Influence of Fuel Properties on Flashback in Turbulent Swirl Flows

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1 Introduction

In lean premixed combustion flashback into the premixing section is a major instability mode compromising the integrity of the combustion system. In highly swirled flows the vortex breakdown (VB), which is used to stabilize the flame by an axial recirculation zone (RZ) inside the combustion chamber, can occur inside the premixing section and promote flashback. If the RZ of the non-reacting flow is located far inside the premixing zone, flashback is caused by turbulent burning along the vortex axis (TBVA). If the VB in the non-reacting flow occurs downstream the premixing duct, it can still propagate into the premixing duct because of the aerodynamic influence of the heat released inside the reaction zone. The flame then moves upstream together with the RZ leading to flashback caused by combustion induced vortex breakdown (CIVB).

In this study flashback caused by TBVA is taken as reference case to separate the aerodynamic effect leading to flashback caused by CIVB from the turbulent combustion conditions inside the recirculation zone. The turbulence level is varied by increasing the overall Reynolds number Re.

In a given turbulent flow field the onset of flashback can be characterized by the critical equivalence ratio Φ_{crit} at which the flame is able to propagate upstream. The difference in Φ_{crit} for both flashback modes is investigated experimentally for methane and propane. Maximum burning velocity and heat release of these fuels are comparable whereas preferential diffusion and ignition temperature differ. The fuel specific influence captured mainly by the laminar unstretched burning velocity $S_{L,0}(\Phi)$ and the Markstein number $Ma(\Phi)$ is transferred to turbulent conditions according to the study of Weiss et al. [1] to explain the differences in flashback limits for methane and propane.

2 Experimental Method

The experimental setup consists of a geometrically variable swirl generator (according to the design of [2]) and a cylindrical glass tube representing the generic premixing zone (Fig. 1 left). The burner is supplied by a perfectly premixed mixture of fuel and air at ambient temperature and pressure. The mixing tube diameter D is 40 mm. The swirl number S can be varied by adjusting the flow path cross section area a and b. Axial velocities of the flow inside and downstream the glass mixing tube (Fig. 1

right) were measured in the axial plane by PIV to identify the flashback mode. In reacting cases, the cemiluminescence of the flame was recorded simultaneously by an ICCD-camera.
Depending on the level of swirl, the VB of the non-reacting flow may be located inside (flashback caused by TBVA) or outside the glass mixing tube (flashback caused by CIVB). A flow field with the VB located

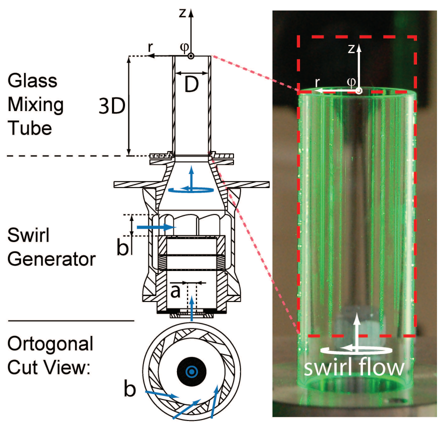

Figure 1: Swirl generator and generic glass mixing tube

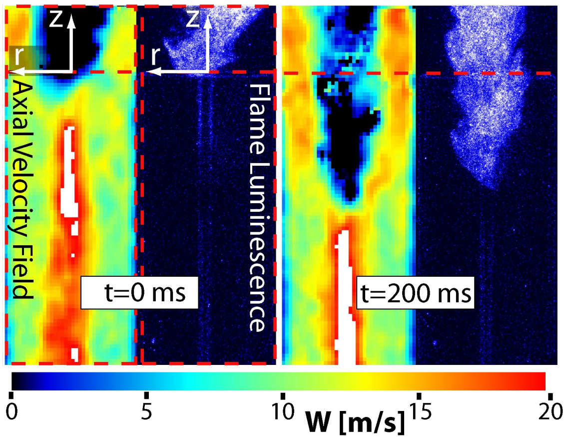

Figure 2: Simultaneous axial velocity fields and flame positions during flashback, methane, $\Phi = 0.66$, $Re = 28000$

directly at the exit of the mixing tube establishes at $S = S_0$. For this case snap shots of axial velocity fields and related flame positions are shown in Fig. 2 at the onset of flashback caused by CIVB. For $S > 1.25S_0$ the VB and the attached RZ are located far upstream the exit of the mixing section and flashback is caused by TBVA. Per definition, instability is reached if the flame is able to propagate more than one D upstream into the mixing tube. The critical equivalence ratio Φ_{crit} at the stability limit was recorded over Re for both fuels and for $S = S_0$ and $S > 1.25S_0$. Details will be discussed in section 4.

3 The Two Flashback (FB) Modes

Even in a turbulent recirculation zone, averaged velocity fields can still exhibit considerable downstream velocities. Thus, the identification of the flashback mode must be done instantaneously. Fig. 3 and Fig. 4 exemplary compare time series of axial velocity fields and related flame luminescence for the FB modes TBVA and CIVB for methane. In the configuration with $S = 1.25S_0$ the recirculation zone extends

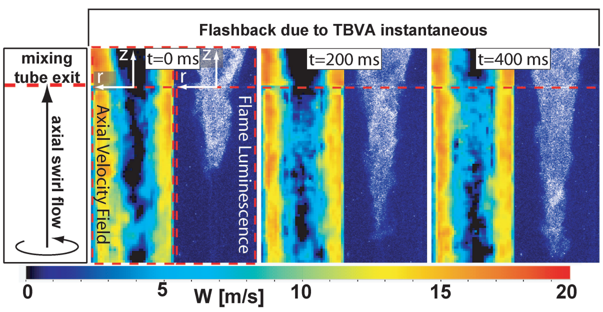

Figure 3: Turbulent burning along vortex axis, $S = 1.25S_0$, $Re = 28000$, $\Phi = 0.64$

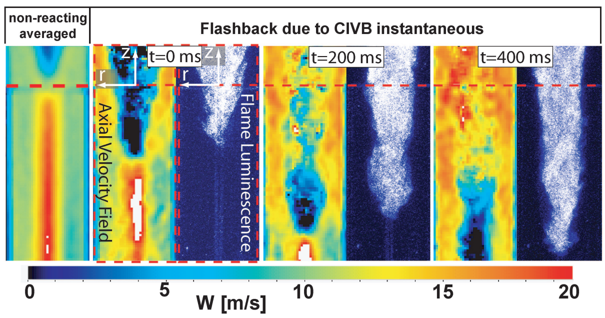

Figure 4: Combustion induced vortex breakdown, $S = S_0$, $Re = 28000$, $\Phi = 0.66$

upstream along the mixing tube. For the flame to propagate into this region, the burning velocity of the flame must exceed the average axial velocities. Secondly, the flame must not be quenched. For a swirl number of $S = S_0$ the RZ in the non-reacting flow is established downstream the exit of the mixing tube. In this case the flame additionally needs to alter the flow field to be able to enter the mixing tube. More precisely, the aerodynamic impact of the reaction heat release and the corresponding volume expansion will promote an upstream movement of the VB and the corresponding RZ. Then the flame will follow the RZ back into the mixing tube. As it can be seen in the instantaneous axial velocity fields from Fig. 4, the VB is attached to the flame tip.

4 Dependency of Flashback Limits on Fuel Properties

Fig. 5 shows Φ_{crit} determined in dependency of Re as described in section 2 for both fuels and FB modes (TBVA, CIVB). As expected the general trend of all stability limits increases with Re. The comparison

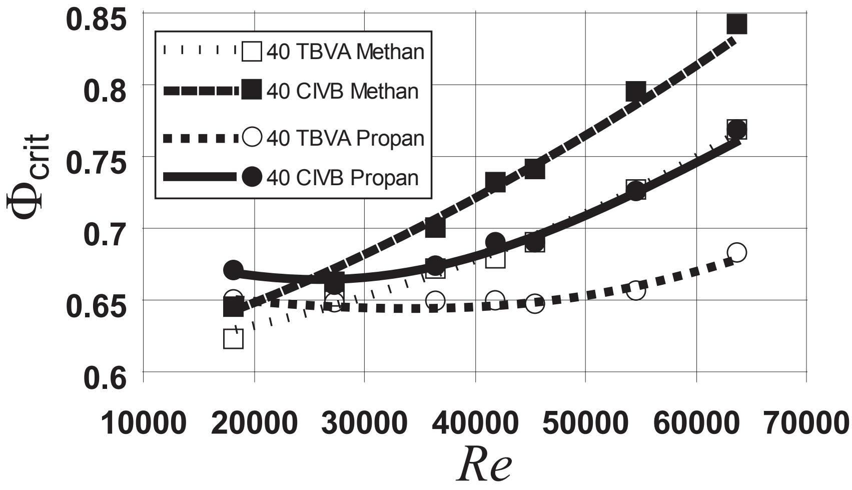

Figure 5: Φ_{crit} over Re for FB caused by CIVB and TBVA, fuels: methane and propane

of the stability limits of CIVB and TBVA shows that Φ_{crit} for CIVB is always higher than for TBVA. According to the PIV and CTA flow field measurements, the turbulence conditions in the recirculation zone of both cases are comparable. Thus, the difference in Φ_{crit} for CIVB and TBVA can be linked to the additionally required heat release of the flame necessary to alter the flow field.

A strong fuel dependence becomes obvious comparing the stability limits of methane and propane. For a specific flash back mode and $Re < 27000$, Φ_{crit} for methane is lower than for propane, whereas propane has a lower stability limit for $Re > 27000$. This is partially explained in the following by the fuel specific sensitivity of the burning velocity to stretch.

The laminar burning velocity S_L decreases from its unstretched value $S_{L,0}$ because of stretch (expressed by the Karlovitz number $Ka = \tau_c \cdot K$; characteristic chemical time scale: τ_c; stretch rate: K). A measure for the sensitivity of S_L to this stretch in the laminar case is the Markstein number Ma.

$$S_L = S_{L,0}(1 - Ma \cdot Ka) \quad [1] \tag{1}$$

Ma and $S_{L,0}$ depend on fuel and Φ. Reference values shown in Fig. 6 and 7 are taken from [3, 4].

In turbulent combustion the Ma-effect additionally depends on the transient nature of local stretch. The sensitivity of laminar flamelets to time varying stretch reduces with increasing fluctuation frequency. Therefore laminar flamelets in turbulent flows can withstand much higher strain rates as expected from laminar theory. The stretched laminar burning velocity of a flamelet $S_{fl,s}$ in turbulent flow is calculated following the work of [1] and compared for methane and propane corresponding to turbulent conditions in the RZ at $Re = 27000$ (Fig. 8). Critical strain rates necessary for this calculation have been taken from [5]. For low Φ, $S_{fl,s}$ of propane is lower than for methane because the big difference in Ma dominates over the higher $S_{L,0}$ of propane. As Ma for both fuels converge with increasing Φ, $S_{fl,s}$ of propane exceeds the value of methane due to the higher $S_{L,0}$.

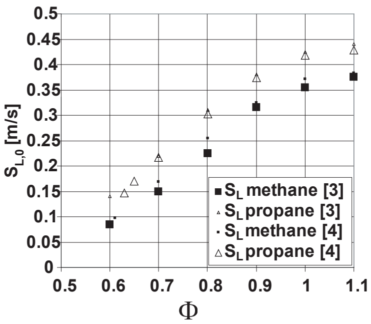

Figure 6: comparison of $S_{L,0}$

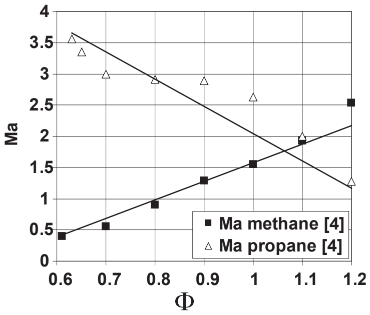

Figure 7: comparison of Ma

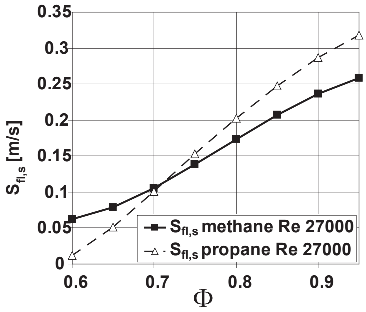

Figure 8: $S_{fl,s}$ according to [1]

Referring to the general trend of increasing stability limit Φ_{crit} with increasing Re, it is assumed that this crossover in stretched flamelet burning velocity contributes to the crossover in Φ_{crit} for both flashback modes. Thus, Ma-number effects seem to be governing the flashback mechanism in turbulent flow significantly. As a next step this approach must be extended by the influence of Reynolds number especially considering turbulent extinction limits and ignition behaviour for both fuels to capture the flashback characteristic.

Acknowledgments

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