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Maximum stretched flame speeds of laminar premixed counter-flow flames at variable Lewis number

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ABSTRACT

This paper examines Lewis-number effects on stretched, laminar, premixed flames near extinction. It presents the experimental measurement of maximum stretched flame speed and extinction limit for the premixed laminar combustion of selected low, unity and high-Lewis number mixtures. Stretched, fuel-lean, laminar flames of methane with $\mathrm{Le} \cong 1$, propane with $\mathrm{Le} > 1$ and hydrogen with $\mathrm{Le} \ll 1$ are studied experimentally in a counter-flow flame configuration. Flow velocity is measured in these flames by particle tracking velocimetry. Results show that a maximum reference flame speed exists for mixtures with $\mathrm{Le} \gtrsim 1$ at lower flame-stretch values than the extinction stretch rate. In contrast, a continually-increasing reference flame speed is measured for $\mathrm{Le} \ll 1$ mixtures until extinction occurs when the flame is constrained by the stagnation point. Laminar flame results are also compared to numerical simulations employing a one-dimensional stagnation flame model. The chemical-kinetic models for each respective mixture capture the important trends of a maximum in $s_{u,ref}$ ahead of the extinction stretch rate for methane and propane, and an increasing $s_{u,ref}$ to extinction for hydrogen. These results are important to the investigation of the leading edge theory of premixed turbulent combustion, in which maximum stretched flamelet speed is a key parameter.

1. Introduction

The effects of hydrodynamic stretch and curvature are highly important in premixed combustion; properties of both laminar and turbulent flames depend on a mixture's response to these phenomena. Both stretch and curvature have been studied extensively for laminar combustion [e.g., 1–3]. Much of the theory describing such flames is now textbook material [e.g., 4]; however, detailed experimental results of premixed stagnation flames – especially highly-stretched flames *below* the extinction limit – are scarce. While there is a wealth of computational and experimental work investigating increasing stretch and the extinction stretch rate [5–8], as well as the Markstein lengths [9–14] of premixed laminar flames, there are few, if any, measurements of the maximum stretched flame speed prior to extinction. This maximum stretched flame speed is important in the study of premixed turbulent combustion, as discussed below.

Premixed, laminar flames can be studied experimentally using the powerfully simple geometry of the counter-flow burner [15,16]. This apparatus provides clear boundary conditions and a compact experimental zone that is ideal for performing detailed local measurements of laminar flames. In the constrained flow geometry of a counter-flow burner, stretch limits the laminar flame's reaction zone thickness and causes extinction for mixtures with Lewis numbers ($\mathrm{Le} = \alpha/\mathcal{D}$) near unity, where α is the thermal diffusivity and $\mathcal{D}$ is the mass diffusivity of the deficient reactant. For cases in which thermal diffusivity dominates ($\mathrm{Le} > 1$), maximum flame temperature falls below adiabatic flame temperature and decreases with increasing stretch due to heat losses to the unburned mixture, causing extinction at lower flame stretch. When $\mathrm{Le} \ll 1$, burning rates are enhanced by preferential molecular diffusion of the deficient reactant into the reaction zone, such that stretched flame temperature and flame speed are greater than the adiabatic flame temperature and unstretched laminar flame speed of the bulk reactant mixture, respectively [1]. Extinction occurs in such cases only when the flow conditions force the reaction zone against the stagnation surface and its thickness, and the associated residence time available for chemical reactions, is thereby reduced by the imposed physical constraint. Counter-flow burners have also been used in many fundamental studies of turbulent flames [17–19], as well as more recent investigations of detailed turbulent flame properties [20–24].

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Preferential diffusion effects have also been observed for turbulent flames and have been explained by the theory of leading points. The theory was first put forward in literature by [25], was expanded in [26] and has figured prominently in recent studies [27–30]. The theory of leading points regards the turbulent flame front as a collection of stretched and curved laminar flamelets [2], as do many theories of turbulent premixed flames. The leading points of the flamelet are located on the front that propagates farthest into the unburned reactants. These leading fronts, or leading edges, must be positively curved. The leading points theory argues that the flame speed of these leading edges controls the overall propagation speed of the turbulent flame. The maximum stretched flame speed, $s_{u,max}$, of a laminar flame has been shown to be the maximum speed at which a turbulent flamelet will propagate [25,26]. Since the leading edge is stretched and positively curved, the local burning rate at the leading point will increase for $Le < 1$ [1]. An increase in burning rate will drive the flame to propagate further into the unburned reactants, further increasing the curvature and stretch experienced by this leading point. This process of increasing velocity is predicted to continue until the leading point reaches $s_{u,max}$ [29].

Additionally, results from experimental laminar flames may also be of great utility to combustion kineticists. To validate kinetic models, results from laboratory experiments can be compared directly to results from simulations of the same experiment. This method, direct comprehensive comparison, represents a departure from the traditional method of measuring multiple quantities in order to derive one fundamental target for comparison, typically via extrapolation. Direct comprehensive comparison can provide results of equal quality, while reducing experimental complexity and uncertainty [31,32]. Direct comprehensive comparison is most successful when the experimental apparatus is designed to maximize the physical simplicity in the domain's geometry and minimize uncertainty in all necessary measurements. With careful design, a simple numerical model of the domain, typically one-dimensional, can be used, reducing computational cost. Many recent studies have employed this technique and have contributed key experimental data to the numerical modelling community [33–41].

In summary, the experimental results in this paper will (1) provide new measurements of highly-stretched premixed flames below the extinction limit, (2) assess the accuracy of chemical kinetic models across all stretch rates and (3) measure $s_{u,max}$ and investigate the effect of preferential diffusion. These experimental velocity measurements will be performed on stretched lean methane (CH_4), propane (C_3H_8) and hydrogen (H_2) flames. The preferential diffusion effects measured in this paper for laminar flames will also inform the study of local instantaneous burning rates in premixed turbulent flamelets in future work. Recent studies have investigated the effect of stretch and preferential diffusion on turbulent flamelets [28–30,42]; studying stretch behaviour of laminar flamelets will ultimately lead to an improved understanding of turbulent premixed combustion.

2. Experimental method

Experiments for this investigation are performed in a counter-flow burner. Identical premixed fuel and air mixtures are sent to the top and bottom nozzles of the burner. These mixtures flow through 60 mm diameter bronze plena and high contraction-ratio nozzles with exit diameter of 20 mm, corresponding to $A_{plenum}/A_{nozzle} = 9$. The inner contour of the high-contraction ratio nozzle is designed to accelerate the flow into a flat profile without generating turbulence. A laminar, axisymmetric velocity profile exiting the burner nozzle leads to a flat flame profile, which allows the system to be reasonably modelled as one-dimensional flow [15,43,36]. An annular flow of inert gas through the co-flow nozzles helps to stabilize the edges of the flames. The gaseous jets, with equal compositions, velocities and momenta, impinge upon one another between the two nozzle assemblies, separated by a distance of $L = 24$ mm in these experiments. The nozzles and stagnation plane are shown in Fig. 1.

For the experiments performed in this study, combustible mixtures are delivered to the burner assembly at room temperature. Each nozzle's flow rates of fuel and air are controlled by two mass flow controllers, each with an associated uncertainty of ±0.9% which leads to an uncertainty in the equivalence ratio, ϕ, of ±1.3%. The gases are mixed in a 500 mL stainless steel mixing vessel filled with glass wool to promote mixing. From the mixing vessel, the mixture is seeded with micron-sized aluminium oxide particles for laser diagnostics.

The centreline flow velocity is measured using particle tracking velocimetry (PTV), performed by illuminating 1 μm alumina particles seeded into the flow with green laser light, manipulated into a thin sheet [34,44]. The laser used in these experiments is the Litron LDY 303, a high-repetition rate, frequency-doubled Nd:YLF laser. The laser emits 527 nm-wavelength light at 7.5 mJ per pulse at 1 kHz. The pulse frequency is selected to ensure that particles at the velocity minimum (in the flame zone) can be distinguished and varies between 800 Hz and 3.1 kHz.

The light scattered by the particles in the flow is captured by a Cooke PCO.2000, 2048 × 2048 pixel, 14-bit, monochrome CCD camera capable of capturing 14.7 images per second. To limit the interference of chemiluminescence in PTV images, a 527 nm optical notch filter is attached to the lens, a Nikon macro lens at *f*-stop = 5.8. Each exposure is set to last 50 ms to capture a streak of particles, as shown in Fig. 2. The spatial extent of each image is approximately 36 mm × 36 mm with a resolution of 17.6 μm/pixel. At least 30 particle streaks traveling on or near the centreline are processed by hand to give the velocity profiles for each run. An example resulting velocity profile is given in Fig. 3, where u is axial velocity and z is axial distance away from the stagnation plane. Note that this figure shows the results from

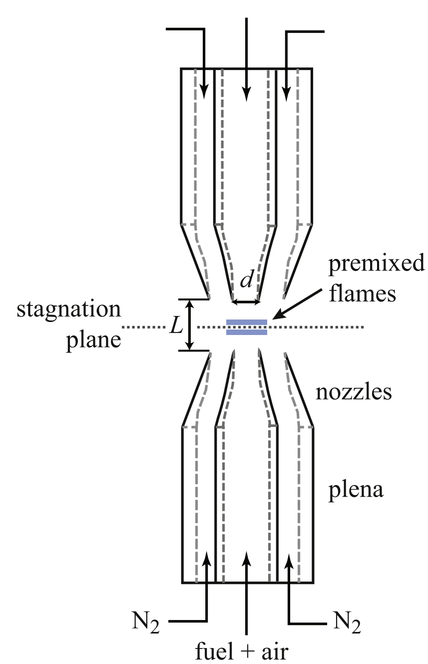

Fig. 1. Schematic of nozzle assembly with premixed nozzles, inert coflow nozzles and plena.