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# Measurement of unstable burning velocities of iso-octane–air mixtures at high pressure and the derivation of laminar burning velocities

A.S. Al-Shahrany, D. Bradley*, M. Lawes, R. Woolley

*School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK*

**Abstract**

A new technique is reported for measuring burning velocities at high pressures in the final stages of two inwardly propagating flame kernels in an explosion bomb. The flames were initiated at diametrically opposite spark electrodes, close to the wall, in quiescent mixtures. Measurements of pressure and flame kernel propagation speeds by high-speed photography showed the burning velocities to be elevated above the corresponding laminar burning velocities as a result of the developing flame instabilities. The enhancement increased with increase in pressure and decreased with increase in Markstein number. When the Markstein number was negative, instabilities could be appreciable, as could the enhancement. For the iso-octane–air mixtures investigated, where the mixtures had well-characterised Markstein numbers or critical Peclet numbers at the relevant pressures and temperatures, it was possible to explain the enhancement quantitatively by the spherical explosion flame instability theory of Bechtold and Matalon, provided the critical Peclet number was that observed experimentally, and allowance was made for the changing pressure. With this theoretical procedure, it was possible to derive values of laminar burning velocity from the measured values of burning velocity over a wide range of equivalence ratios, pressures, and temperatures. The values became less reliable at the higher temperatures and pressures as the data on Markstein and critical Peclet numbers became less certain. It was found that with iso-octane as the fuel the laminar burning velocity decreased during isentropic compression.


*Keywords:* Unstable flames; Laminar burning velocities; High pressures; Explosion bomb

## 1. Introduction

It is well known from experiments [1–4] and theory [5–7] that laminar spherical explosion flames are, or can become, unstable above a critical Peclet number (flame radius, $r$, normalised by flame thickness, $\delta_\ell$,). These instabilities become manifest as flame wrinkling over a range of wavelengths. As a consequence, the key physico-chemical parameter, the laminar burning velocity, can be difficult to measure experimentally. The paper addresses problems associated with this subject. Flames display, on a plot of wave number against Peclet number, see Fig. 1, a peninsula within which the wave numbers are associated with flame instability and wrinkling, which increase the burning velocity [5–7]. The range of unstable wave numbers increases with an increase in the Peclet number, $Pe$, and a decrease in the strain rate Markstein number, $Ma_{sr}$. Large values of $Pe$ arise

* Corresponding author. Fax: +44 113 343 2150.
*E-mail address:* d.bradley@leeds.ac.uk (D. Bradley).

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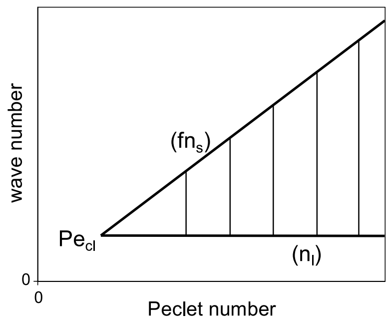


Fig. 1. Instability peninsula, with limiting wave numbers.

in large atmospheric explosions. They also arise at higher pressures, such as occur in engines, due to the smaller values of $\delta_\ell$. A higher pressure also decreases $Ma_{sr}$ [3,4,8,9]. The associated instabilities create a continually increasing burning velocity and tentative estimates of the magnitudes of this due to increases in both flame radius and pressure are given in [10]. The present paper reports a detailed experimental study of these influences, introduces a new means of measuring burning velocity at high pressure, and uses it primarily to measure those of iso-octane–air.

Spherical bomb explosions, with central ignition, have been widely employed to measure the burning velocities of gaseous mixtures [11]. The provision of strong windows facilitates observations of the flame during the earlier stages of propagation. Unfortunately, the flame moves out of the field of view as the pressure increases, and the safe working pressure of the vessel must be designed to be much greater than the pressure at which measurements are made. The Princeton group [12] has overcome this difficulty by employing two concentric cylinders, an inner one containing the combustible mixture with an annulus between them that is filled with inert gas at the same pressure. Just prior to ignition, an encasing sleeve of the inner cylinder is moved to align holes that then connect the inner vessel and annulus. By this means, the flame is quenched in the annulus after initial propagation in the inner vessel at the initial pressure, close to the maximum value.

Another approach would be to implode the mixture after ignition over the entire spherical wall of the bomb and make measurements in the final high pressure stage through central windows. Although spherical implosions have been modelled mathematically [8], they are impractical. As an alternative, the present studies utilised two inwardly propagating flame kernels. Spark ignition occurred at diametrically opposite points at the wall of a spherical bomb and the two flame fronts met at the centre of the bomb where they could be observed. In this way, burning velocities were measured closer to the maximum pressure rather than earlier at low pressure. With the emphasis on unstable flames, this method was advantageous in that Peclet numbers were maximised by large flame radii and small flame thicknesses.

The inwardly propagating flame kernels have been analysed in detail, and the two expressions for burning velocity, $u_n$, given in Appendix A, were derived in [13]. The analysis involved expressions for the volume of burned gas and the flame area. It was assumed that the surfaces of the two flames continued to be of spherical form until mutual flattening of them was observed at the leading fronts. It was also assumed that pressures, $p$, were equalized throughout the vessel, and unburned gases were compressed isentropically.

All the present mixtures and pressures were selected to give unstable flames, with burning velocities appreciably higher than their stable, unstretched, laminar, values, $u_\ell$. Indeed, for many mixtures it was impossible to measure stable laminar values directly because of the rapid onset of instabilities. The alternative of computing $u_\ell$ for one dimensional laminar flames, with detailed chemical kinetics but with suppressed flame stretch and instability, can also prove difficult. This is due to kinetic uncertainties at high pressure, particularly for rich iso-octane mixtures, the very ones that give negative values of $Ma_{sr}$ and very unstable flames.

Burning velocities of unstable flames are not constant, but develop with time. The present studies employed linear instability theory [5,6], first to predict the increases in $u_n$ above $u_\ell$, in terms of the increasing range of unstable wavelengths. Where values of $u_\ell$ were known, measured values of $u_n$ were shown to be in satisfactory agreement with such predictions. This validated the second, inverse, procedure of predicting values of $u_\ell$ from measured values of $u_n$, for iso-octane–air mixtures. This was applied to the experimental measurements of $u_n$ that covered equivalence ratios, $\phi$, between 0.8 and 1.4 at initial pressures of 0.5 and 1.0 MPa, both at 358 K. The twin kernel technique enabled $u_\ell$ to be inferred at pressures of up to 3 MPa. These measurements supplemented the recent ones of $u_\ell$ for these mixtures on burners at 0.1 [14] and in explosions at 1.0 MPa [3].

## 2. Burning velocity of unstable flames

The procedure adopted was first to use the theory of Bechtold and Matalon [5] to identify the wave numbers at the limits of flame instability. Spherical explosion flames at constant pressure begin to show cracks propagating across their surfaces at critical Peclet numbers, close to the theoretically predicted values for the onset of flame instability [5–7,15]. However, full cellularity and an associated increase in flame speed only occur