Prediction of CIVB Driven Flame Flashback for CH_4-H_2-Air Mixtures and Moderate Turbulence

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1 Introduction

Under certain conditions the reliability of swirl stabilized lean premixed gas turbine burners is limited by sudden flame flashback leading to overheat and severe damage. In former studies [1]Combustion Induced Vortex Breakdown (CIVB) has been identified as one possible cause. This phenomenon is characterized by a formation of a closed recirculation bubble generated by production of negative azimuthal vorticity. Anchored at this bubble, the flame can start propagating upstream on the burner axis against high axial flow velocity with propagation speeds far beyond the turbulent flame speed. Especially burner systems without central bluff body and aerodynamic stabilization are prone to CIVB, but even for burners with a central obstacle flame propagation caused by CIVB can be observed.

The pioneering work on CIVB by Kröner et al. [2], who employed an industrial type swirl burner with a cylindrical mixing duct, delivered the C_{quench} model for the prediction of flashback limits:

$$C_{quench} \leq \frac{\tau_c^*}{\tau_u} = \frac{\tau_{PSR} \cdot Le \cdot \overline{u}}{D} \tag{1}$$

The geometry specific constant C_{quench} compares two characteristic time scales taking into account the dominating influence of quenching: τ_c^* represents a chemical time for quenching of the reaction, τ_u a mixing time scale represented by the characteristic burner diameter D and the bulk velocity $\bar{u}$. The underlying idea of the model is that flame propagation driven by CIVB can only be interrupted or even inhibited by the local extinction of the reaction. For ratios smaller than C_{quench} sudden upstream propagation occurs. A detailed analysis of different mixture temperatures and fuel compositions showed that the model correlates the observed flashback limits very well in the highly turbulent case. However, in the regime of lower turbulence, where the underlying assumption of local stirring is not fully justified, systematic deviations between measured and predicted limits were observed.

A numerical URANS study [3] and an additional experimental investigation [4] lead to the conclusions that the force driving the sudden flame propagation stems from the production of negative azimuthal vorticity and that its magnitude correlates well with the relative position of the flame with respect to the propagating recirculation bubble. On the basis of these findings an extended scaling law for the prediciton of CIVB driven flame propagation was proposed and published in [5]. It is shown there for natural gas ($X_{CH_4} > 99\%$) that the model allows the calculation of the CIVB limits with high accuracy in the entire operation range covered in the study ($22,000 < Re < 100,000$) on the basis of one single reference measurement. In the following an investigation concerning the extension and validation of this model for fuel mixtures containing up to 40% vol. hydrogen is presented.

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2 Theory

Using time scale modeling, Kröner showed that the onset of CIVB driven flame propagation can be correlated with two characteristic time scales τ_u and τ_{PSR}. The scaling law according to eq.(1) is based on the operating experience with one specific swirler design that was tested predominantly at the high volumetric flow velocities characteristic for gas turbine operation [2]. However, the underlying assumption that the closed recirculation bubble can be interpreted as stirred reactor (PSR) is not always strictly valid in the entire operation field of turbulent premix burners. The experimental study [4] of a swirl burner with larger vortex core than in [1] and [2] shows a combustion regime with a well defined flame surface, in particular when operated at moderate volumetric flow velocities. In Fig. 1 the local reaction regime inside the recirculation bubble is analyzed in the Borghi diagram (*"TD1"-burner*) in order to confirm the observation of lack of stirring at the flame tip in contrast to [1] and [2]. Obviously, corrugated flame fronts have to be expected. For this regime the authors derived a scaling law, that was then coupled with the model according to eq.(1) to obtain a generalized model for the prediction of the flame flashback that covers a wide range of pressure drops and volumetric flow velocities [5].

The observations made in the experimental studies [4] and [5] lead to the following equations for the characteristic turbulent time scale τ_t and the characteristic time scale τ_b for the burnout of the reactive volume inside the bubble (Fig. 2):

$$\tau_t = \frac{L_t}{u'} \sim \frac{D}{\bar{u}} \qquad (2) \qquad\qquad \tau_b = \frac{\Delta x_{crit}}{S_t} \sim \frac{\Delta x_{crit}}{S_l} \qquad (3)$$

Herein the values L_t and u' characterize the turbulence, $\bar{u}$ is the bulk velocity, S_t and S_l are the turbulent and laminar flame speeds of the fuel mixture, respectively, and Δx_{crit} represents the spatial separation of flame tip and stagnation point of the bubble as shown in Fig. 2a. For flame transition is required that the spatial separation of flame tip and bubble tip reaches a critical lower limit Δx_{crit} (Fig. 2b) where the negative production of azimuthal vorticity becomes intense enough for triggering of CIVB [3]. The observation that the flame inside the bubble exhibits a smooth and moderately wrinkled surface and the finding that the reaction inside the bubble is only weakly turbulent indicate $S_t \sim S_l$ following the early work of Damköhler. As usual [2] , both characteristic time scales are compared with each other and the ratio is used to define a characteristic constant C_b. For all operation points which do not fulfill the following condition CIVB will occur:

$$\frac{\tau_b}{\tau_t} \sim \frac{\Delta x_{crit} \cdot \bar{u}}{D \cdot S_l} \geq C_b \qquad (4)$$

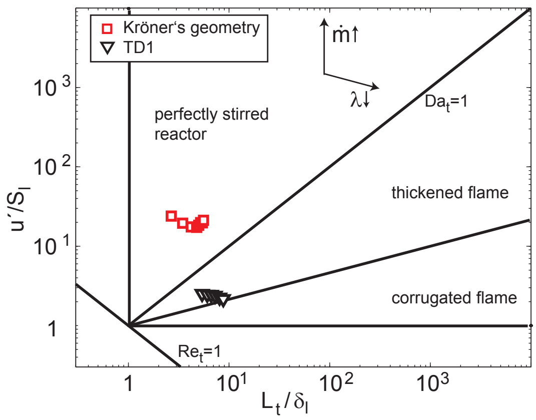

Figure 1: Local reaction regime in the bubble on the vortex core axis (natural gas).

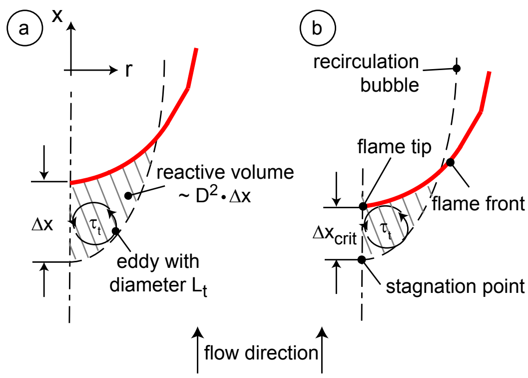

Figure 2: Concept for the prediction of CIVB driven flame flashback at moderate turbulence.

3 Experimental

The burner configuration used for the investigation of the *"TD1"- burner* was derived from the swirler design published in [6]. This burner (Fig. 3) applies aerodynamical flame stabilization without bluff body on the center line. The stabilization of the reaction is achieved with an internal recirculation zone (IRZ) at the burner exit. The tangential inlet ports for the main air provide the swirl required for the breakdown of the flow downstream of the mixing tube. With the open slot length s the global degree of swirl is selected. An axial jet is added on the burner axis for tailoring the velocity field (see [4] for details). The flame propagation from the combustion chamber into the swirl generator can be observed using a silica glass cylinder serving as mixing tube.

CIVB driven flame propagation can be initiated either by the reduction of the air excess ratio λ or by the reduction of the mass flow rate [2]. In this study the first procedure was chosen. After ignition of the burner under lean conditions ($\lambda \approx 2.0$), CIVB driven flame propagation was initiated by reducing λ with a temporal gradient of about $\Delta\lambda/\Delta t = 0.01\ s^{-1}$. For the determination of the stability limits every operation point was measured several times and the average of the critical air excess ratio λ_{crit} (Fig. 4) was calculated.

4 Results

The CIVB limits for the *"TD1"-burner* with $D = 40\ mm$ burner diameter, $s = 22\ mm$ open slot length, and $d = 12\ mm$ axial inlet diameter (Fig. 3) are plotted in Fig. 4. For this geometry $C_b = 0.395$ was determined from least squares fitting of the natural gas data (CH_4:H_2=100:0, open squares) to eq.(4). The lowest curve in Fig. 4 reveals that the effect of thermal power (representing also volumetric flow velocity) on the flashback limits is very well captured by eq.(4). The reasons for this success are that the corrugated flame regime in the bubble is preserved in the range of the experiments (Fig. 1) and that the local burning velocity is well represented by the laminar flame speed S_l.

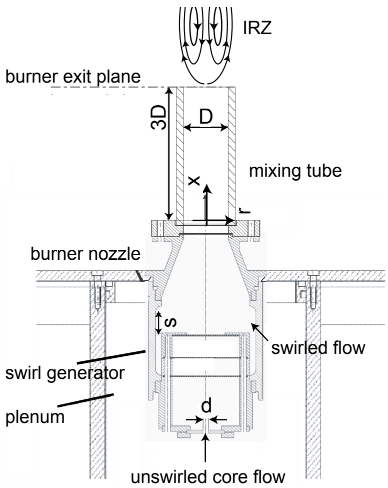

Figure 3: Scheme of the investigated *TD1* burner.

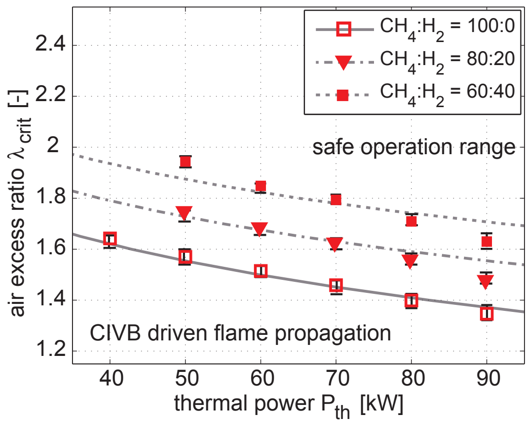

Figure 4: Stability limits of the investigated swirl burner for CH_4-H_2-air mixtures.

The extension of the model (eq.(4)) from natural gas only to mixtures of natural gas with hydrogen requires that the high diffusivity of hydrogen is properly taken into account. For this purpose, an effective fuel-in-air Lewis number is introduced into eq.(4):

$$C_b^* \leq \frac{\Delta x_{crit} \cdot Le \cdot \bar{u}}{D \cdot S_l} \tag{5}$$

The laminar flame speed S_l of the pure gases was determined according to [7]. Following [8] and [2] Le and S_l of the CH_4-H_2-air mixtures were calculated according to:

$$Le = \left(\frac{X_{H_2}}{Le_{H_2}} + \frac{X_{CH_4}}{Le_{CH_4}} \right)^{-1} \quad (6) \qquad S_l = \left(\frac{X_{H_2}}{S_{l_{H_2}}} + \frac{X_{CH_4}}{S_{l_{CH_4}}} \right)^{-1} \quad (7)$$

The two dotted curves in Fig. 4 show the predicted flashback limits for methane-hydrogen mixtures using only natural gas data as reference. The comparison with the experimentally obtained flame propagation limits (filled squares and triangles) indicates that all relevant effects are properly captured by the scaling law (eq.(5)) for fuel mixtures containing hydrogen. The experiments show that the increase of the laminar flame speed caused by the addition of hydrogen to the air fuel mixture leads to the increase of the critical air excess ratio λ_{crit} for the sudden flame propagation driven by CIVB. This effect is well captured by the scaling law.

5 Conclusions and Outlook

The scaling law for the limits of CIVB driven flame propagation depends on the degree of stirring of the flame front in the bubble. The presented new law for moderate turbulence captures natural gas data very well. After its extension using a fuel-in-air Le-number the flashback limits of CH_4-H_2-air mixtures are very well modeled on the basis of natural gas data only. The successful coupling of this newly defined scaling law with the former model of Kröner et al. [2], already shown in [5] for natural gas, will be presented for CH_4-H_2-air mixtures in more detail at the conference.

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