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Full Length Article

Laminar burning velocity measurements in constant volume vessels – Reconciliation of flame front imaging and pressure rise methods

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ABSTRACT

Laminar burning velocity measurements have been made in a constant volume vessel using both flame front imaging and the pressure rise methods. Results from the two different methods are shown to be the same, so long as appropriate techniques are used for analysing the data. Comparisons are presented for the laminar burning velocity of mixtures with air of methane, ethanol and biogas (60% methane, 40% carbon dioxide) for a wide range of flammable mixtures at pressures of 2 and 4 bar and temperatures of 380 and 450 K.

Methods for measuring the laminar burning velocity are still the subject of controversy, with different researchers favouring different approaches. Open flame techniques are very popular and the so-called heat flux method is now well established. The alternative technique of using a constant volume combustion vessel is also in common use, and has two distinct methods of use: either the imaging of flame front propagation at conditions of constant pressure, or the measurement of the pressure rise combined with a constant volume combustion model. The pressure rise method requires a more complex analysis, but has the advantage that a single experiment generates data across a range of linked temperatures and pressures, and the pressure and temperature rise also mean that data can be obtained for engine-like conditions.

1. Introduction

In the transport sector, biofuels such as blends including ethanol are becoming increasingly common as a way of reducing the greenhouse gas intensity of fuels, in conjunction with developments in engine technology that provide large gains in fuel efficiency. To fully realise these benefits, fundamental combustion performance of new fuels needs to be well understood, both to evaluate the potential performance of the fuel, but also to provide input parameters for models used in technological development.

The laminar burning velocity is a fundamental property of a propagating premixed fuel-air flame that is dependent upon the mixture temperature, pressure, equivalence ratio and presence of inert components. It is defined as the speed of propagation of an unstretched, adiabatic, one-dimensional flame relative to the unburned gas into which it is propagating. Flame speed is when the mixture ahead of the flame front is not stationary, for example, when the burned gas behind the flame front is contained, so that the reduction in density of the burned gas and its increased volume displaces the mixture into which the flame is propagating. Values of laminar burning velocity are required for the validation of both full and reduced kinetic mechanisms, and as an input to turbulent combustion and engine models. For many applications such as modelling of combustion in engines, data is required for a wide range of temperatures and pressures, as well as a variety of equivalence ratios and diluent fractions, making burning velocity correlations a particularly convenient method of implementation [1].

A number of techniques have historically been used to determine the laminar burning velocities of fuel-air mixtures, and are described more fully in Section 2. Those using constant volume combustion vessels are in common use, and broadly offer two distinct methods of determining burning velocities: imaging of the flame front propagation at conditions of constant pressure, or measurement of the pressure rise combined with a constant volume combustion model. Whilst these two techniques exist, researchers tend to prefer one technique or the other, or in some cases where optical access is not possible, are limited to a single method. No studies have been found which show direct comparisons of the results from these two methods to agree, in part due to the fact that results from the two techniques in a single experiment will relate to different conditions of temperature and pressure, or due to the fact that only one method is employed. Given that there are advantages to each method, the current work aims to reconcile results from the two

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techniques to demonstrate each as a viable method, thereby extending the potential range of data obtainable. Many studies are published that use the constant pressure data (see for example some recent papers [2–4]), yet these experiments could also have generated measurements for higher pressures and temperatures when a spherical vessel is used.

2. Background to measurements of laminar burning velocities

Measurements of laminar burning velocities have historically been made using a variety of techniques, broadly divided into the categories of stationary and non-stationary flame methods. Stationary flame methods will typically use a burner into which a continuous mixture of fuel and oxidant is fed at a constant velocity. The stationary flame is then established at the mouth of the burner, from which measurements can be made. Simple burner techniques establish a conical flame, although problems exist regarding identification of the exact position of the flame front, heat losses to the burner rim, and the effect of flame shape on determined burning velocity [5]. More advanced flat flame burners are considered to provide more reliable results, and in particular the Heat Flux Burner [6] is increasingly used by many groups to establish highly accurate values of burning velocity. Another approach is to use a diverging channel, and a recent example of this is provided by Katoch et al. [7]. Whilst such methods are being developed to provide higher pressure measurements [8], limitations remain on the pressure at which data can be obtained. Non-stationary flame techniques are predominantly propagating spherical flames, either at conditions of constant pressure or constant volume. The following review summarises the key steps in technique development and identifies the precautions and procedures that are needed for accurate measurements, namely: the exclusion of data affected by cellularity, appropriate corrections for the effects of stretch, use of a comprehensive calculation of the state of the burned and unburned gases, and choice of an appropriate equation when experimental data are being correlated.

Experiments involving constant volume combustion vessels date back to the work of Hopkinson [9], who measured the pressure rise during combustion. Hopkinson also identified the temperature gradient in the burned gas (about 500 K), though only recently has the pressure rise method taken account of the temperature gradient in the burned gas. Early examples of constant pressure flame speed measurements include the soap bubble method used by Stevens [10], in which a flammable mixture was ignited within a boundary which was free to move, preventing compression of the unburned gas ahead of the flame front as the flame propagates ahead of the expanding burned gas. By maintaining constant pressure, the flame speed can be evaluated using photography of the flame front. However, control of the initial conditions with this method is difficult and the range of fuels that can be tested is limited. Constant volume combustion bombs with rigid walls therefore became preferred and have been used extensively. Due to the fact that the initial stages of constant volume combustion take place at conditions of effectively constant pressure, flame front imaging at constant pressure, and measurement of the pressure rise as the flame propagates further, can both beused to determine the burning velocity. Knowing the density ratio between the unburned and burned gas enables the flame speed to be converted to the laminar burning velocity.

Fiock et al. [11] pioneered the use of imaging of flame fronts within a solid spherical vessel by means of a thin cylindrical glass ring mounted between the two halves of the vessel. However, their analysis combined the radius measured by imaging of the flame front with measurements of pressure rise and a model of constant volume combustion to determine the burning velocity (based upon consideration of the change of volume of a shell of unburned gas of small thickness) and so is therefore considered as a pressure rise measurement with imaging needed only to determine the flame radius as the pressure rises, rather than for constant pressure analysis. Subsequent developments of the constant volume vessel technique used the pressure rise to calculate the flame front position.

Lewis and von Elbe [12] were first to derive burning velocities from pressure measurements alone, by using a linear assumption between mass fraction burned and pressure rise, so as to estimate the radius of the flame during combustion. Metghalchi and Keck [13] developed a subsequent model based on the mass burning rate, and introduced a two zone numerical model in which the gas in the vessel is divided into burned and unburned gas zones separated by a thin flame front, and the equations of conservation of energy and volume are solved numerically. However, a limitation of using just two zones is that recompression of the burned gas is ignored. This recompression leads to a temperature gradient within the burned gas (as identified by Hopkinson) which cannot be modelled by just two zones. It has been shown by Stone et al. [14] that the difference between the linear mass fraction burned assumption of Lewis and von Elbe [12] and the results of the two zone model of Metghalchi and Keck [13] are not significant for the methane-air mixtures tested.

A number of studies attempted to include the effect of including the burned gas temperature gradient such as that of Bradley and Mitcheson [15]. Hill and Hung [16] and Elia et al. [17] both extended the analysis of Metghalchi and Keck [13] to include multiple shells within the burned gas region, to enable the temperature gradient within the burned gas to be modelled more accurately. The gases in each shell are assumed to be in chemical equilibrium, with the burned gas states calculated using the STANJAN solver [18] and thermodynamic properties of all gases calculated from JANAF tables [19]. However, as summarised by Saeed and Stone [20], agreement between these models is generally poor, prompting development of a more rigorous multizone computational model. In this model, the mass inside the vessel is initially divided into a number of zones, which can be of either equal radius or equal mass. Each zone is then divided further into a number of elemental shells. The total number of elemental shells in the vessel corresponds to the number of time-steps chosen in the simulation, with flame front propagation seen as the consecutive consumption of the elemental shells. The equations of conservation of volume and internal energy are solved as first order differential equations of the pressure and unburned gas temperature in the vessel. The formulation is based upon the approach of Ferguson [21], with a program derived from the multi-zone spark ignition engine simulation program of Raine et al. [22]. This model then allowed the determination of burning velocities from the pressure record over the range of pressures and temperatures encountered during combustion; differences in burning velocity of up to 10% occurred when comparing the burning velocity values derived from the multi-zone model with the Lewis and von Elbe assumption of mass fraction burned being proportional to the pressure rise [12].

Advantages of the constant volume vessel technique include the ability to obtain data over an increased range of temperatures and pressures, as well as the ability to obtain a large number of data points from a single experiment. It is also possible to retain some of the residuals from a previous experiment, thereby eliminating approximations with 'synthetic residuals' [23]. These advantages led Rallis and Garforth [5] to describe the constant volume technique as "the most versatile and accurate" of the propagating flame methods. The ability to obtain such quantities of data also lends itself well to the fitting of burning velocity correlations. However, there are commonly objections to the technique, because the effects of flame stretch are ignored, and that without optical access, it becomes difficult to determine the onset of any flame front instabilities, (which violates the assumption of a smooth flame front and invalidates calculations of the burning velocity).

The concept of flame stretch was first introduced by Karlovitz [24], and has been well documented since. The effects of stretch on flame speed is first acknowledged by Palm-Leis and Strehlow [25]. It can be considered that the effects of stretch consist of curvature of the flame front, and straining of the flame front as it propagates, and is expressed as: