Flame propagation in a tube: the legacy of Henri Guénoche

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Abstract

Since the time of Mallard and Le Chatelier there has been a fascination with the problems of flame propagation in tubes. An important goal has been the development of a reliable technique to measure accurately the most basic combustion parameter, the laminar burning velocity. On the one hand a stable, steady-state, flame is necessary to do this, while on the other hand many flames are inherently unstable. These conflicting tendencies have been the source of much creative combustion thinking, not least from Guénoche. The paper attempts to indicate how his work has contributed to our present appreciation of the effects of flame stretch, thermo-diffusion, Darrieus – Landau and Taylor instabilities. Some practical consequences of the effects of these on the burn rate are briefly discussed.

Laminar burning velocity and its measurement

The purpose of the present paper is to show how Henri Guénoche's painstaking descriptions and analyses of experimental findings concerning flame propagation in tubes contribute greatly to our current fundamental understanding of combustion.

In 1883 Mallard and Le Chatelier [1] showed that the condition of a tube closed at one end with ignition at the other, open, end is probably the one best able to achieve a constant flame speed over a distance sufficient for the measurement of the laminar burning velocity. Thereafter, the flame oscillates, particularly with lean CH_4 and H_2 and rich hydrocarbon mixtures with air, and then assumes a cellular structure with an enhanced flame speed [2]. Their painstaking studies of the factors that give rise to a regime in which the flame speed is constant led Guénoche and Laffitte [3] to suppress any tendencies to acoustic oscillations by fitting an orifice to vent the burned gas at the open end of the tube, a practice adopted by subsequent workers, to make the vertical tube method a recommended one for measuring burning velocity [4]. Conversely, in the unstable regime forcing oscillations can induce a cellular structure [5]. When the flame attains a constant flame speed through the use of orifice damping its shape hardly changes and hence the effects of flame stretch rate are minimal.

In the last decade the quantitative understanding of these effects stretch has advanced considerably and it is now almost mandatory to measure stretch-free values of burning velocity, u_λ, together with values of Markstein numbers, *Ma*, to express the effects of flame stretch rate, in conjunction with the Karlovitz stretch factor, *K*. Flame stretch can either increase or decrease the burning velocity to a value, u_n, given by [6]:

$$\frac{u_\lambda - u_n}{u_\lambda} = K_s Ma_s + K_c Ma_c \qquad (1)$$

Here the stretch rate is separated into two components, comprising the strain rate tensor, suffix *s*, and the stretch rate due to flame curvature, suffix, *c*. That these two components have different Markstein numbers is shown by computations for stationary spherical flames which have a total stretch rate of zero, but equal and opposite strain rate and flame curvature contributions. Values of u_n are different at different radii, a consequence of the changes in these contributions [6]. Similarly, values of Markstein numbers are differentiated in spherical implosions, where K_s is zero and K_c is finite and negative.

A plot of all known measured values of maximum burning velocities for methane-air against the year of publication shows a much reduced scatter in the results from the last decade, as the importance of allowing for the flame stretch rate has become recognised. Values now are consistently close to 0.37 *m/s*, lower than most of the earlier values. Attempts to measure u_n, which exhibits a negative value of the dominant Markstein number, Ma_s, combined with a failure to eliminate the effects of stretch, resulted in overestimations of u_λ. On the other hand, earlier values from the open–tube method, as recommended by the French researchers, were never far from 0.37 *m/s*, with a tendency to be somewhat lower. The greater accuracy of this method is probably due to the absence of significant stretch, although the values are revised upwards when allowance is made for a reduction in burning velocity close to the wall.

Unstable flame propagation in tubes

From considerations of the wave deformation of a planar flame, it can be reasoned from Eq. (1) that when *Ma* is positive and *K* is large, then thermo-diffusive effects are stabilising against the underlying Darrieus – Landau instability. Conversely, if *Ma* is negative and *K* is large, thermo-diffusive effects also are de-stabilising. Flame instabilities arise when any stabilising effects of thermo-diffusion are no longer able to neutralise the inherent Darrieus – Landau instability.

Although the recommended conditions of constant flame speed, shape, and minimal stretch rate, are conducive to accurate direct measurement of burning velocity in a tube, they are not conducive to flame stability. This explains the developing oscillations, flame cellularity and acceleration that occur in the later stages of flame propagation. This is in contrast to the initial stage, just after ignition, when the stretch rate is high and exerts a stabilising role (provided *Ma* is not too low).

After ignition at the centre of the end of a tube, flame propagation and expansion of the burning gas create a gas velocity ahead of the flame and along the tube. When part of the flame surface reaches the wall, both the flame speed and the gas velocity ahead of the flame decrease and a transition to a tulip flame occurs: a forward pointing finger of flame becomes a backward pointing cusp. In discussing this phenomenon, Guénoche [2] drew a parallel with Markstein's studies [7] of flame front distortions by shock waves, as a consequence of Taylor instability. Clanet and Searby [8] have subsequently demonstrated experimentally the transition to a tulip flame in a half–open tube and explained this as a manifestation of Taylor instability, arising from deceleration due to the reduction in flame surface area at the wall.

Matalon and Metzener [9], in a mathematical study, have employed a non-linear evolution equation to describe flame propagation in a closed tube. This shows that, after the flame surface has contacted the wall, it flattens and a tulip shape can develop. A linear stability analysis shows that above a critical Markstein number the flame is stable, but below it the flame can be either cellular or tulip shaped due to Darrieus – Landau instabilities. In the case of the tulip shape, the curved flame generates vortical motion in the burned gas and a vortex pair advects the central part of the flame upstream.

For a tube closed at the ignition end and open at the other, the less impeded gas flow ahead of the flame now more readily generates turbulence and an increased flame speed through turbulent flame propagation [2]. More recent turbulent burning velocity correlations show the conditions for 'runaway' and shock wave generation, that can sometimes lead to detonation.

Unstable spherical flame propagation

For flame propagation in a tube, a limit is set to the longest possible unstable wavelength by the tube diameter. At the other end of the spectrum, the structure of the perturbation of the shortest wavelength is governed by thermo-diffusive effects. Similarly, for spherical flame propagation, the longest unstable wavelength is governed by the radius of the flame. Plots of upper and lower unstable wave numbers for spherical flames against Peclet number, *Pe* (the flame radius normalised by the flame thickness, δ_λ), based on the linear stability of Bechtold and Matalon [10], show peninsulas of instability for different Markstein numbers [11]. Only when a critical value of *Pe*, which decreases with *Ma*, has been attained can instabilities develop, although a complete cellular structure only first develops through fissioning of a few larger, into smaller, cells at a second, higher, critical value of *Pe* [12]. This also implies that *K* must fall *below* corresponding critical values.

For the largest values of *Ma*, the computations show the shortest unstable wavelength to be larger than the overall flame thickness. However, for values of *Ma* less than about 3, the shortest unstable wavelengths have been shown experimentally to be close to the overall flame thickness [13]. For negative values of *Ma* the cellular structure residing at these wavelengths is conditioned by thermo-diffusive effects; at the bottom of the troughs or cusps, where the localised flame stretch is highly negative, the local burning velocity is decreased, the deficient reactant is depleted by diffusion to the flanks, and the flame front is locally fractured.

As a spherical flame propagates, a cascade develops from the longest unstable wavelength, with a value close to that of the flame radius, through progressively decreasing unstable wavelengths, which gives rise to fractal-like wrinkling. This cascade terminates at the small cells, which are stabilised by thermo-diffusion. These cells are in a state of dynamic equilibrium. The smallest cells grow in size and this decreases the localised flame stretch on their surface. As a result, the cells become unstable, but are re-stabilised by fissioning into cells of smaller wavelengths, with greater localised convex curvatures and stretch rates [13]. In this regime, two limiting cell wavelengths are apparent, one comprised of the smallest, stable, newly-formed cells, associated with the first critical Peclet number, the other comprised of the largest, unstable, older cells about to fission, associated with the second critical Peclet number. As *Pe* increases, so also does the longest unstable wavelength, whilst the shortest wavelength remains fixed.

The increasing flame wrinkling that arises from the cascade of unstable wavelengths results in increasing flame speeds. It is possible to estimate these from fractal considerations, if due account is taken of the time lag in the growth of the instabilities [11]. For a given value of *Ma,* the inner and outer cut-offs (between which wavelengths lies the regime of instability) are a function of *Pe*. For containing walls of fixed size, it therefore follows that at a higher pressure, because δ_λ decreases with pressure, flame instability develops at a smaller radius. At any radius greater than this critical value the pressure increase will also increase the flame wrinkling, and hence the flame speed.

This is an important effect in the measurement of burning velocities using explosion bombs. In his discussion of it in [2] Guénoche, after noting the development of cellular flames at a critical Reynolds number (so defined that it is equivalent to *Pe*), comments that the increased flame wrinkling can lead to "an excessive value of burning velocity" from bomb measurements. He points out that, when using the tube method for such measurements, Combourieu [14] always adjusted the experimental conditions to obtain a stable flame front. The concerns of Guénoche have proved to be well-founded and are confirmed by recent bomb measurements, made in the stable regime and with allowance for the flame stretch rate [12]. The values of u_λ for iso-octane-air mixtures made in this way were found to decrease with pressure more markedly than those measured in bombs under conditions in which instabilities would increase with pressure and would increase the burning rate. The increased instability at increased pressures also affects laminar flamelets in turbulent combustion, with the result that turbulent burning velocities are increased on this count by higher pressures [15,16]. This has important consequences for the modelling of combustion in engines.

Vented explosions

Finally, attention is drawn to the relevance of the present considerations in the important practical area of explosion hazards. These unwanted explosions can occur in large containers in which the pressures can be high – both conditions conducive to the instabilities that have been discussed. In addition to these, vorticity can also be generated at the flame front by the baroclinic effect, which is created by the pressure waves that arise when the vent opens, triggered by the rising pressure. All these instabilities can increase the burning rate and hence the over-pressure, which, in turn, feeds back and further increases the instabilities and the burning rate. Here the venting of burned gas, introduced by Guénoche and Laffitte to stabilise flame speeds in tubes is valuable, but in a slightly different context.

Although the mass rate of venting of *burned* gas is less than that of *unburned* gas, the volumetric rate, that more directly controls the overpressure, is greater. For a given value of the venting parameter, $\bar{A}/\bar{S}_o$ (the ratio of the product of the vent coefficient of discharge and its area normalised by the container surface area to the gas velocity just ahead of the flame normalised by the acoustic velocity in the unburned gas), burned gas venting can reduce not only the maximum over-pressure in the vessel by at least an order of magnitude, compared with unburned gas venting [17], but also the instabilities that contribute towards its creation.

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