate parameters. Experimental investigations, however, have been limited only to measuring S_T and the flame crossing frequency ν [18] which is the simplest means of describing the mean reaction rate. Current understanding of the changes in the local reaction rate with turbulence is based on studies of stretched laminar flames [19]. It is interesting to note that for non-premixed flames there is no equivalent global rate parameter, consequently the research focus has been on measuring mean and local reaction rates, while investigations of the mean flowfield is less emphasized.

The local reaction rates can be described in terms of four phenomena i.e. wrinkled laminar flame, stretched flamelets, locally quenched flamelets, and distributed reaction zones. They are very difficult to investigate in real turbulent combustion situations. Typical scales relevant to the reaction rates are about the same order of magnitude as the laminar flame thickness (< 1 mm). Probing their internal structures is quite challenging even with the use of sophisticated laser diagnostic because of their rapid movements. Another obstacle to experimental investigation of the local reaction rate is the lack of measurable parameter or correlation which characterize the different type of reaction zones and their reaction rates.

The statistical mean reaction rate $\overline{w}$ is the source term in the products mass conservation equation. Models for $\overline{w}$ such as the the eddy breakup model by Spalding, the flamelet model by Bray-Moss-Libby [18] and the fractal model by Gouldin [20] have appeared in the literature. The eddy breakup model and gradient transport type models relate the mean reaction rate to turbulent transport. The are generally not appropriate for premixed flames because the fluctuating flamelets lead to the so-called counter-gradient transport of scalar. The BML model and the fractal model are both based on the flamelet description of the flame structures. Central to Gouldin's reaction rate is the fractal dimension which is a means to express the distribution of the flame wrinkle scales. The BML mean reaction rate is based on the flame crossing frequency ν which is directly related to the spatial scales of the flame wrinkles. This parameter can be measured by rather simple diagnostic methods and the results reported by several investigators show that the distribution of ν is self similar for different flame configurations.

At present, the influence of the flowfield on the mean reaction rate is one of the least understood aspects of premixed turbulent flame propagation. It is the key to the development of theoretical models to predict the burning rate. The lack of understanding can be partly explained by the fact that recent experimental investigations have been focusing on validating theoretical models. The 1-D conservation equations are often expressed in terms of the reaction progress variable c. Very often, experimental data are presented only in $\bar{c}$ space. Although this is a convenient means for direct comparison between experiments and theory, the self similarity of the flame crossing frequency mentioned above is such an example, the use of this representation seems to place less emphasis on the flowfield characteristics.

In a recent work by Cheng et al. [21], the flame crossing frequencies measured following mean-flow streamtubes are used to estimate the turbulent/laminar burning speed ratio. The results of this attempt to link between mean reaction rate to burning speed are quite encouraging. The method is based on intergrating ν in the direction along the streamtube. The integration essentially determines a turbulent flame brush thickness along the streamtube δ_T which varies depending the location of the streamtube and the flame configuration. The turbulent/laminar burning speed ration can be interpreted as the ratio between the length scales indicated by the flame crossing frequency and the local turbulent flame brush thickness. This clearly shows that prediction of the burning speed require knowledge of the mean reaction rates as well as the local characteristics of the flowfield.

In a recent paper Bray [22] developed a means to evaluate the turbulent burning speed based on the BML model. An expression was derived for the mean velocity at the leading edge of the flame, i.e. S_T, by expanding the BML model for $\bar{c} \rightarrow 0$. The S_T expression has a disposable constant I_0 and can be compared directly with the correlation of Abdel-Gayed et al [23]. The difference between the correlations and theory basically appears in I_0. Its variation is interpreted as the ratio between the stretched and unstretched laminar burning speed and therefore is a function of the the Karlovitz number K i.e. $I_0(K)$. Although Bray's approach seem promising, he is also aware of the many limitations to his conclusions. Factors affecting his conclusions include experimental uncertainties and the difference between the experimental flame geometries and the 1-D flame model. He suggested that future studies of turbulent flame propagation require solution of differential equations with appropriate initial and boundary conditions to match particular experiment.

CHARACTERIZING INCIDENT TURBULENCE

The determination of the incident turbulence characteristics is significant to the interpretation and correlation of turbulent burning speed data. The turbulent/laminar burning speed ratios S_L/S_T are usually shown against the ratios of the rms velocity fluctuations and the laminar burning speed u'/S_L. Other turbulence characteristics such as the length scales and turbulence dissipation rate are useful for estimating non-dimensional parameters such as the Reynolds number, Re, Karlovitz number, Ka and Damkhöler number, Da which are used as additional parameters in some correlations. They also define the initial conditions of premixed turbulent flames on the map of premixed turbulent flame regimes which are phase diagrams such as Da versus Re or u'/S_L versus l_x/δ_L. These phase diagram are only meaningful for isotropic turbulence where relationship exists between Reynolds number and the integral and the Kolmogoroff length scales. The isotropic assumption is appropriate for most of the flame configurations reviewed here because turbulence is generated in a controlled manner. But it is not suitable for describing the turbulence characteristics in flame configurations with shear.

Except for several pioneering works, most studies have reported measurements of turbulence intensities, and mean velocity when appropriate. The measurement methods used by various investigators have been tabulated by Abdel-Gayed et al. [23]. The use of hot-wire technique for velocity measurements have been replaced by the use of laser Doppler anemometry (LDA) in the last ten years. LDA has the advantage that it is non intrusive and is capable of measuring reverse flows or flows with no mean velocity. Most of the reported results, however, have been obtained in non-reacting flows without the presence of the flames. For steady flames, Cheng and Ng [7] have shown that the turbulence flame can increase turbulence intensity in the reactants and this effect may needs to be considered in the correlation. Abdel-Gayed [20] proposed the use of a correction to the incident turbulence intensity for unsteady flame experiments. They argued that the effects of large scale turbulence on flame propagation are not alway significant because the lapse time of typical unsteady flame experiments are shorter than the largest turbulence time scale. This correction does not appropriate for steady flames. In general, the effects of the flame on turbulence intensities and the corrections associated with the limited experimental lapse time are small.

FLAME CONFIGURATIONS FOR MEASURING S_T

Many flame configuration have been used for determining S_T and Fig. 3 shows seven of the most common configurations. They consist of steady (Fig. 3 (a) and (b))and unsteady flames Fig. 3 (c). Except for the two unsteady flame configurations, all the rest are at best simulators of the 2-D flames. The steady flames all require some form of flame stabilization. The v-flames utilizes rods or heated wires [5,6,7], the Bunsen flame [10] and the inverted conical flames [11,12,13] are stabilized by pilot flames (Fig. 3(a)). Flame stabilization in stagnation flows, either against a plate [8,9] or in two equal and opposed streams [24] are achieved by flow divergence (Fig. 3(b)). The flame brush thicknesses of the v-flames, Bunsen flames and inverted conical flames are non-uniformed, evolving from about the laminar flame thickness near the stabilization point to a much larger thickness. The flame brushes are curved and oblique to the incident flow, with the tip of the the Bunsen flame being the exception. These configurations can only be considered as very poor approximations of the planar flames of Fig. 1(a). The stagnation flow configurations produce turbulent flame brushes which are planar and more uniform. Along the stagnation line, the flame is locally normal to the approaching flow. In fact, one of the motivations to develop this configuration for turbulent flame studies was to facilitate the determination of S_T [8].

The flowfields of the steady flames, as shown by the flowlines are drastically different. In the open configurations, i.e. the v-flame, the Bunsen flame, and the stagnation flow stabilized flames, significant flow divergence occurs. The difference in flow divergence not only affects the turbulence characteristics throughout the entire flowfield but, as discussed later, also affects the turbulent burning speed. Also the interaction between the flame flowfield and the ambient air may also have a significant effect on flame propagation. On the other hand, flame propagation in the enclosed steady flame configurations may not be influence by flow divergence but the flame induces flow acceleration and creates a favorable pressure gradient downstream which may have a significant effect.

Enclosing the unsteady flame systems (Fig. 3(c)) causes mean pressure rise as the flame propagates away from the initiation point. To avoid its influence, burning speed measurements are often made within a short time after ignition before the mean pressure in vessel begins to rise. This allows only a few microseconds to observation flame propagation. The main drawback is that the flame only has time to react to small scale turbulence. Otherwise, the pressure rise has to be measured and used to calculate a bulk burning rate. In an open unsteady system, the flame ball is transported by the mean flow downstream and the interaction between the reactant stream with the surrounding air may have some effects on flame development. These differences between in the flowfields of the steady and unsteady turbulent flames make it difficult to accept that the turbulent burning speed determined from these configurations can be directly compared.

METHODS FOR DETERMINING S_T

Flow Visualization Method

In the review of Abdel-Gayed et al. [23], a total of 1650 published turbulent burning speed data were collected and compared. They also tabulated the methods used for determining S_T, the incident turbulence characteristics and length scales. Except for a number of recent works, the overwhelming majority of the data have been obtained using schlieren technique. Schlieren is a light intergration method which essentially gives a silhouette of the outer cold boundary of the flame brush (approximately the $\bar{c}$ = 0.0 contour) in addition to some qualitative features of the flame wrinkles. It does not provide information on the flame structure such as the flame brush thickness or flamelet wrinkle scales. In many of the earlier works, the mean flame flame area indicated by the schlieren images and the volumetric flow rate of the reactants were used to estimate S_T. This method seems too arbitrary and the data may not be sufficiently precise to meet the standard of present day investigations.

In the series of works by Abdel-Gayed and Bradley and their collaborators e.g. [1,2,3], the turbulent burning speed was determined by analyzing high speed schlieren movies of unsteady twin spherical flame enclosed in a vessel (Fig. 3(c) right). The rate at which the two flame front approach each other along the axis joining the points of ignition was considered as twice the turbulent burning speed. In the earlier studies, the underlying assumption is that the reactants ahead of the flame brushes remain stationary during flame propagation. However, it is well known that the propagating flames induce fluid motion ahead of it. Between the two flames, a stagnation flow situation may be created. Therefore, the flame speed relative to the laboratory frame is higher than that relative to the reactants. Subsequent studies have used LDA to measure the flow velocity ahead of the flame. A concern recently pointed out by Bray [22] is that the leading edge velocity, i.e. the velocity of the schlieren silhouette at $\bar{c} \approx 0.0$, may exceed the turbulent burning speed. Their explanation is that the flame brush "stores" unburned reactants as it grows. In other words, the rates at which the mean flame radius associated with various $\bar{c}$ contours are not uniform when the flame brush thickness growths with time, i.e. $dR_{\bar{c}=0.0}/dt > dR_{\bar{c}=0.5}/dt > dR_{\bar{c}=1.0}/dt$. This suggests that the schlieren method used by Abdel-Gayed and Bradley consistently provides a upper bound value of S_T.

Cheng et al. [25] also used high speed schlieren movies to determine S_T for spherical unsteady flames drifting down a wind tunnel (Fig. 3(c) left). Because the schlieren images show that the flames are not quite spherical and are characterized by large wrinkles, a mean radius R_{mean} is needed in order to estimate S_T using Eq. (2). Towards this aim, the schlieren silhouettes were digitized to deduce the an apparent flame center and thus the mean radius R_{mean}. This mean radius, however, is not the same as the instantaneous $R_{\bar{c}=0.5}$ through the wrinkled flame sheet as shown in Fig. 1. The reason is that schlieren does not provide a cross-sectional image of the flame ball. In a subsequent study, Cheng et al. attempted to use tomography to determine S_T. This aspect of their work will be discussed later in this paper.

Flame Geometry Method

The use of schlieren for measuring S_T in steady flames is also known as the flame inclination or flame geometry method. This method is relatively simple requiring only one schlieren record for each flame condition. The orientation of the flame brush is shown by the schlieren silhouette representing approximately the mean $\bar{c} = 0.0$ contour. Other techniques can also be used to determine flame orientation for the steady flames by mapping the scalar properties within the flame brush. The techniques include measurements of temperature by thermocouples, gas density by Rayleigh scattering, and mean reaction progress variable by Mie scattering. As mentioned above, the mean velocity component of the incident flow normal to the local flame angle is considered as the local S_T. Schlieren method was used in the series of work by Ballel and Lefebvre [11-13]. For their enclosed inverted conical flames Fig. 3(a), the streamlines are more confined and the estimation of S_T only requires the additional information on the mean bulk flow velocity.

The application of flame geometry method to open steady flames without considering flow deflection or flow divergence can lead to some very interesting implications. For example, at the tip of the Bunsen flame, the flame brush is locally normal to the mean flow. The flame geometries method then implies that the S_T at the tip is equal to the incident mean velocity. This is, none-the-less, the most striking example. In the oblique flame regions of the Bunsen flame or in the v-flames, S_T can be estimated if the flow deflection in the reactants is known. Such measurement requires the determination of both the streamwise and transverse velocity components. Thus the only means available is the directional sensitive LDA. In the v-flame configuration (Fig. 3(a)), the flow in the the reactants is deflected away from the center. If the flow is assumed to be undeflected, the flame geometry method will give a higher S_T value. This is the case in the earlier works of Smith and Gouldin [5] in v-flames where the flow velocity was measured with hot-wire and thermocouples was used to estimate flame inclination.

The growth of the flame brush thickness in steady flames also introduce uncertainties. As mentioned earlier, the flame brush thickness increase with distance away from the stabilization point. The $\bar{c}$ contours, therefore, are not parallel. Because S_T is defined as the velocity component of the incident flow normal to the local flame orientation, a choice has to be made on which contour to use. This situation is made worse by the fact that the flame inclination angles are typically small, between 10 to 30 degrees. If the divergent angle of the flame brush is 10 degrees, the difference between S_T determined based on the contours of $\bar{c} = 0.0$ and $\bar{c} = 1.0$ can be larger than the laminar burning speed S_L. To reconcile this situation, Cheng and Ng [7] proposed the use of an effective mean flame orientation for v-flames. This method is based on the argument that through the flame zone the velocity component parallel to the flame zone must be conserved. Therefore, the velocity vectors obtained in the reactants and in the products at $\bar{c} = 0.0$ and $\bar{c} = 1.0$ can be used to deduce this orientation. The results obtained by the effective flame orientation methods are generally comparable to those obtained using $\bar{c} = 0.5$. The main drawback is that the method cannot be generalized to other configurations. Furthermore, there is no meaningful physical interpretation for this effective flame orientation.

The problem with the choice of $\bar{c}$ contour for determining S_T seems to be circumvented by using the stagnation flow stabilized flame [8,9] (Fig. 3(b)). At the centerline. the flow is locally normal to the flame brush and the velocity at the cold boundary of the flame zone conveniently defines S_T. In the works of Cho et al. [8] and Liu and Lenze [9] S_T for methane, hydrogen, and mixtures of methane/hydrogen have been reported and the results are quite satisfactory. This suggests that the stagnation flow stabilized flame may be the best configuration for determining S_T. However, recent tomographic studies have shown that flow divergence in the flame flame zone is significant and its effects on the turbulent burning speed may need to be taken into consideration.

Tomography

As demonstrated in Fig 1(a), a more direct means to investigate turbulent burning speed for flames propagating in low to moderate Reynolds number turbulence is to determine the area of the wrinkled flame sheet. The 2-dimensional(2-D) tomographic techniques is a very convenient means to estimate the flame area thus providing a much needed alternate independent method. Here, tomographic technique refers to the flow visualization method which shows instantaneous 2-D cross-sectional images of the flame brush. It is based on visualizing the flow by illuminating micron size seed particles within the flow with a laser sheet. To distinguish between the reactants and products zones, seed particles which evaporate at the flame sheet are used. The instantaneous flame sheet is shown on the tomographic records by the boundary between light (cold reactants with seed particles) and dark (hot products without particles) regions.

Cheng et al. [25] used high speed tomographic movies to study the development of unsteady spherical flame. The procedure to analyze the flame boundary is the same as the one used in an earlier study for schlieren. This analysis estimates the $\bar{c} = 0.5$ contour from each of the instantaneous flame boundary. Because the development of the flame kernel immediately after ignition is dominated by the influence of small scale turbulence, the flame kernels are found to drift in and out of the laser plane. This results in large fluctuations of R_{mean} in time making it difficult to determine dR_{mean}/dt and hence S_T. Their somewhat disappointing results suggest that ensemble average from many movies may be required.

Many investigator have reported tomography studies of steady premixed turbulent flames. Still records and high speed movies are now available for all of the open steady flame configurations shown in Figure 2. The most common feature shown by all of the tomographic records is the flame cusping toward the products side. Also, the formation of isolated flame pockets are not shown in these flames which are all within the flame sheet regime. The flame boundaries obtain by tomography have been analyzed to derive the mean flame crossing length, an analogy to the flame crossing frequency, and other scalar length scales [26]. Other flame properties such as the radius of curvature can also be determined for comparison with turbulence intensity and stretch rate.

Fractal analysis is by far the more established and most commonly used means to characterize the flame boundaries. The distribution of the flame wrinkle scales, the smallest and largest significant scales are represented respectively by the three fractal parameters : the fractal dimension, D, the inner cut-off, ε_i, and the outer cut-off, ε_o. As discuss earlier, the fractal dimension D is a parameter in Gouldin's model of the mean reaction rate and it is also used in other models for predicting the turbulent burning speed. As to the estimation of the flame area ratio A_L/A_T the inner and outer cutoffs are the two relevant parameters. Although most studies have reported values for the fractal dimension and the outer cutoff, few studies have been successful in resolving the inner cutoff. This renders the results useless for deducing the flame area ratio.

In a recent investigation of the statistical errors of fractal analysis, Shepherd and Cheng [27] demonstrated that digitization noise and insufficient pixel resolution can obscure the inner cut-off. These effects, however, can be minimized by optimizing the resolution and smoothing the digitized flame boundaries. The inner cutoff is then shown more clearly on the fractal plot. Recognizing that the flame sheet is not an isotropic fractal object, Shepherd and Cheng proposed that the flame area ratio is equal to the square of the ratio of the flame lengthes at ε_i and ε_o. This is the basis for deducing the flame area ratio for their methane/air and ethylene/air v-flames and stagnation plate stabilized flames reported in their paper.

Compared to the flame area ratio determined for the stagnation plate stabilized flames, the corresponding turbulent/laminar burning speed ratios are consistently higher. Such comparison for the v-flames data indicates the same trend. This discrepancy may seem surprising for the stagnation flow stabilized flames. But it serves to illustrate that, our notion that these flame have normal planar flame brushes tends to obscure the consideration of flow divergence. Flow diverges within the flame brush means that the cross-sectional area of a streamtube increase with $\bar{c}$. Defining S_T as the velocity at $\bar{c} = 0.0$ again gives an upper bound value, as in all the cases discussed above. For the stagnation point flow the divergence is conveniently shown by the off center time mean streamlines, this may provide a means to correct the cold boundary S_T. For the v-flame and the other flame configuration, it may not be possible to correct for the flow divergence effect. This suggests that for most flame configuration, the tomographic method may provide the only means for accurate determination of the turbulent burning rate.

CORRELATING S_T

The effects of flow divergence and the uncertainties of the S_T data associated with different experimental methods may be the explanation for the large scatter shown by the data reviewed by Abdel-Gayed et al. [23] (Fig. 4). In some places, the scatters in the S_T data are more than ten times the laminar burning speed. The correction offered by the use of the effective rms velocity fluctuation seem insignificant compared to scatters of this magnitude. This also suggests that attempts to correlation the entire set of available data using other parameter may not be the most rewarding approach to again better insight into premixed turbulent flame propagation. Even if the results were encouraging, they may not be appropriate for generalization. This is because some of the data obtained in earlier works may not be precise. Perhaps these data should be retired and excluded from further consideration. In addition, the data are affected by many interacting phenomena which are not represented by parameters of the incident flow and the mixture composition.

Perhaps the needs of fundamental theoretical studies and practical applications may be better served if the S_T correlations are made specific to a given system or flame configuration. Only under this condition can the effects of flame geometry and flow divergence be corrected and other effects such as flame instability be identified and resolved. For example, the measurement of S_T in stagnation plate stabilized flames have shown very little scatter for the same fuel. The correction of stream tube divergence is not expected to increase the scatter because the divergence in all of the flames are similar. The most encouraging aspect is that the data are reported by two independent studies. Although the conditions investigated are all for flows with low Reynolds number, the facility at Karlshrue is capable of providing conditions with higher turbulence intensity.

SUMMARY

This review of the approaches and methods to study turbulent burning speed has brought to light the following points:

I Most of the available S_T data are based on measuring or estimating the velocity at the leading edge of the flame brush. This method consistently gives an upper bound value of S_T as confirmed by comparing the ratio of turbulent/laminar burning speed to the flame area ratio derived from tomography.

II The discrepancy between the leading edge velocity and the true burning velocity is mainly caused by the effects of flow divergence. In most configurations, this effect is difficult to estimate and tomography may be the only convenient means to infer the turbulent burning speed.

III Because premixed turbulent flame propagation is affected by many different phenomena in addition to the turbulence characteristics of the incident flow and combustion chemistry, correlation of all available data is useful only for indicating a general trend. The use of other flow or mixture parameters to gain better correlation may not be rewarding.

IV Some of the S_T data reported in earlier studies were obtained with methods which provide an approximation of the averaged burning speed. These data should be retired and new measurements should be made.

V Correlation of S_T data obtained for specific flame configuration seems to be the most promising approach to gain more insight into the concept of turbulent burning speed. A necessary prerequisite is to correct for the effect of flow divergence. At present this requirement limits such studies to the stagnation flow stabilized flames.

NOMENCLATURE

$\overline{c}$	reaction progress variable
Da	Damkhöler number
l_x	integral length scale
Re	Reynolds number based on integral length scale
S_L	laminar burning speed
S_T	turbulent burning speed
$\lvert\vec{U}\rvert$	flow speed $= \sqrt{U^2 + V^2}$
U, u'	mean and rms axial velocity
V, v'	mean and rms radial velocity
$\underline{w}_f$	local reaction rate
$\underline{w}$	mean reaction rate
W	ratio of turbulent/laminar burning rates
x	axial distance
y	radial or transverse distance
δ_L	laminar flame thickness
δ_T	turbulent flame thickness along streamtube
ϕ	equivalence ratio
ν	flame crossing frequency
ρ	gas density
ξ	co-ordinate along flowline

Subscripts

L	laminar condition
T	turbulent condition

p	conditioned products properties
r	conditioned reactants properties
∞	free stream

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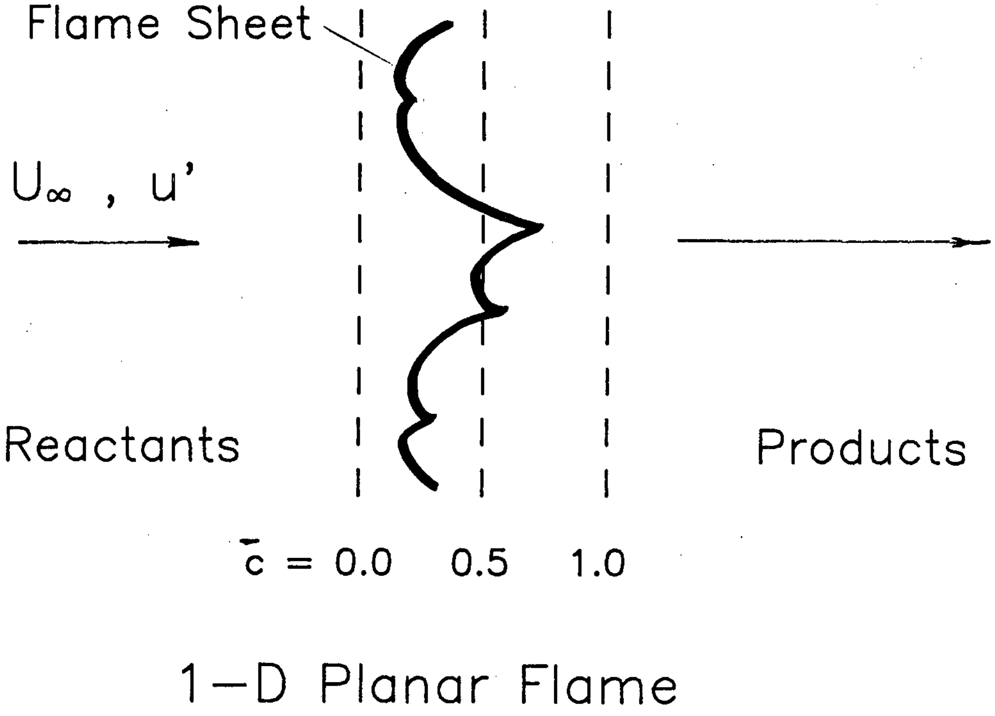
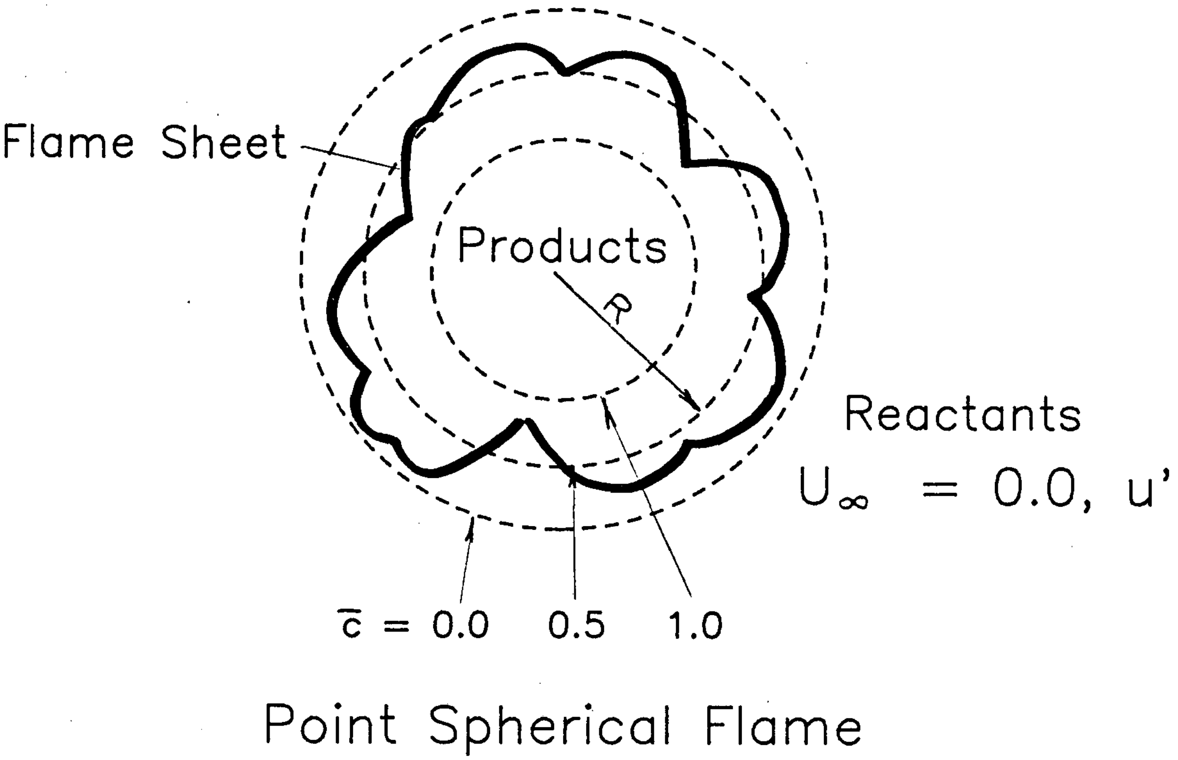


(a)



(b)

Figure 1 The two unambiguous configurations for S_T determination.

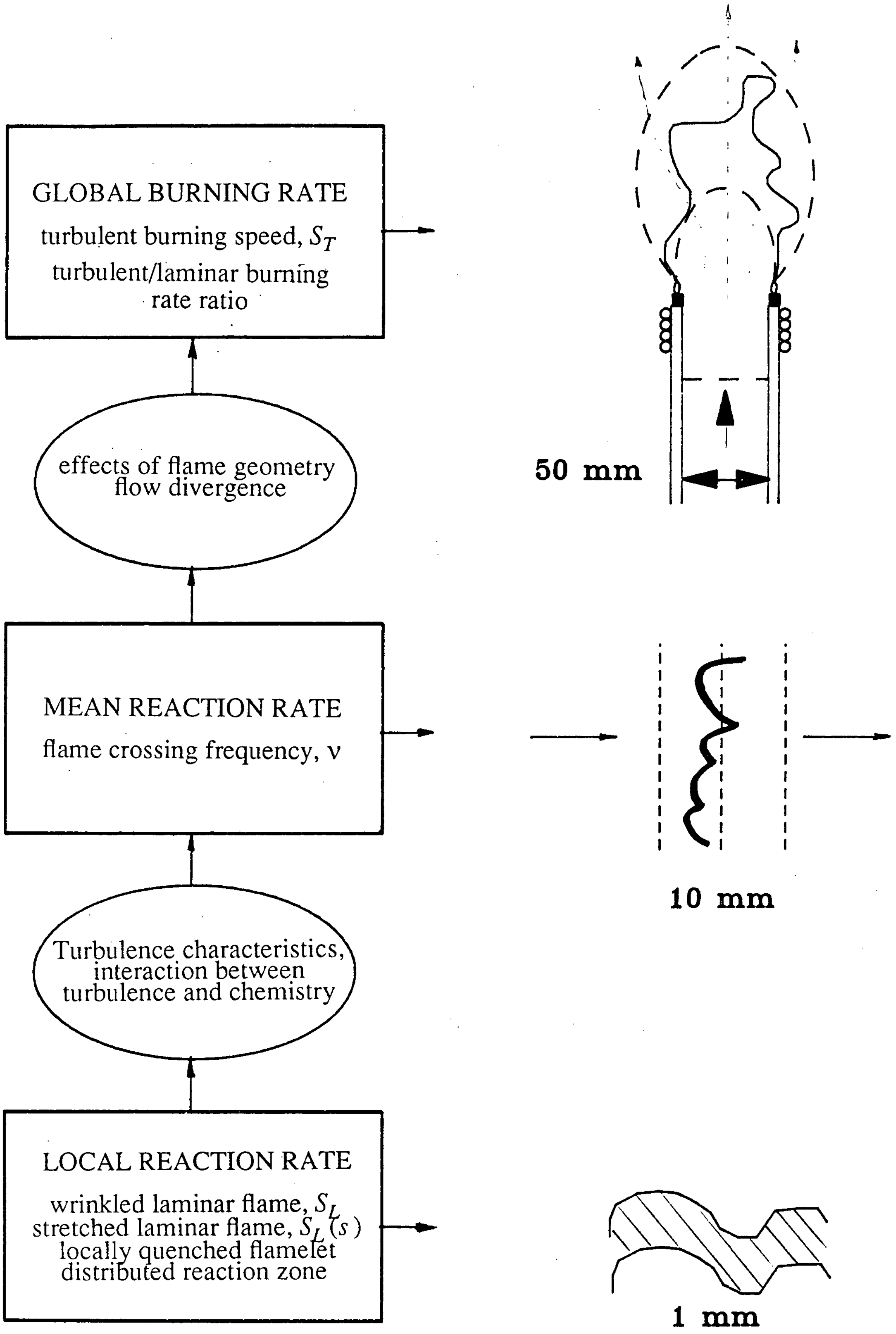
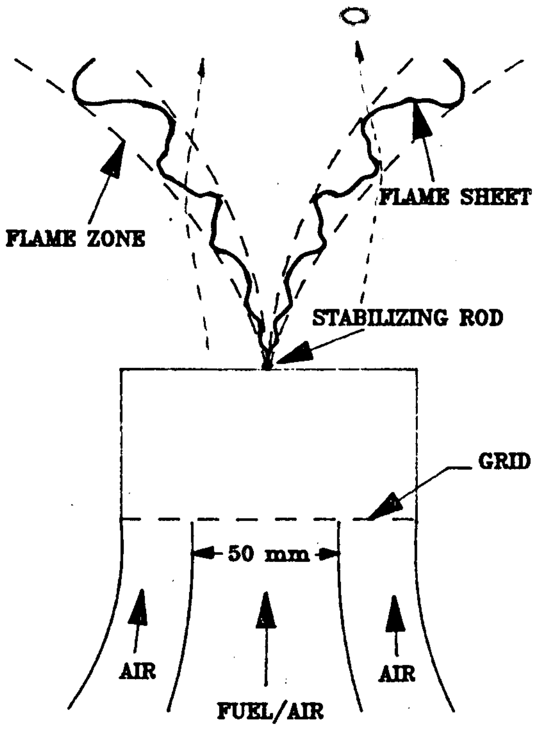
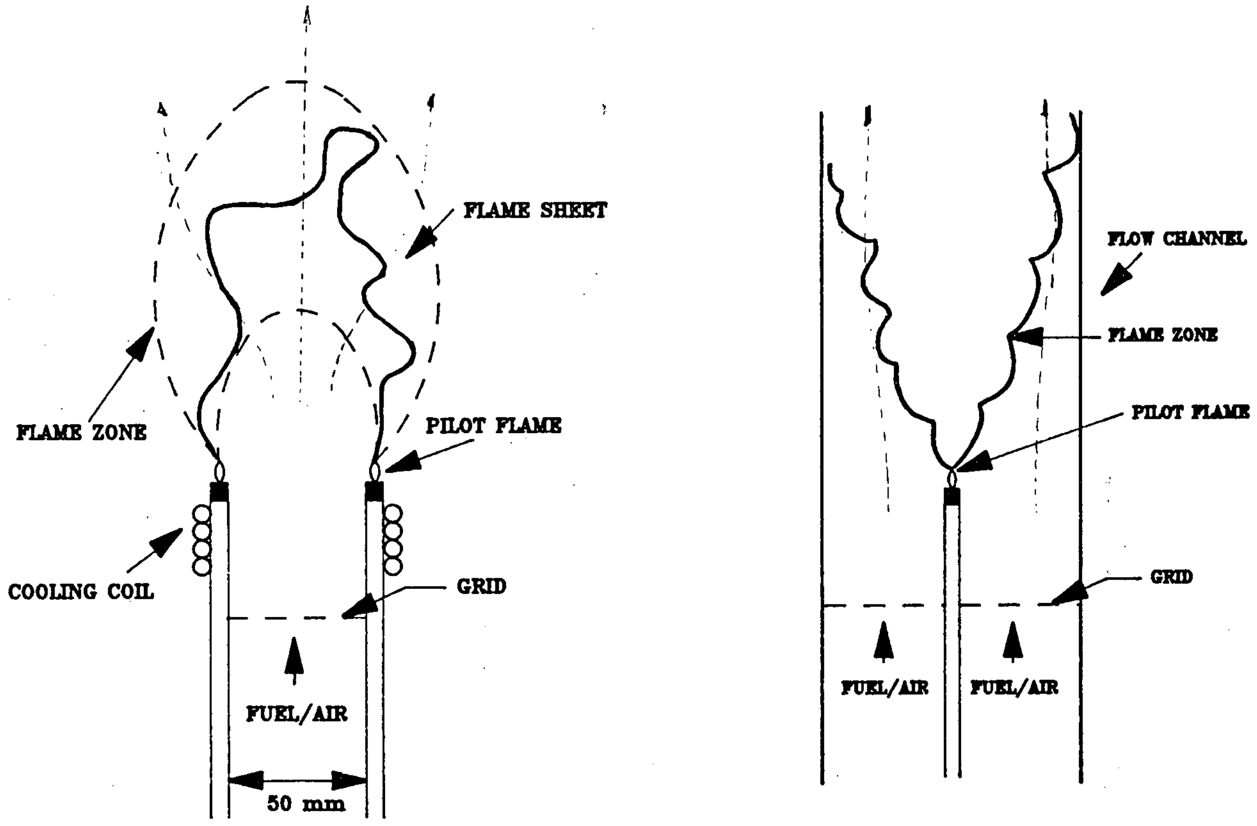


Figure 2 Relationship anoung S_T, mean and local reaction rates.



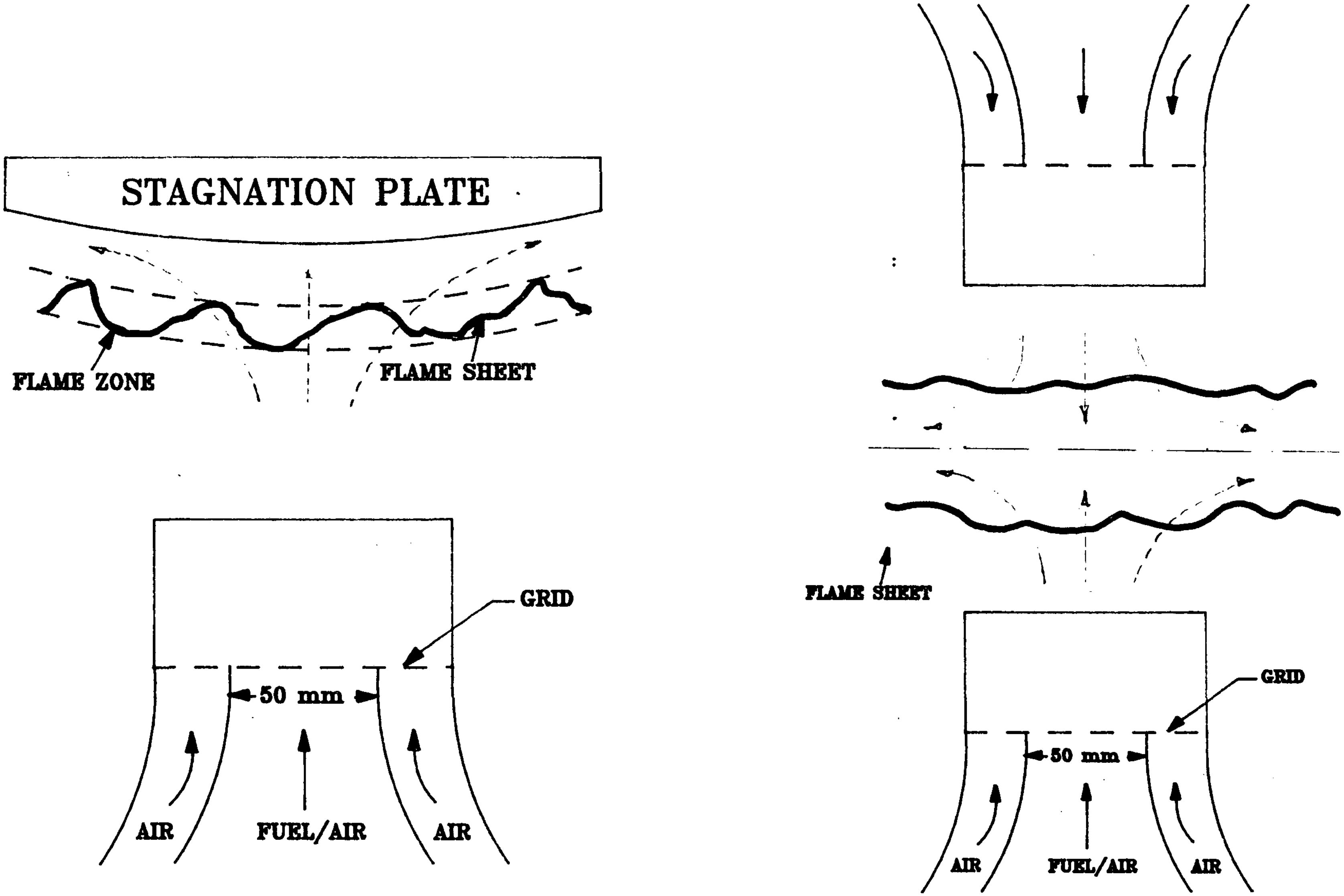
Rod Stabilized V−flame



Enclosed Piloted Flame

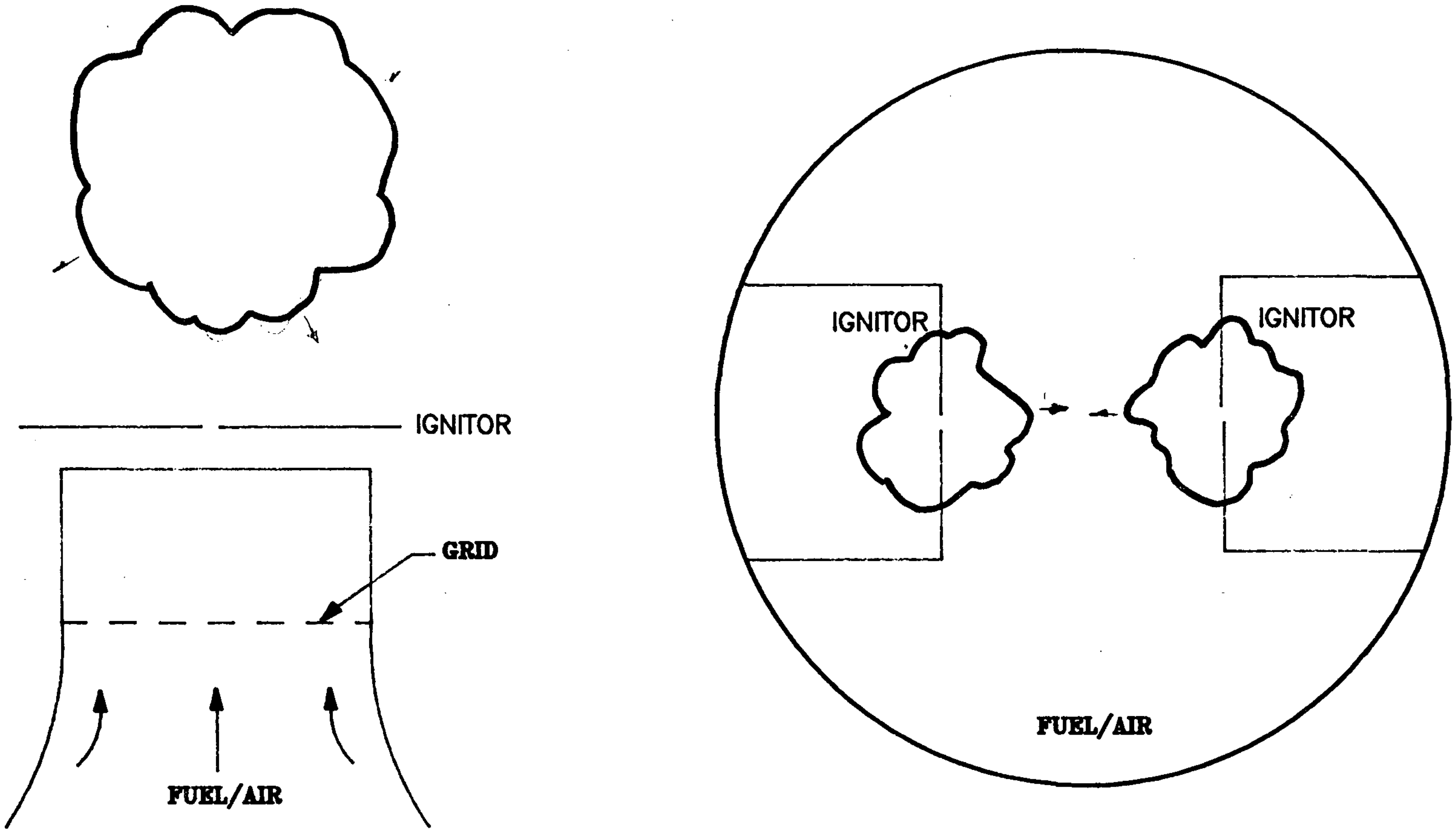
Large Bunsen Flame

Fig 3(a) Steady oblique flame configurations.



Stagnation Flow Stabilized Flames

Figure 3(b)



Point Spherical Flame

Twin Spherical Flames

Figure 3(c) Unsteady flame configurations

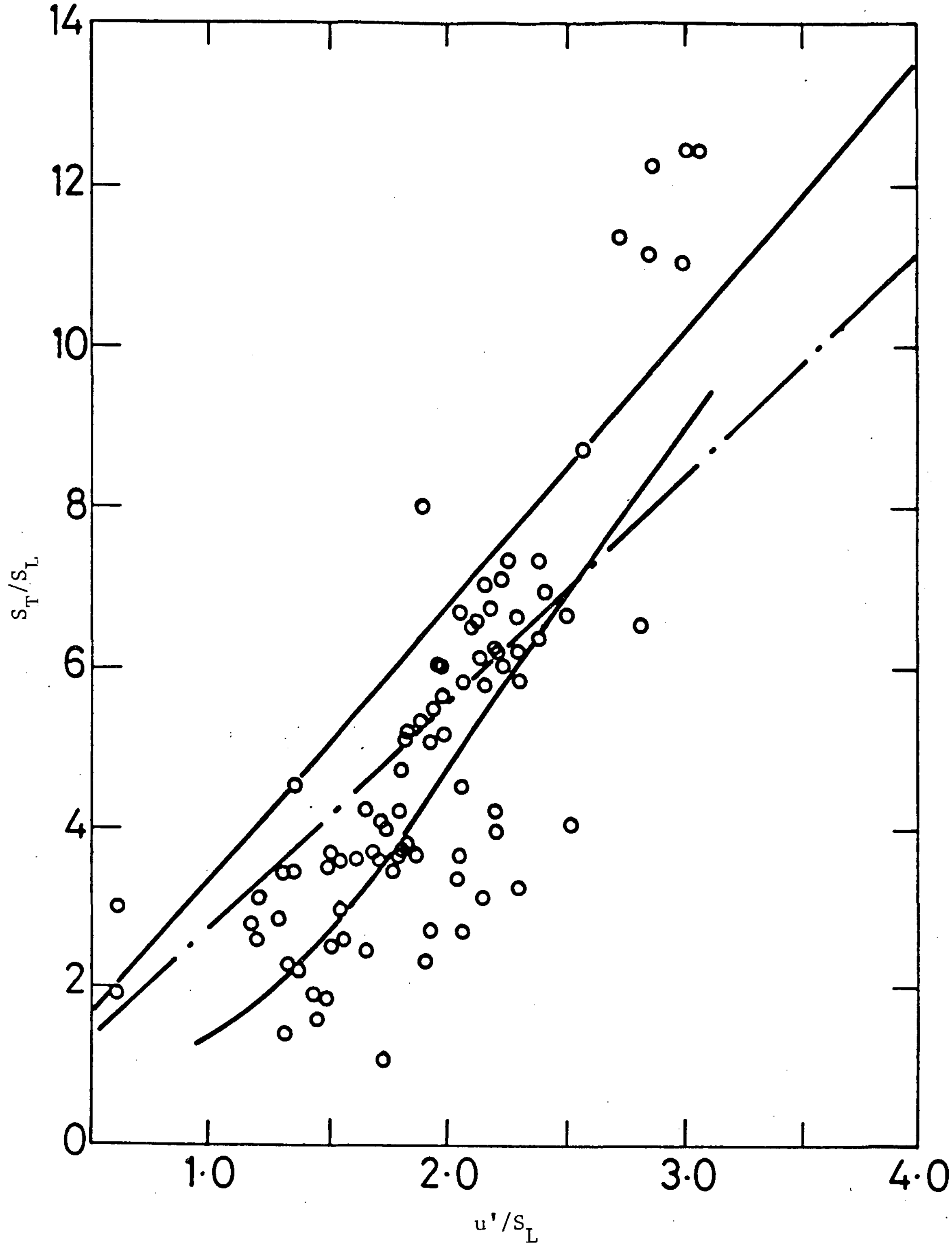


Figure 4 Data points and full curve: turbulent burning speed data from Abdel-Gayed et al. [23] Dashed line: emperical correlation from Bray [22]. Figure source Bray [22].