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Hysteresis and transition in swirling nonpremixed flames

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ABSTRACT

Strongly swirling nonpremixed flames are known to exhibit a hysteresis when transiting from an attached long, sooty, yellow flame to a short lifted blue flame, and vice versa. The upward transition (by increasing the air and fuel flow rates) corresponds to a vortex breakdown, i.e. an abrupt change from an attached swirling flame (unidirectional or with a weak bluff-body recirculation), to a lifted flame with a strong toroidal vortex occupying the bulk of the flame. Despite dramatic differences in their structures, mixing intensities and combustion performance, both flame types can be realised at identical flow rates, equivalence ratio and swirl intensity. We report here on comprehensive investigations of the two flame regimes at the same conditions in a well-controlled experiment in which the swirl was generated by the rotating outer pipe of the annular burner air passage. Fluid velocity measured with PIV (particle image velocimetry), the qualitative detection of reaction zones from OH PLIF (planar laser-induced fluorescence) and the temperature measured by CARS (coherent anti-Stokes Raman spectroscopy) revealed major differences in vortical structures, turbulence, mixing and reaction intensities in the two flames. We discuss the transition mechanism and arguments for the improved mixing, compact size and a broader stability range of the blue flame in comparison to the long yellow flame.

1. Introduction

Swirl is frequently used to stabilise nonpremixed flames in industrial burners. A sufficiently strong swirl creates a high depression in the jet core, which leads to a vortex breakdown, i.e. the formation of a closed, standing, toroidal vortex with flow reversal in the core region. The reverse flow carries hot combustion products back to the burner exit thus providing a stable source of heat and active species for flame ignition. The enhanced shear intensity and the expanded length of the curved shear layer promote turbulence production, enhance mixing and entrainment of ambient air close to the burner exit, thus creating favourable conditions for efficient combustion. These bring several benefits of practical relevance: dispensing with a pilot flame, a reduction of the flame length, and expansion of the range of operating parameters at which the burner can function in stable regime, resulting in compact combustion processes with reduced emission of nitrogen oxides [1,2].

Many studies on swirling flames consider confined flows since these are more relevant to practical applications such as combustors in gas turbines and utility boilers. Detailed experimental studies of confined swirling flames were recently reported by, for example, Weigand et al. [3], Meier et al. [4], Vanoverberghe et al. [5,6] and Olivani et al. [7]. The TECFLAM research program also considered confined swirling flames when producing the extensive database aimed at improvement and validation of numerical combustion models, see e.g. [8] and [9]. However, the confinement increases the complexity of the flow due to stronger effects of jet precession and possible acoustic instabilities, the presence of additional (outer) recirculation zones, and complicates the specification of boundary conditions, as was pointed out by Al-Abdeli and Masri [10].

Unconfined swirling flames were investigated within the framework of the Sydney swirl project for the purpose of validating and developing computational methods for swirling flames, see [11,12]. The database (http://www.aeromech.usyd.edu.au) includes information on time-averaged velocity and scalar measurements for eight swirling flames with different fuel mixtures, swirl numbers and normalised fuel jet momentum. The swirling flames considered in the present work are also unconfined. Although of less practical interest, the unconfined stable swirling flames are considered to be more amenable to computational studies and easier accessible to laser diagnostic techniques. The stable flames in the vortex-breakdown regime are still of a higher level of complexity than e.g. jet diffusion flames because of the presence of a strong reverse flow, intense mixing of hot products, fuel and air, the occurrence of local extinction, and (delayed) re-ignition.

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Nomenclature

d	central rod diameter (m)	N	rotation rate (rpm)
r	radial coordinate (m)	S	swirl number (–)
u	axial velocity (m/s)	$\overline{U}$	air mean exit velocity (m/s)
v	radial velocity (m/s)	W_w	wall velocity (m/s)
x	axial coordinate (m)	Φ	equivalence ratio (–)

The present work reports on the results of a detailed experimental investigation into the effects of swirl on turbulent transport, mixing and chemical reaction in two different flame regimes. The aim of the study is to shed light on the interaction between the turbulent flow field and the flame structure, and the role of this interaction in the transition between different flame states. In contrast to most other research reported in the literature, where a number of swirling flames with different operating conditions were investigated in parallel, we focused on two flames in different regimes operating at identical controlling parameters. The blue flame at these conditions was achieved by starting with a blue flame at higher flow rates and gradually decreasing the flow rates until the desired values were achieved while keeping the equivalence ratio and rotation rate fixed. Likewise, starting with a low-flow-rate yellow flame (at the same rotational rate as in the blue flame), the desired conditions were achieved by gradually increasing the flow rates until the pre-specified values were achieved, equal to that of the blue flame investigated. The different regimes at the same conditions appeared possible owing to the inherent system hysteresis.

Because swirling flames that operate within the hysteresis range and close to the stability limits can be sensitive to the manner in which the swirl is generated and on the inflow turbulence intensity and structure at the burner mouth, care needs to be taken to generate swirl with clearly identifiable and reproducible features. This is in particular important if the experiments are aimed to serve as a reference for other studies, especially for computer modelling and simulations. The most common and convenient ways of generating swirl in industrial combustion appliances are the tangential inlets and the use of guide vanes. However, each has some shortcomings that make them a sub-optimal choice for the experimental investigation of the physics of swirling flames. Tangential inflows are difficult to adjust to achieve the desired profile of the tangential velocity. Adjustable guide vanes offer more flexibility than the tangential inflows, though at higher costs, but suffer from limitation in achieving sufficient swirl strengths. However, the common deficiency of both the tangential inlet and guide vanes is the difficulty in achieving and controlling the desired and computationally reproducible inflow conditions at the burner mouth (the velocity, turbulence intensity and scales field), which is crucial for the computational mimicking of an experiment. As it is well known, many excellent measurements could not serve as a reference for validation of computational models primarily because of the uncertainties in the inflow conditions.

For this reason we have built an axisymmetric burner in which the swirl is generated by rotating the outer pipe of the annular air supply. A long annular passage ensures fully developed rotating flow at the exit, which can be easily reproduced in computational studies. Apart from this, the relatively simple geometry provides excellent optical access enabling the use of modern laser diagnostic techniques. Particle image velocimetry (PIV) was used to study instantaneous and time-averaged velocity fields. Coherent anti-Stokes Raman spectroscopy (CARS) was used to measure temperature, and qualitative information on turbulent structures and reaction zones followed from OH PLIF (planar laser induced fluorescence).

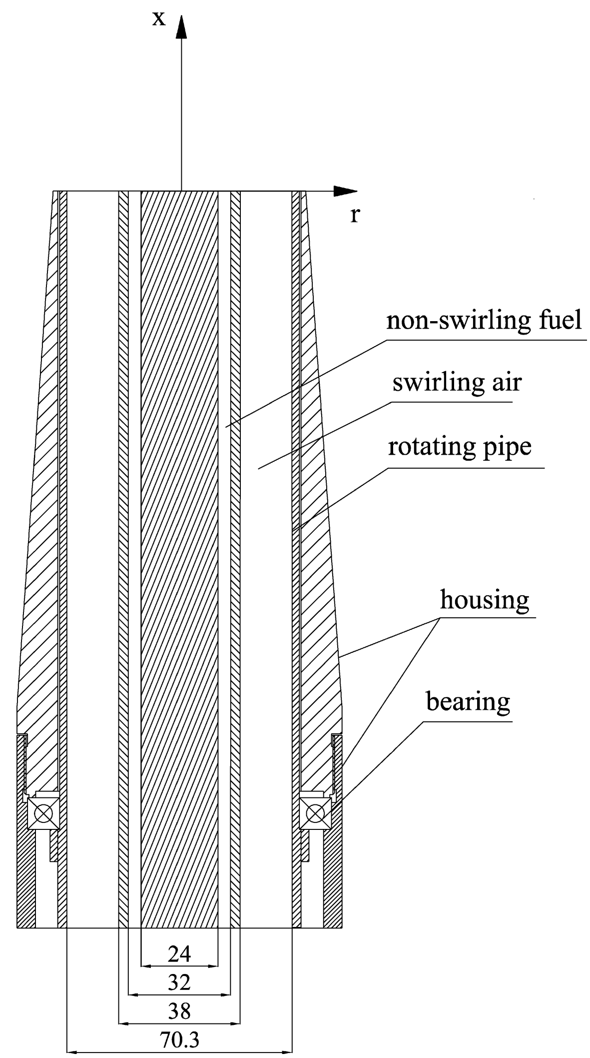

Fig. 1. Cross section of upper part of the burner. Dimensions are in mm.

2. Experimental rig and measuring techniques

2.1. Burner configuration

The burner configuration was described in detail in an earlier publication by Hübner et al. [13] and it will suffice here to briefly outline its main characteristics.

A cross section of the burner exit region is shown in Fig. 1. The main constituents of the burner are two concentric pipes with inner diameters of 70.3 mm and 32 mm, and a solid rod with a diameter of $d = 24$ mm that is placed centrally. The two pipes and the rod each have a length of approximately 1 m. Swirling air issues from the outer annulus, while the inner annulus provides the (nonswirling) fuel. Both the fuel and the air are supplied through radial inlets at the base of the burner. The fuel is Dutch natural gas which has the following composition: methane (81.3 vol%), ethane