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Lean premixed opposed jet flames in fractal grid generated multiscale turbulence

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ABSTRACT

The opposed jet configuration presents an attractive canonical geometry for the evaluation of burning properties of turbulent flames with past studies typically limited to low Reynolds numbers. Fractal grid generated turbulence was used to remove the low turbulence level limitations associated with conventional perforated plate generators with the turbulent Reynolds number range moved from 50–120 to 130–318. Optimal grid configurations were determined with particular emphasis on reducing the impact of the flow upstream of the turbulence generators in order to facilitate simpler boundary conditions for computational studies. The resulting flow structures were analysed using proper orthogonal decomposition and conditional proper orthogonal decomposition. Velocity and reaction progress variable statistics, including conditional velocities and scalar fluxes, are reported for fuel lean methane, ethylene and propane flames approaching extinction. The instrumentation comprised particle image velocimetry with the flows to both nozzles seeded with 1 μm silicon oil droplets or 3 μm Al_2O_3 particles. Probability density functions were determined for the instantaneous location of the stagnation point to eliminate the possibility of low frequency bulk motion distorting velocity statistics. Probability density functions of flame curvature were determined using a multi-step flame front detection algorithm with estimates of the turbulent burning velocity provided along with a discussion of alternative determination methods. The data sets show that fractal grids generate multi-scale broadband turbulence and present an opportunity for a systematic evaluation of calculation methods for premixed turbulent flames that undergo a transition from non-gradient to gradient turbulent transport while approaching extinction.

1. Introduction

Opposed jet geometries have been used extensively to investigate premixed and non-premixed combustion under laminar and turbulent flow conditions. The comparatively simple flame stabilisation method and essentially adiabatic conditions lead to flame dynamics and extinction being related to the aerothermochemistry of the combustion process rather than heat losses. Combined with the comparatively simple boundary conditions, the opposed jet geometry provides an attractive standard test case for the assessment of fuel effects and closure approximations as proposed by Bray et al. [1], Lindstedt and Váos [2,3] and subsequently by Geyer et al. [4,5] in the context of large eddy simulations (LES). Preparatory isothermal flow studies have also been presented by a number of investigators (e.g., Geipel et al. [6], Kostiuk et al. [7], Korusoy and Whitelaw [8], and Lindstedt et al. [9]) and flame structure studies include velocity and scalar field measurements by Mounaïm-Rouselle and Gökalp [10], Kostiuk et al. [11] and Lindstedt et al. [12]. Strain effects and extinction and relight characteristics were discussed by Kostiuk et al. [13], Mounaïm-Rouselle and Gökalp [14], Sardi and Whitelaw [15], Korusoy and Whitelaw [16] and Luff et al. [17] amongst others. Mounaïm-Rouselle and Gökalp [10], Kostiuk et al. [13] and Kostiuk [18] showed that larger nozzle separations caused a low frequency axial movement made visible by a bouncing of the flame brush. The stabilisation of the flame brush off the symmetry plane of the burner was also noticeable. It was suggested that an interaction of the jets with the surrounding air caused both phenomena and difficulties were reduced with the introduction of co-flowing streams as confirmed by a more homogeneous turbulence distribution with less energy at lower frequencies. Subsequent studies (e.g., [12,17]) have shown that the flow symmetry can be much improved for nozzle separations $H/D \simeq 1$, where H is the nozzle separation and D the nozzle

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diameter, with low frequency instabilities removed and overall improved stability [6].

The comparatively low turbulence levels achieved in earlier studies at the point of flame extinction have proved problematic for computational methods based on high Reynolds number assumptions. The same observation [9] also applies for isothermal flows at Reynolds (*Re*) numbers below 10,000 and higher values were required in order to provide good agreement with numerical simulations when perforated plates were used as turbulence generators. However, such conditions were found to lead to early extinction for flames featuring alkane fuels due to the presence of bulk strain at nozzle separations small enough ($H/D \leqslant 1$) to prevent axial bulk instabilities in the flow. Coppola and Gomez [19] used high blockage ratio turbulence generators to increase turbulence levels substantially and suggested [20] the use of the geometry as a benchmark for practical systems. The turbulence generators were subsequently found trigger large scale oscillations of the stagnation surface at frequencies <200 Hz and it was suggested that such instabilities need to be screened, e.g., using Proper Orthogonal Decomposition (POD), to eliminate artifacts (e.g., in turbulence levels) from the measurements [21]. However, it has subsequently been suggested [22] that flows with combustion require conditional POD (CPOD) as conventional POD does not distinguish between fluid structures in reactants and products. The filtering of instabilities using the latter approach can hence arguably only be applied to flows without significant density variations. Fractal grids are here used to avoid such difficulties and to provide significantly increased turbulence levels without any issues arising with respect to bulk flow instabilities. The use of fractal grids was first presented in the context of wind tunnels by Vassilicos and Hunt [23] and Seoud and Vassilicos [24] and later by Hurst and Vassilicos [25]. The first application of fractal grids in an opposed jet geometry was presented by Geipel et al. [6] in a study of isothermal flows. It was shown that such grids can increase turbulent Reynolds (Re_t) numbers in excess of a factor of two for the same bulk velocity as compared to conventional perforated plate turbulence generators. It has also been shown that fractal grids can substantially enhance turbulent diffusion [26,27]. The consequence is a significant change in the balance of turbulent to bulk strain while also maintaining acceptable flow symmetry [6]. The fractal grid approach was subsequently used by Goh et al. [28] to explore the transition of premixed JP-10 flames from the corrugated flamelet regime to a Homogeneous Charge Diffusion Ignition (HCDI) [29] related flameless combustion mode and by Goh et al. [22] to analyse conventional opposed jet flames.

The current work extends past studies of opposed jet flames by: (i) The use of multiscale fractal grid generated turbulence in a substantially revised configuration aimed at providing increased turbulent strain while providing simplified upstream boundary conditions in order to facilitate computational studies. The turbulent Reynolds number range is moved from 50–120 to 130–318, as compared to conventional perforated plate generators. (ii) Velocity and reaction progress variable statistics, including conditional velocities and scalar fluxes, are reported for stoichiometric and fuel lean methane, ethylene and propane flames approaching extinction. (iii) The turbulence structure obtained using conventional and fractal grids was analysed using POD and CPOD [22] techniques. (iv) Probability density functions were determined for the instantaneous location of the stagnation point and show the movement to be of the order of the integral length scale and hence not influenced by unstable bulk flow motion. (v) Probability density functions of flame curvature were determined using a validated multi-step flame front detection algorithm [22,28]. (vi) Estimates of turbulent burning velocities are provided and differences associated with alternative determination methods quantified. Finally, (vii) the rate of dissipation was estimated using the velocity gradient based technique of George and Hussein [30]. Overall, the data sets present an opportunity for a systematic evaluation of calculation methods for premixed turbulent flames approaching extinction.

2. Experimental configuration, techniques and uncertainties

The opposed jet geometry used as a starting point in the current work consists of two nozzles in a vertical arrangement originally designed by Geyer et al. [5,31] and is identical to that described by Geipel et al. [6]. Both nozzles were water-cooled to prevent differences in the reactant densities due to preheating. The maximum positional uncertainties for the nozzles with the current configuration are 0.2 mm for the coaxial alignment and 0.5° in the angular alignment. The outlet of each nozzle is 30 mm in diameter and, for the base case configuration, turbulence is generated 50 mm upstream of the nozzle exit plane using perforated plates with a hole diameter of 4 mm and a blockage of 45% as shown in Fig. 1. The perforated plates are similar to those used by Mastorakos et al. [32–34], Sardi et al. [15,35,36] and Lindstedt et al. [9,12]. Fractal grids [6,23–25] subsequently replaced the perforated plates and were used to increase turbulence intensities at the nozzle exits. Following an extensive experimental study of the corresponding isothermal flow field [6], a space-filling fractal cross grid with a total blockage of 65% and fractal dimensions corresponding to a maximum bar width of 2.0 mm and a minimum width of 0.5 mm was chosen as shown in Fig. 1. The selected fractal grid increased the turbulent Reynolds number range from 50–120 to 130–318 for the same bulk velocity range of 4.0–8.0 m/s, based on the integral length scale (l_t) of ≃3.1 mm determined by Geipel et al. [6], with turbulence levels measured at the nozzle exits. Goh [37] determined the corresponding integral length scales for the current revised geometry, discussed below, and obtained marginally higher values of ≃3.5 mm at 4.0 m/s bulk velocity and ≃3.2 mm at 8.0 m/s. The estimation of length scales and the impact on the fitting of longitudinal energy spectra based on hot wire anemometry and PIV data has been discussed by Geipel et al. [6]. The axial instability of the flow observed at higher nozzle separations (e.g., [13,17,18]) was effectively removed by the selected H/D (=1) ratio and further reduced by the presence of a co-flow [10]. The co-flowing stream of air was set to a velocity of ⩾10% of the corresponding bulk flow velocity of the reactant mixture in order to reduce the effect of the shear layer that forms between the opposed jet flows and the ambient air.

Dry and filtered air was supplied to each nozzle at 4 bar(g) by a compressor using digital mass flow controllers (Bronkhorst UK LTD). The deviation of each mass flow controller was ⩽0.8% RD (reading) plus ⩽0.2% FS (full scale) and the reproducibility better

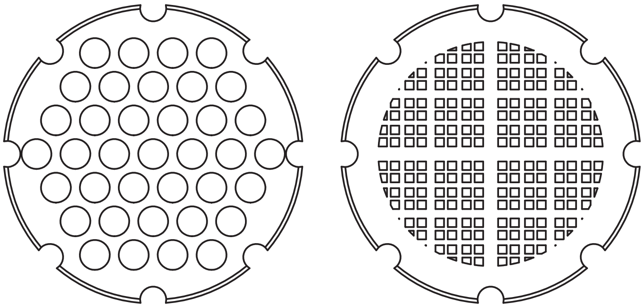

Fig. 1. Left: Traditional perforated plates at a blockage ratio of 45%. Right: Dimensions of the fractal cross grid used in the current study. The dimensions correspond to Grid I used in the study by Geipel et al. [6] and provides a blockage ratio of 65% with maximum and minimum fractal bar widths of 2.0 mm and 0.5 mm.