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IS TURBULENT BURNING VELOCITY A MEANINGFUL PARAMETER?

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Abstract

The concept of turbulent burning velocity arises from an analogy with that of the laminar burning velocity. Experimental measurement or theoretical computation of the latter must take account of the effects of flame stretch. This is also necessary for turbulent flames and when flame propagation originates at a point source, there is a temporal development of the turbulence acting on the flame and also of the thickness of the flame brush. Under these conditions, whilst the turbulent burning velocity is a measure of the propagation rate of the front relative to unburnt mixture, it cannot be a direct measure of the mass rate of burning.

Introduction

Initially, the laminar burning velocity was seen as a physico-chemical parameter, whereas the turbulent burning velocity additionally required aerodynamic parameters to be specified. With improved understanding of the effects of flame stretch on laminar flames this difference has been eroded. Although the accuracies of the different methods for measuring laminar burning velocity have been well discussed [1], it is only recently that the importance of control and measurement of the flame stretch has been sufficiently recognised [2]. A similar recognition has occurred with regard to mathematical models of laminar flames with detailed chemical kinetics: allowance must be made for flame stretch by not imposing upon the model a purely one-dimensional flow. Valuable computational studies have revealed the effects of flame stretch [3].

Even greater care must be taken with experimental measurements and the mathematical modelling of the turbulent burning velocity. Measurements on burners become progressively more difficult as the turbulence is increased because of problems of flame stability, whilst a freely propagating flame in the fan-stirred bomb avoids such problems [4, 5]. However, flame propagation from a point source poses problems associated with the measurement of the effective turbulence acting upon the propagating flame. Some mathematical models express the rate of reaction in terms of the turbulence decay rate, but account must be taken of the ways in which flame stretch can quench a flamelet [6].

Turbulent Flame Propagation from a Point Source

The measured r. m. s. turbulent velocity, u', in a stirred bomb is not necessarily that acting on the flame front. Initially, only the highest frequencies of the spectrum of turbulent can wrinkle the flame surface: lower frequencies merely bodily convect the flame kernel. As time passes, progressively lower frequencies wrinkle the surface and the r. m. s. velocity, u'_k, effective in the wrinkling process can be derived, at any given dimensionless time, from the measured dimensionless power spectral density function [7]. Eventually, u'_k, attains the value of u', but this does not occur during the pre-pressure period of bomb explosions. Development of the turbulent flame, including the thickness of the flame brush, is proceeding during this time. The fully developed turbulent burning velocity, u_t, is associated with u'. That associated with, u'_k, is correspondingly less and will be denoted by u_{tk}.

As measured by the double kernel method [8], u_t or u_{tk}, is the velocity of the turbulent flame front relative to the unburnt gas. With a developing spherical turbulent flame, of radius r, because of the existence of unburnt gas behind the flame front, this does not give a direct measure of the mass rate of burning. For this purpose, another burning velocity, u_{tr}, has been proposed such that the total mass burning rate is equal to $u_{tr}\ 4\pi r^2\rho_u$ [9]. Laser sheet photographs reveal an appreciable amount of unburnt gas behind the flame front and $u_{tr} < u_t$. As $r \to \infty$, the spherical flame structure tends towards that of a flame and $u_{tr} \to u_t$. The intensity of chemiluminescent emission from the CH radical in the flame reaction zone has been used to measure u_{tr} [9]. It can also be found from measurements of u_{tk} and the turbulent flame speed in laboratory coordinates. Karpov and coworkers have adopted another approach and measured turbulent burning velocities, u_t^k, in a fan-stirred bomb from pressure records [4, 10]. This more accurately expresses a mass burning rate than does u_t. However, it readily can be shown that $u_t > u_{tk} > u_t^k > u_{tr}$.

It cannot be regarded as satisfactory that a fundamental parameter for the burning rate can have four different interpretations. On the other hand, all are legitimate and, in their own ways, informative. One type of parameter expresses the propagation rate of a front whilst another expresses a mass rate of burning. It is also necessary to quantify the way in which the spectrum of turbulent acting on the flame front develops.

Two principal influences determine the ratio of turbulent to laminar burning velocity: one, the wrinkling factor, u'_k/u_1, increases this ratio while the other, the stretch factor, decreases it. The fractional reduction in a laminar burning velocity due to stretch is equal to the product of the Karlovitz stretch factor, K, and the Markstein number and this dimensionless grouping seems to be an appropriate one to express the stretch factor for laminar flamelets in turbulent combustion. However, pending the availability of reliable values of Markstein number, the product KLe has been used as a stretch factor, to correlate values of turbulent burning velocity with Le, the Lewis number, based on the diffusion of the deficient component [11].

Turbulent Burning Velocities Compared

One theory of turbulent explosive burning envisages gas entrainment at the flame front with a mass rate of burning behind it that is equal to the total unreacted mass there divided by a reaction time, τ, usually related to the Taylor scale of turbulence, λ, divided by the laminar burning velocity. Experiments by Mushi at Leeds suggest $\tau = 0.28\lambda/u_1$. This modelling approach, together with the correlation of experimental turbulent burning velocities, has enabled the relationships between u_t, u_{tk} and u_{tr} to be obtained during spherical explosions.

Shown in Figs. 1 and 2 are variations of u_{tr}/u_t with dimensionless time from ignition, tu'/L, in which t is the elapsed time and L the integral length scale. Each figure is for a separate value of KLe and it can be seen that u_{tr}/u_t increases with the wrinkling factor u'/u_1 and decreases with the stretch factor KLe. The same trend, not shown, exists for u_t/u_1. As time and flame front radius increase, so u_{tr}/u_t tends towards unity. The temporal development of u_{tk} towards u_t, as more of the spectrum of turbulence becomes effective in flame propagation is shown by the broken curve on each figure.

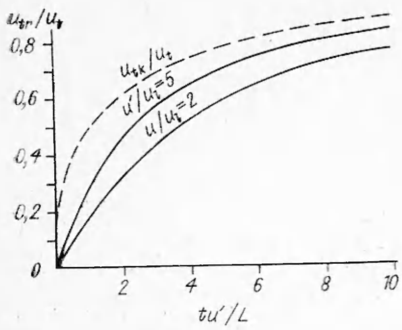

Fig. 1. Spherical turbulent flame propagation from a point source: temporal variation of mass burning to fully developed normal turbulent burning velocity, u_{tr}/u_t, for two different values of u'/u_l. Broken curve gives the temporal variation of u_{tk}/u_t. KLe = 0.07.

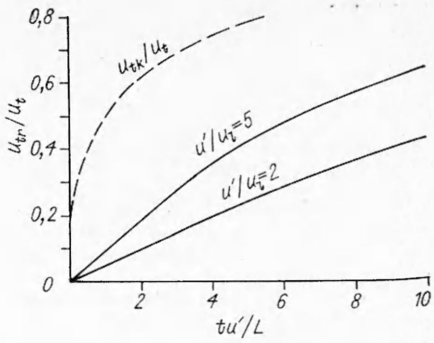

Fig. 2. Spherical turbulent flame propagation from a point source: temporal variation of mass burning to fully developed normal turbulent burning velocity, u_{tr}/u_t, for two different values of u'/u_l. Broken curve gives the temporal variation of u_{tk}/u_t. KLe = 0.21.

The deficit of u_{tr} below u_t is indicative of the amount of unburnt gas behind the flame front. This is large in the early stages, particularly at the higher value of KLe.

The values of u_{tk}/u_t are less than unity because the turbulent flame is nowhere fully developed. At the same instant, values of u_{tr}/u_t are less than those of u_{tk}/u_t because of the amount of unburnt gas behind the front.

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