URANS and Large-Eddy-Simulation of Combustion Induced Vortex Breakdown in Premixed Swirling Flows

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1 Introduction

Typical configurations of stationary gas turbine combustors operating in premixed combustion mode feature a mixing tube containing the swirling fuel-air-mixture followed by a combustion chamber of larger diameter, where the vortex breaks down, forming a recirculation zone. In normal operating conditions the premixed flame is stabilized in this recirculation zone just downstream of the mixing tube.
Recent experiments [1] show that under certain conditions the premixed flame can propagate upstream into the mixing tube although the mean axial velocity of the flow is well above the turbulent flame speed. This phenomenon has been called the "Combustion Induced Vortex breakdown" (CIVB). The flashback behaviour is influenced by mass flow, equivalence ratio, mixture temperature and properties of the swirling flow field.
The goal of the present work is to asses, whether the experimental findings regarding the CIVB phenomenon can be reproduced numerically by either URANS and Large-Eddy-Simulations qualitatively and quantitatively. It is shown that both URANS and LES methods can reproduce the flashback qualitatively, and that the flashback limits can even be predicted quantitatively if accurate turbulence and combustion models are used.

2 Configuration

In the experiments the configuration consits of a cylindrical mixing tube with the perfectly premixed swirling fuel-air-mixture attached to a cylindrical combustion chamber of larger diameter. Different fuels and various configurations of the flow velocity profile within the mixing tube were investigated. The experiments show that the flame is stabilized by the recirculation zone inside the combustor at sufficiently lean conditions. At larger fuel-air-ratios the flame is able to move upstream into the mixing tube although the mean axial velocity is higher than the turbulent burning velocity save close to the walls where the flame is quenched anyway. In the flashback state the recirculation zone moves upstream in the flame front so that the vortex breakdown occurs just upstream of the flame tip.
The flashback of the flame only occurs for certain configurations of the swirling flow field. The flashback limit also depends on the mixture temperature, the mass flow and the fuel-air-ratio. For the simulation of the CIVB a CFD method has to be chosen which is capable of reproducing the flow field inside the mixing tube and the breakdown zone of the vortex accurately, to model the turbulent premixed combustion process and to capture the flashback process with an adequate accuracy. Therefore the different approaches used for the simulation first need to be validated seperately under conditions that are similar

to those in the experiments.

3 Simulation of the cold swirling flow

The first step of the model validation is the simulation of the statistically stationary cold swirling flow in the burner. For several test cases mean velocities and Reynolds stress tensor data were available as inflow boundary conditions from the experiments. Calculations of the rotationally symmetric velocity field were performed using a commercial URANS Solver (FLUENT 6.2). The application of different turbulence models showed as expected that two-equation models are not able to reproduce the swirling flow and the vortex breakdown. Only the Reynolds-Stress-Transport Model (LRR) did reproduce the proper behaviour of the flow.

In furter studies Large-Eddy-Simulations are preferred due to the unsteady nature of the CIVB phenomenon. Thus the cold flow also has to be validated using an LES code [2]. The inflow boundary conditions for the LES need to be compatible with the profiles of measured velocity, Reynolds stress components and the local turbulence length scale as they are used in the URANS case. Since the LES requires unsteady boundary conditions a method based on diffusing and scaling of initially random fields is applied [3].

4 Combustion modelling

As combustion model to simulate the premixed turbulent flame a BML-type model by Lindstedt and Vaos (LV) [4] is used describing the reaction by a singe reactive scalar $\tilde{c}$. The reaction source term is modelled using a correlation for the flame surface density Σ:

$$S_C = \rho_u \cdot s_L^0 \cdot \Sigma = C_R \cdot \rho_u \cdot \frac{s_L^0}{\nu^{\frac{1}{4}}} \cdot \frac{\tilde{\varepsilon}^{\frac{3}{4}}}{\tilde{k}} \cdot \tilde{c} \cdot (1 - \tilde{c})$$

The model has been validated in the RANS context at different turbulence intensities, length scales and pressures for methane fuel with a turbulent Bunsen flame configuration showing good agreement with experimentally measured turbulent burning rate data [5], [6], [7].

Like all models of the Eddy-Breakup-type the LV-model tends to produce an unphysical jump of the flame to the wall due to the vanishing mixing time irrespective of the wall temperature. To avoid this behaviour the combustion model is supplemented with two different quenching models. The first quenching model applied was adapted from [8]. It suppresses the reaction in regions of unburnt gases by multiplying the reaction source term with a step function: $S_C^* = H\left(c - c^*\right) \cdot S_C$ with the reaction progress variable c and the threshold c^* representing a quenching temperature $c^* = \left(T_q - T_u\right) / \left(T_b - T_u\right)$.

The other model based on the ITNFS model [9] introduces kind of an efficiency function in the reaction source term $S_{C,ITNFS} = \Gamma_k\left(u'/s_L^0, l_t/\delta_L^0\right) \cdot S_C$. Both models effectively prevent the flame propagation along cold walls.

Other combustion models were also used in addition to the LV model, but did not show improvement. The LES code uses a thickened flame model [10] for the simulation of combustion. To resolve the flame front within the LES grid it is thickened by a factor that is introduced into the diffusion term of the reaction progress transport equation. In order to keep the flame propagation speed constant the reaction rate is reduced by the same factor. To account for the unresolved wrinkling of the flame surface an efficiency function is introduced. The flame thickning has a strong effect on the interaction of combustion and turbulence. Thus other combustion models also will be used in further calculations.

5 Simulation of the flame flashback

URANS calculations of the combustion induced vortex breakdown using the RSM turbulence model and the Lindstedt-Vaos combustion model were performed of the stable steady state flame as well as of the flashback process at different flow conditions. Rotational symmetry was assumed allowing to use a two-dimensional grid with cyclic boundary conditions to account for the swirling flow.
Figure 1 shows the resulting temperature field of the stable flame burning downstream of the mixing tube and during a flashback. The recirculation zone is marked by an isoline of zero axial velocity. The influence of the quenching model is pointed out in Figure 2. Without the quenching model the flame tends to spread along the actually cold wall of the mixing tube. With the quenching model applied the flame only propagates into the mixing tube in the backflow zone far away from the walls.

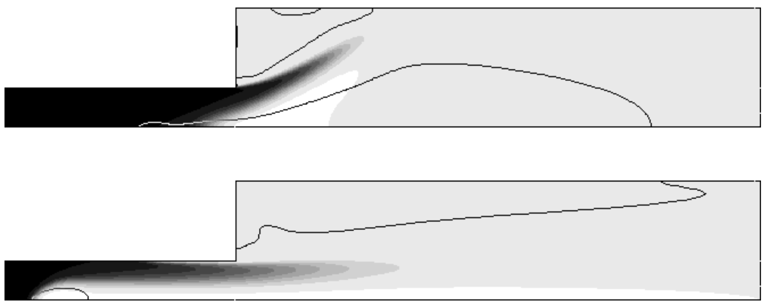

Figure 1: URANS of stable flame and flashback - temperature field and backflow zone

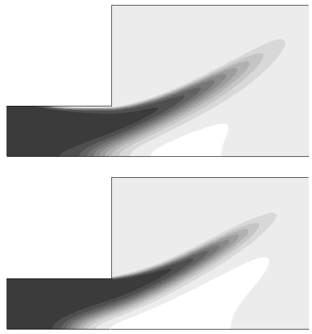

Figure 2: Flame propagation along the wall and prevention by flame quenching

The mass flow and the temperature at which the flashback occurs in the experiment can be reproduced qualitatively with good accuracy after the single model constant of the combustion model is fitted to a single condition (see figure 4). So the tendency of the flashback phenomenon is reproduced accurately with the current numerical method although a full predictive capability is not achieved yet.
Figure 3 shows the stable flame resulting from the Large-Eddy Simulation. Calculations of the full flashback process with LES are underway.

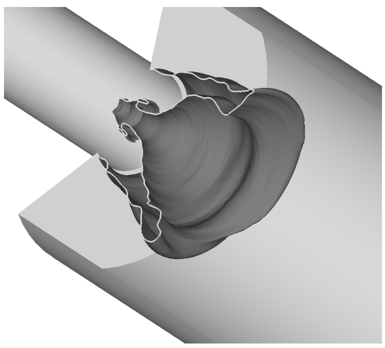

Figure 3: LES of the stable flame

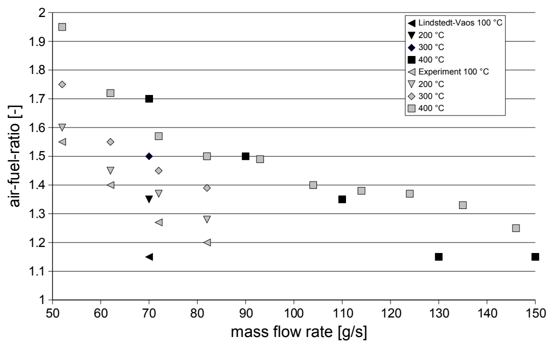

Figure 4: Flashback limits from experiments and simulations for different mass flow rates and inflow temperatures.

6 Discussion and outlook

The presented work shows, that the CIVB and flame flashback phenomena can be reproduced qualitatively with a relatively simple quasi-2D-URANS method. It is, however, not able to resolve the detailed flame structure or the precessing vortex core close to the axis. It is expected that the Large-Eddy simulations will lead to a more detailed computational view of the flashback process at the time of the conference. Further development on the inflow generator and the LES premixed combustion model are expected to improve the accuracy of the simulations further on.

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