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Temperature measurements of the bluff body surface of a Swirl Burner using phosphor thermometry

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ABSTRACT

Flames are often stabilised on bluff-bodies, yet their surface temperatures are rarely measured. This paper presents temperature measurements for the bluff body surface of the Cambridge/Sandia Stratified Swirl Burner. The flame is stabilized by a bluff body, designed to provide a series of turbulent premixed and stratified methane/air flames with a variable degree of swirl and stratification. Recently, modellers have raised concerns about the role of surface temperature on the resulting gas temperatures and the overall heat loss of the burner. Laser-induced phosphorescence is used to measure surface temperatures, with $Mg_4GeO_6F:Mn$ as the excitation phosphor, creating a spatially resolved temperature map. Results show that the temperature of the bluff body is in the range 550–900 K for different operating conditions. The temperature distribution is strongly correlated with the degree of swirl and local equivalence ratio, reflecting the temperature distribution obtained in the gas phase. The overall heat loss represents only a small fraction (<0.5%) of the total heat load, yet the local surface temperature may affect the local heat transfer and gas temperatures.

1. Introduction

The location and temperature profile in laminar burners is known to be a strong function of the flame holder temperature [1–3]. In turbulent flames, flame stabilisation and flashback is produced by a combination of aerodynamics and heat transfer, depending on the particular geometric configuration [4,3,2], yet there have been few measurements of temperature holder temperatures. Prior simulations by Ketelheun et al. [3] suggest that heat losses do affect the gas phase temperatures, and presumably flame stability, particularly in the case of flame holding using a bluff body. The present work addresses this question directly, providing highly accurate surface measurements for a class of flames used in turbulent model validation.

Fuel lean, premixed combustion is often desirable, since it reduces the flame temperature, which results in lower NO_x emissions. In many practical systems such as internal combustion engines and gas turbines, flames often propagate through fuel-oxidizer mixtures with spatial variation in composition, by accident or design. Such stratified flames can yield better flame stability and ignitability in very fuel lean conditions. Recent experiments have aimed to generate experimental data for well-characterised, turbulent stratified flames in order to test numerical models [5–9]. The Cambridge/Sandia Stratified Swirl Burner (SwB) is a co-annular burner outfitted with a bluff body to stabilize the generated turbulent premixed and stratified flames. Multiple measurement techniques [6–9] have been applied to this burner, building a comprehensive database. Available data include simultaneous line measurements of temperature, major species mass fractions and three-dimensional orientation of the flame fronts using cross-planar OH-PLIF (Planar Laser-Induced Fluorescence), 2D and 3D velocity measurements including PIV (Particle Image Velocimetry), HSPIV (High Speed Particle Image Velocimetry) and pairwise LDV (Laser Doppler Velocimetry). These measurements provide appropriate boundary conditions, serve as a database for model validation, and shed light on to the fundamental structures of turbulent premixed and stratified flames.

Recent simulations [10,11] and discussions with modellers have suggested that heat loss through the bluff body may affect the measured scalars. Moreover, a suitably accurate boundary condition is desirable for the bluff body temperature for the computations. Information on the surface temperature of the bluff body during combustion can provide accurate thermal boundary conditions for modelling, as well as studying the combined effect of recirculation flows and stoichiometry on the bluff body temperature, and thus

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the heat loss during combustion. The present paper presents measurements of spatially resolved temperature maps of the bluff body surface using thermographic phosphor thermometry for a range of stoichiometries and flow fields documented in previous studies of the Cambridge/Sandia Swirl Burner.

2. Experimental setup

2.1. Cambridge/Sandia Stratified Swirl Burner

The burner was designed to provide flows with a variable degree of fuel stratification as well as swirl. The stratification provides test cases for the turbulent-stratification interaction, while the swirl assists flame stabilization. The geometry of the swirl burner is detailed in Fig. 1. The burner is formed from co-annular tubes with a development length exceeding 25 hydraulic diameters to ensure well developed turbulent flow. A ceramic central bluff body is used to stabilize the flame with minimal heat loss. The geometry is described in detail in [6]. The equivalence ratio of the inner (Φ_i) and outer (Φ_o) annuli were independently controlled using mass flow controllers, allowing the stratification ratio ($SR = \Phi_i/\Phi_o$) to be easily varied. The swirl flow ratio (SFR), defined as the ratio of outer annulus flow passing through a swirl plenum relative to the total outer annulus flow, could be independently set, creating flows with swirl numbers ranging from 0 to 0.55 [9].

2.2. Operating conditions

The operating conditions for the present study are shown in Table 1. The bulk velocity in the outer annulus, $U_o = 18.7$ m/s, was set to more than twice the value of the velocity in the inner annulus, $U_i = 8.3$ m/s, in order to generate substantial levels of shear between the two flows. Co-flow air was supplied around the outer annulus with a bulk velocity $U_{co} = 0.4$ m/s to provide well-defined boundary conditions. The Reynolds numbers derived from the bulk velocities at the exit geometry are $\mathrm{Re}_i = 5960$ for the inner flow and $\mathrm{Re}_o = 11,500$ for the outer flow. The stratification ratio was varied from 1 for premixed cases to 3 for the most stratified cases. The swirl flow ratio was varied between 0 for non-swirling flow to 33% for highly swirling flow, corresponding to the swirl numbers (SN = ratio of tangential to axial momentum) indicated in parentheses.

Table 1
Operating conditions for the Cambridge/Sandia Stratified Swirl Burner.

Flame	SFR (%) (SN)	Φ_i	Φ_o	SR	Φ_g	Power (kW)
SwB1	0 (0.03)					
SwB2	25 (0.33)	0.75	0.75	1		25.8
SwB3	33 (0.55)					
SwB5	0					
SwB6	25	1	0.5	2	0.75	21.5
SwB7	33					
SwB9	0					
SwB10	25	1.125	0.375	3		19.3
SwB11	33					

2.3. Experimental details

The bluff body consists of a plug made of machined alumina. The plug has a radius of 6.35 mm, a 2.5 mm-thick step with diameter aligned with the outer surface of the metal tube, and a 5.0 mm total depth. The surface of the plug was coated with the thermographic phosphor $Mg_4GeO_6F:Mn$ (Osram, München, Germany, product code: SV067). Soudal Calofer, which is heat-resistant up to 1500 °C, was used as binder for the thermographic phosphor powder. This paste-like binder was applied using a scraper. A fine pored sponge was used to dab the phosphor powder on. The applied binder dries very fast, and as a result the edges dry out before the phosphor powder can adhere to it. Thus, there is less phosphor powder at the edges, which gives a lower phosphorescence signal and results in a higher signal standard deviation, as shown in Section 2.5. Our usual coating technique, where we apply a suspension of phosphor powder and liquid binder using an airbrush, proved not to be feasible for the ceramic bluff body surface, as there was no adhesion. The fourth harmonic (266 nm) of a pulsed Nd:YAG laser (Quanta Ray, INDI, pulse width: 5–8 ns) was used as an excitation source, at a repetition rate of 10 Hz. The beam profile was homogenised by a beam homogenizer from Holo-Or Israel with a diffusion angle of 0.68°. The laser beam hit the coated bluff body with an energy density of 0.2 mJ/mm^2 at an angle of 21°, as illustrated in Fig. 2.

Temperatures are obtained by measurement of the decay time of the phosphor, which is a unique function of temperature for this particular phosphor. The two-dimensional detection of the phosphorescence signal was conducted using a 12 bit LaVision HSS6 CMOS high speed camera system. A Zeiss 85 mm photo objective

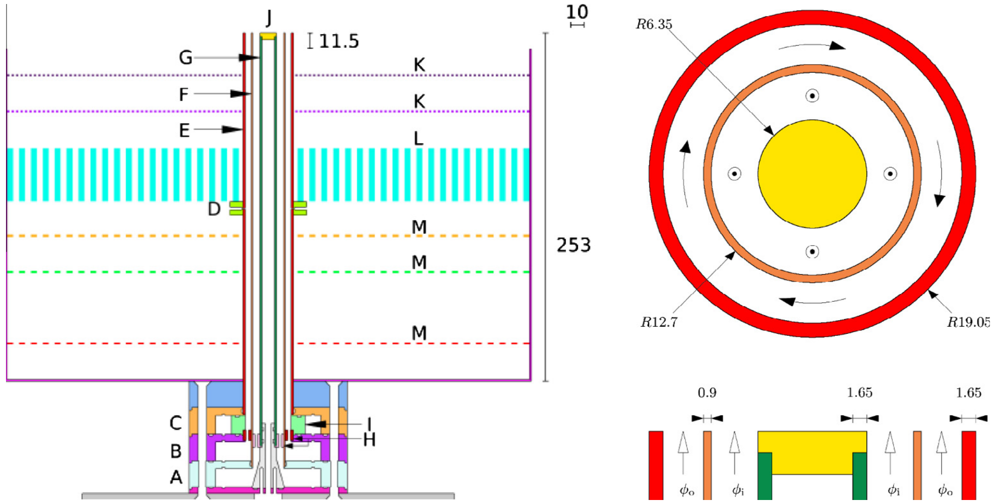

Fig. 1. Burner geometry. Left: Cross-section of the burner. Right: Exit geometry of the burner. (Reproduction from [6].)

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