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# Experimental investigation of upstream flame propagation during boundary layer flashback of swirl flames

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ABSTRACT

Boundary layer flashback of swirling turbulent lean-premixed methane–hydrogen–air flames is investigated in a model combustor featuring a mixing tube with center body. The focus of our work is on improving the understanding of the flow–flame interaction during flashback. We combine high-speed chemiluminescence imaging, stereoscopic and tomographic particle image velocimetry, and a three-dimensional flame front reconstruction technique to reveal the time-resolved, volumetric velocity field in the vicinity of the flame front during flashback. We find two different ways in which a flame front propagates upstream along the center body wall. The first mode concerns small-scale bulges counter-propagating into the approach flow, similar to channel-flow flashback, but is found not to be a dominant propagation mechanism. Instead, flashback occurs primarily in the form of large-scale flame tongues swirling in the bulk flow direction as they propagate upstream. The approach flow is modified significantly in both cases, but the scale and nature of the resulting velocity fields differ fundamentally. A key characteristic of the approach flow found previously, both in channel and swirl flame flashback, is regions of negative axial velocity upstream of the flame front. We reveal, however, that in the case of swirl flames the region of negative axial velocity is the result of a primarily swirling motion ahead of the leading flame tongue in contrast to the reverse flow pockets ahead of small-scale bulges. The boundary layer neither separates nor does fluid recirculate in the negative axial velocity region upstream of the flame tongues. Instead, flame tongues impose a local blockage effect causing significant deflection of the approach flow, which results in a constant region of negative axial velocity for the leading side of the flame tongue to propagate into.



## 1. Introduction

The successful design of future lean-premixed and fuel-flexible gas turbine combustors requires an improved fundamental understanding of flashback. Currently employed combustors designed to run on natural gas are challenged by the desire to use high-hydrogen content fuels owing to the fast kinetics, high diffusivity and low density of hydrogen.

Since research on flashback began with the first systematic study by Lewis and von Elbe [1,2], the focus has been on measuring flashback limits in (non-swirling) Bunsen-flame type burners for many years [3–7], including more recent studies carefully testing additional parameters such as confinement, wall temperature and pressure [8–13]. High-speed optical diagnostics and advanced simulation tools have been applied more recently to reveal new information about the flame propagation dynamics [14–17].

Three types of flashback can be distinguished: (i) flashback in the boundary layer of a (non-swirling) pipe or channel flow, (ii) flashback in the core of a swirling flow, and (iii) boundary layer flashback in a swirling flow. In all of these configurations a strong coupling between propagating flame front and approach flow has been found [14–19], which is in contrast to the originally proposed and still widely used critical gradient concept by Lewis and von Elbe. This concept assumes an isothermal flame and hence no effect of the heat release on the flow field. As a result of the coupling, flashback is possible in the non-trivial case of axial velocities exceeding the flame speed.

In recent studies, high-speed imaging and direct numerical simulation has shown that boundary layer flashback in channel flows is facilitated by small-scale flame bulges shaped convex towards the reactants, which intermittently form inside low-momentum streaks of the turbulent boundary layer [16,17]. These bulges cause local pockets of reverse flow reaching above the quenching

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distance, which are associated with a local pressure peak at the tip of the convex bulges. The formation, counter-propagation and break-up process of theses bulges leads to a net upstream propagation of the flame brush and hence flashback. A model to predict the flame shape and propagation speed has been developed recently [20].

Swirl flows are typically employed in practical combustors for enhanced mixing and flame anchoring purposes. The dynamics and stability of swirl combustors has been studied extensively [21]. Combustion instabilities may initiate a flashback process by providing, for instance, a momentary local low-momentum region or equivalence ratio stratification, which allows a portion of the flame to penetrate into the mixing tube. The danger for the combustor hardware lies in the sustained upstream flame propagation and flame anchoring inside the premix section [22].

Upstream flame propagation may occur in the core of a swirling flow, e.g. in combustors without a central fuel tube [23–30]. Flashback in such configurations is related to flame propagation along a vortex axis, and this mode of flame propagation has been studied extensively in laminar flows as summarized by Ishizuka [31]. A number of models have been developed aimed at predicting the significant increase in flame propagation speed with an increase in angular velocity and density ratio. Some of these concepts have been transferred to explain flashback along the mixing tube axis in swirl combustors. Flashback has been found to occur in form of a vortex-breakdown bubble, identified experimentally based on a region of negative axial velocity in an on-axis plane [14,19], which is continuously shifted upstream. The mechanism, termed combustion-induced vortex breakdown (CIVB) [23], points at the production of negative azimuthal vorticity due to baroclinic torque at the flame tip in analogy to the model by Ashurst [32], which induces a negative axial velocity on the tube axis and hence facilitates flashback [14,33,34].

The third configuration concerns flashback of swirl flames along a wall, which by geometry combines aspects of boundary layer flashback and flashback along a vortex axis. In swirl combustors featuring a mixing tube with center body, flashback typically occurs along the center body wall [15,35–38]; however, boundary layer flashback has also been observed along the mixing tube outer-wall in hydrogen–air swirl flames [39]. Flashback along the center body wall has been attributed to CIVB based on the finding of regions of negative axial velocity ahead of the flame tip, identified as boundary layer separation, which pulls the flame upstream [15]. A model based on the modification of the axial pressure gradient along the center body wall due to the low-density burnt gas has been proposed [15]. Subsequent measurements of the static pressure on the center body wall during flashback revealed a pressure increase in the burnt gas, which supports this model [38].

Despite significant progress, the driving mechanism for flashback in swirl flames is not yet fully understood [15]. In particular, it remains unclear whether swirl-flame boundary-layer flashback is dominated by the mechanism driving flashback in non-swirling channel flows or that governing flashback in the core of swirling flows [38]. Furthermore, it is still unknown how the approach flow is modified ahead of the flame front in swirl flames as time-resolved measurements during the upstream flame propagation have so far focused on the axial and radial velocity fields only. Neither the azimuthal velocity component, which plays an important role in the models predicting flame propagation along the vortex axis, nor the full volumetric velocity field, have previously been measured with temporal coherence during flashback. We address the physics of flame propagation in swirling wall flashback by measuring in detail the modified approach flow, including the time-resolved volumetric velocity field, in the vicinity of leading flame fronts and study the resulting upstream flame propagation.

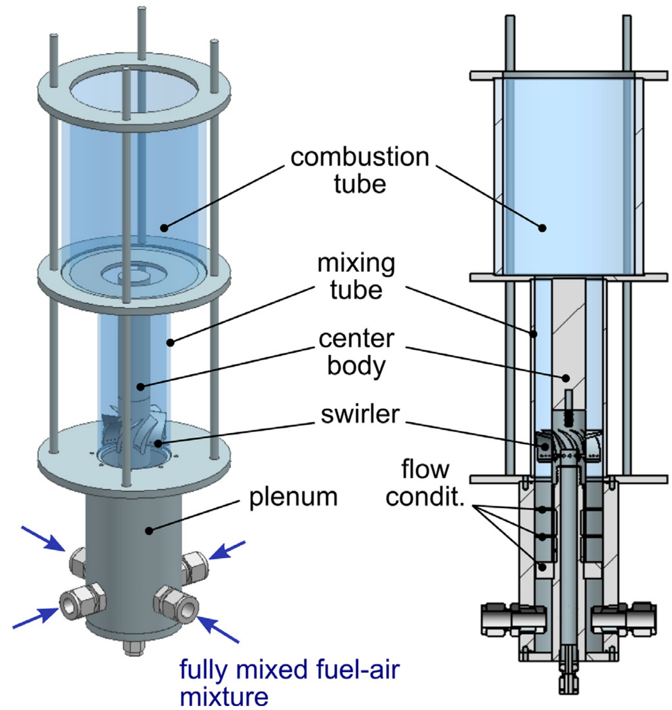


**Fig. 1.** Model swirl combustor.

## 2. Experimental setup

### *2.1. Swirl combustor*

The swirl combustor features an axial swirler with attached bluff body (center body) as shown in Fig. 1 allowing the investigation of boundary layer flashback of swirl flames. The burner is operated in fully-premixed mode in which the reactants are mixed before passing through the swirler. The fuel–air mixture is supplied through the four symmetrically arranged air-supply tubes. A combination of honeycomb section and wire-mesh elements inside the plenum ensured a clean inflow to the mixing tube. The single-axial swirler consisted of eight vanes and the vane trailing-edges were at an angle of 60° relative to the tube axis. The swirl number is approximately $S \approx 0.9$ based on a numerical simulation of the flow field and is calculated as the ratio of axial to circumferential momentum flux based on time and space averaged radial profiles in a plane 10 mm upstream of the mixing tube exit. The hub diameter of the swirler is 25.4 mm. A stainless-steel center body, of equal diameter to the swirler hub, was attached to the swirler, ending flush with the end of the mixing tube. The mixing tube was made of fused silica with high optical homogeneity (no lengthwise striations due to the manufacturing process) and had an inner diameter of 52 mm and a length of 150 mm. The combustion section was directly downstream of the mixing tube and was composed of a quartz tube with an inner diameter of 100 mm and length of 150 mm.

Experiments are conducted at atmospheric pressure. Air and fuel are supplied to the combustor at room temperature. Methane–air and hydrogen–methane–air mixtures are used as a fuel. Fast mass flow controllers (ALICAT MCR), controlled with LabVIEW, regulated the air and fuel mass flow rates. Flashback experiments started with a stable flame in the combustion chamber. The sudden expansion at the exit of the mixing tube caused vortex breakdown, which, together with the wake of the center body, led to a region of low axial velocity in the core of the combustion chamber. This low velocity region held the conically-shaped flame in