URANS- AND LARGE-EDDY-SIMULATIONS OF COMBUSTION-INDUCED VORTEX BREAKDOWN IN PREMIXED SWIRLING FLOWS

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ABSTRACT

A swirl burner configuration has been investigated using URANS and LES methods. The flow field was analyzed in isothermal non-reactive state as well as in the reactive state including the flame flashback phenomenon. The URANS quasi two-dimensional calculations have been performed using the Lindstedt-Vaos combustion model supplemented with flame quenching models to prevent the flame from propagating along the cold wall. In the LES an artificially thickened flame combustion model was used. The limits of the flashback starting from a stable flame were determined under several operating conditions and compared with experimental results.

INTRODUCTION

Typical configurations of stationary gas turbine combustors operating in premixed combustion mode feature a mixing tube containing a swirling fuel-air-mixture followed by a combustor of larger diameter, where a vortex breakdown occurs. The premixed flame is usually stabilized within this vortex located just downstream of the mixing tube. Recent experiments (Fritz et al. 2001) show that under certain conditions the premixed flame can propagate upstream into the tube although the mean axial flow velocity there is well above the turbulent burning velocity. Factors influencing this behaviour are mass flow, fuel-air-ratio, mixture temperature and properties of the swirling flow field in the mixing tube. The phenomenon has been called "Combustion Induced Vortex Breakdown" (CIVB).

The goal of the present work is to assess, whether the experimental findings for the CIVB phenomenon can be numerically reproduced by URANS and Large-Eddy-Simulations qualitatively and quantitatively. It is shown, that the CIVB phenomenon can be reproduced, and that the flashback limits can be predicted quantitatively if accurate turbulence and combustion models are used.

CONFIGURATION

The experimental configuration by Fritz et al. (2001) features a cylindrical mixing tube containing perfectly premixed fuel-air-mixture followed by a cylindrical combustor of larger diameter (see Figure 1). Different fuels like methane, hydrogen and propane and different flow configurations inside the mixing tube resulting in different velocity profiles were used in the experiments.

The experiments show, that the premixed flame, which is stabilized in the combustor downstream of the mixing tube at lean conditions, is able to move upstream into the tube if the fuel-air-ratio is increased towards stoichiometric. This happens although the mean axial velocity is much higher than the turbulent burning velocity everywhere in the tube except near the wall, where the flame is quenched anyway.

During the flashback the vortex breaks down within the tube and a recirculation zone inside the flame front moves upstream. The vortex breakdown occurs directly upstream of the flame tip. The flashback occurs only for certain types of swirling flow fields inside the mixing tube. Besides the flow configuration the flashback limit also depends on the temperature of the mixture, the fuel-air ratio and the mass flow rate.

To simulate the CIVB phenomenon, the CFD method chosen needs to be able to reproduce accurately the features of the swirling flow field inside the tube and the vortex breakdown downstream of it, to model the turbulent premixed combustion process and to capture the unsteady flash-back process with sufficient accuracy. Therefore, the different ingredients of the simulation method are first validated separately for conditions similar to the experimental ones.

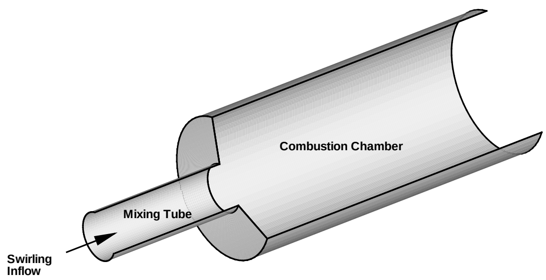

Figure 1: Configuration of the swirl burner.

NUMERICAL SETUP

RANS

First the code is validated for the statistically stationary, cold turbulent swirling flow field inside the tube and inside the combustor downstream. Experimental data of the inflow boundary conditions (mean velocities and Reynolds stress tensor) and of the flow field were available for several flow cases. In the different cases the temperature of the mixture at the inlet and the mass flow rate are varied.
The rotationally symmetric swirling flow field was simulated with a commercial URANS code (FLUENT 6.2). Different turbulence models were used to achieve the correct flow field. However, two-equation turbulence models are not capable of reproducing the strongly swirling tube flow and develop an unphysical flow profile due to the overpredicted diffusion of momentum. As expected the flow field could only be reproduced satisfactorily when using a Reynolds-Stress-Model model. The LRR model was used here. Only this model was used in the further calculations.
Because of the rotationally symmetric nature of the flow field URANS calculations were performed on a two-dimensional grid using cyclic boundary conditions to account for the swirling velocity component. As will be shown, with this method a good agreement with the measured flow field can be achieved. Also the combustion process can be reproduced in stable state and in the flame flashback. A lot of computational time can be saved this way.
Another useful simplification of the setup is the use of apropriate inflow boundary conditions instead of resolving the complex swirl generator for the simulation. As was shown by Kiesewetter (2005), skipping the swirl generator has only few influence on the flow field. It also facilitates the variation of the inflow profiles for the different cases examined.

LES

Though the flame flashback can be reproduced simulating with URANS Large-Eddy-Simulations are necessary for a detailed understanding of the process. LES offer a more accurate capturing of the unsteady flow phenomena. Also three-dimensional effects like a precessing vortex core can be resolved and investigated.
The flow was simulated using an LES code described by Düsing et al. (2005). The code features a finite volume discretization with explicit Runge-Kutta time stepping.

To keep the LES comparable to the URANS and the experimental data the inflow boundary conditions have to be specified to provide the same profiles of mean velocity, Reynolds stress components and turbulent length scale as in the experiment. A mean flow profile with superposed random noise will not complay with this condition since random noise will be damped very quickly due to the lack large length scales. Instead a method based on diffusing and scaling initially random fields was used (Kempf et al. 2005). The ammount of diffusion is varied locally in order to reach the desired profile of the turbulent length scale. By scaling the field the fluctuations are fitted to the correct Reynolds stresses. Finally the generated fluctuations are added to the mean velocity profiles.
Figure 2 shows the spatial variation of the fluctuation length scale, a comparison of the diagonal elements of the Reynolds

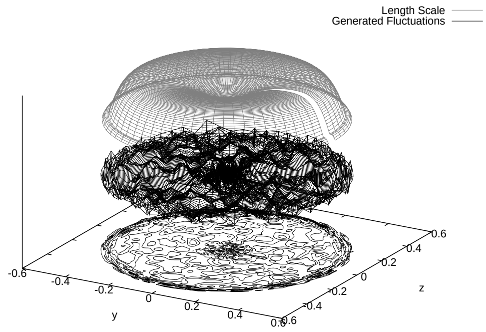

Figure 2: Configuration of the swirl burner.

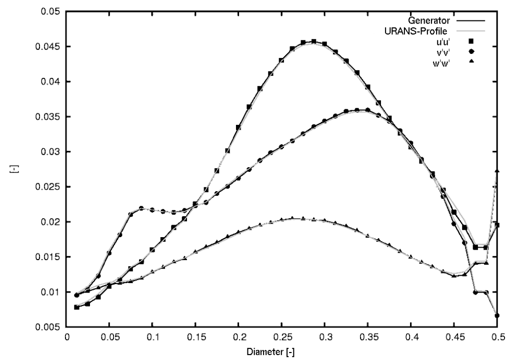

Figure 3: Reynolds stress components from generated fluctuations and target profiles.

stress tensor in the inflow plane evaluated from the fluctuations generated and the target profiles. Near-perfect agreement is achieved.

Combustion Modelling

In the simulations of the combusting flows the Lindsted-Vaos (LV) turbulent premixed combustion model (Lindstedt and Vaos 1999) was used. It has been validated in the RANS context at different turbulence intensities, length scales and pressures for methane fuel using a turbulent Bunsen flame configuration, showing good agreement with the experimentally measured turbulent burning rate (Brandl et al. 2005), see figure 4.
In the LV-Model the reaction is described with one reactive scalar $\tilde{c}$ which is called the reaction progress variable.

$$\tilde{c} = \frac{T - T_u}{T_b - T_u} \tag{1}$$

Its source term S_c for the transport equation of the progress variable is derived from a correlation for the flame surface density Σ:

$$\overline{S_c} = \rho_u \cdot s_L^0 \cdot \Sigma = C_R \cdot \rho_u \cdot \frac{s_L^0}{\nu^{\frac{1}{4}}} \cdot \frac{\tilde{\varepsilon}^{\frac{3}{4}}}{\tilde{k}} \cdot \tilde{c} \cdot (1 - \tilde{c}) \tag{2}$$

where ρ_u denotes the density of the unburnt gas, s_L^0 the laminar burning velocity and ν the viscosity. k and ϵ are the turbulent kinetic energy and its dissipation, respectively. The model constant C_R has to be calibrated for the specific

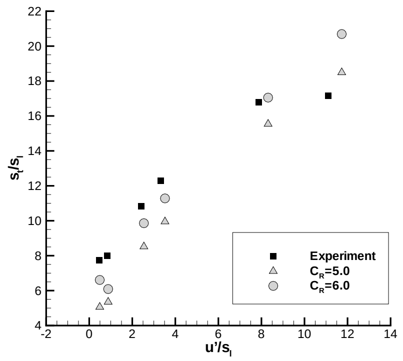

Figure 4: Ratio of turbulent to laminar burning velocity plotted over fluctuations to laminar burning velocity at two different values for the LV-model constant C_R.

application of the model. Lindstedt and Vaos suggest values in the range of 1.25 to 2.6. For some applications higher values of C_R can be necessary like in the Bunsen flame investigations. For the CIVB a value of 1.45 was determined as the best fit of flashback limits with experimental data.
Like all combustion models of the eddy-breakup-type the LV model tends produce to an unphysical jump of the flame towards the walls. This happens because of the vanishing of the mixing time irrespective of the wall temperature. To avoid this behaviour the combustion model was supplemented with quenching models. The first quenching model used was adepted from Catlin and Lindstedt (1991). The reaction of unburnt gases is suppressed by multiplying the reaction source term with a step function:

$$S_{c^*} = H\left(c - c^*\right) \cdot S_c \tag{3}$$

The quenching value of the progress variable c^* represents a quenching temperature which can be determined according to:

$$c^* = \frac{T_q - T_u}{T_b - T_u} \tag{4}$$

Catlin and Lindstedt recommend a quenching temperature $T_q = 780K$ for methane fuel which was also used in the present work.
The second quenching model is based on the intermittent turbulent net flame stretch model (ITNFS) according to Meneveau and Poinsot (1991). The ITNFS model introduces an efficiency function Γ_K into the reaction source term to account for the unresolved wrinkling of the flame surface. The turbulent strain rate $\tilde{\epsilon}/\tilde{k}$ is replaced by $\Gamma_k\left(\frac{u'}{s_L^0}, \frac{l_t}{\delta_L^0}\right) \cdot \tilde{\epsilon}/\tilde{k}$. So the reaction source term becomes

$$S_{c,ITNFS} = \Gamma_k\left(u'/s_L^0, l_t/\delta_L^0\right) \cdot S_c \tag{5}$$

The efficiency function Γ_K is derived from DNS data.
For both quenching models the constant C_R has to be recalibrated. However after it is calibrated for one operating condition of the burner and one model variation it can be used for all other operating conditions.
For the Large-Eddy-Simulation at first a thickened flame model (Colin et al. 2000) has been used. The flame front is too thin to be resolved explicitly by the LES grid in the calculation. The thickened flame model therefore thickens the flame front but keeps the flame propagation velocity constant. To achieve this the diffusivity D is increased by a factor F while the reaction rate $\overline{\dot{\omega}}_F$ is reduced by the same factor.
The thickening of the flame has an effect on the interaction between the combustion and the turbulent flow field. Turbulent eddies with a scale lower than the thickened flame thickness which would wrinkle the real flame cannot wrinkle the thickened flame. To account for the unresolved wrinkling an efficiency function is applied. First a dimensionless wrinkling factor is introduced. The wrinkling factor Ξ represents the ratio of the flame surface to its projection onto a plane normal to the direction of propagation.
The thickened flame with the thickness δ_l^1 is more plane than the real flame with the thickness δ_l^0. Thus the wrinkling factor for the real flame is larger. A formulation by Meneveau and Poinsot (1991) is used for the wrinkling factor.
The efficiency function is defined as the ratio of the wrinkling factor of the real flame and of the thickened flame. So its value is larger than unity for any thickening factor $F > 1$:

$$E = \frac{\Xi|_{\delta_l^0}}{\Xi|_{\delta_l^1}} > 1 \tag{6}$$

With these modifications the transport equation for the fuel mass fraction Y_f becomes:

$$\frac{\partial \rho\, Y_F}{\partial t} + \nabla \cdot (\rho\, \mathbf{u}\, Y_F) = \nabla \cdot (\rho\, D\, F\, E\, \nabla Y_F) + A\, \frac{E}{F}\, Y_F\, Y_O\, e^{-\frac{T_a}{T}} \tag{7}$$

SIMULATION OF THE CIVB PHENOMENON

First the models have been validated for the cold flow. Inside the mixing tube the swirling flow can propagate without great qualitative changes of the velocity profiles. When reaching the combustion chamber the vortex breaks down and forms a recirculation region. This flow field is quite similar to the one with the stable flame. Figure 5 shows a contour plot of the cold flow axial velocity from the URANS. The recirculation zone is marked by an isoline of zero axial velocity.
Figures 6 to 8 show profiles of the axial velocity at three

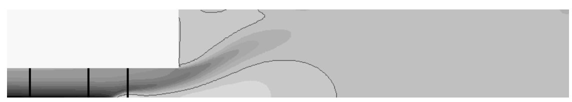

Figure 5: Contours of the axial velocity in the non-reactive flow.

different positions in the mixing tube. The positions are marked in Figure 5. The downstream decay of the axial velocity is slightly underpredicted by the LES. The vortex breakdown and the recirculation region are situated too far upstream in the URANS. In the LES the breakdown is located further downstream. A URANS simulation on a three-dimensional grid shows a similar position of the recirculation zone as the LES.
In the reactive flow the flame front is stabilized in the recirculation area. Figure 9 shows the contours of the temperature field in a URANS calculation. As can be seen, the flame starts propagating along the cold wall of the mixing tube. Figure 10 shows the magnified end of the mixing tube with and without quenching models applied. Both quenching models effectively prevent the flame of burning along the

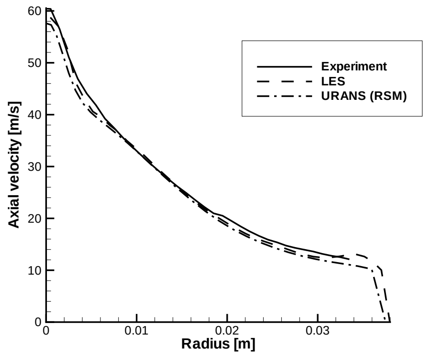

Figure 6: Axial velocity close to inlet.

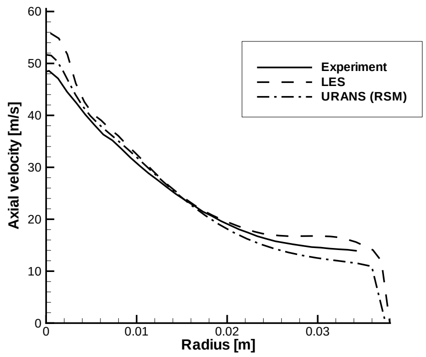

Figure 7: Axial velocity before vortex breakdown.

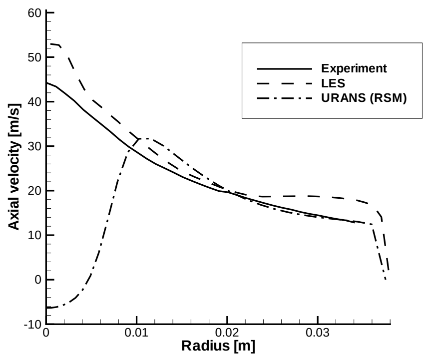

Figure 8: Axial velocity behind vortex breakdown in URANS.

cold walls.

Since in the LES the recirculation zone is located further downstream the flame front also stabilizes downstream of the front in URANS. For a sufficient resolution of the flame in the LES grid the flame needs to be thickened by a factor of 5.0 to 10.0.

For the investigation of the flashback eight different operating configurations were determined. They differ in the mass flow rate and the temperature of the unburnt mixture. The temperature is varied from 100 $°C$ to 400 $°C$, the mass flow from $70g/s$ to $150g/s$. For each case first a stable burn-

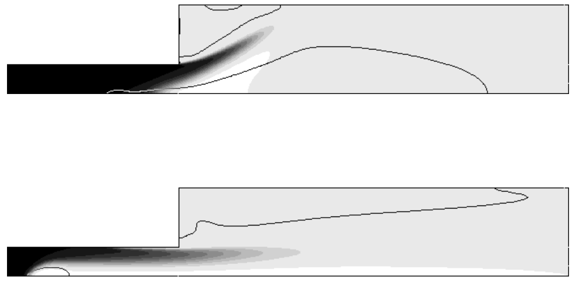

Figure 9: Contours of the temperature, stable flame and flashback state. Recirculation zone marked by an $u_a x = 0$ isoline.

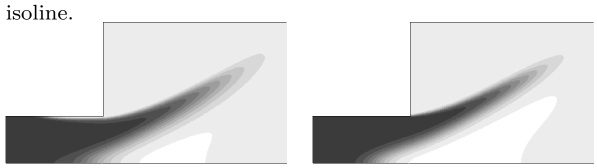

Figure 10: Temperature contours with (right) and without (left) quenching model applied.

ing state with a lean flame was established. Then the flame flashback was triggered by enriching the fuel-air mixture towards the stoichiometric. When reaching a critical air-fuel ratio λ_{crit} the recirculation zone and the flame front start propagating upstream. Because of the boundary conditions the flame stabilizes near the inflow boundary. In the experimental configuration the flame would propagate further into the swirl generator which might be fatally damaged. The flame in a flashback state is shown in figure 9.

In figure 12 the flashback limits for the eight cases are plotted. It shows the limiting values predicted by the two-dimensional URANS simulation with the Lindstedt-Vaos combustion model and quenching model applied together with experimental results. The model constant C_R is calibrated for the central case with a massflow of $\dot{m} = 110g/s$ and an inlet temperature of $T_{in} = 400\ °C$. All other cases are calculated with the same model settings.

For the cases with the inlet temperature of $T_{in} = 400\ °C$ the calculated limits match the experimental values very well. In case of the variation of the inlet temperature a deviation from the experiment can be seen. The simulation tends to underpredict the critical fuel-air ratio so that the flashback takes place at richer conditions.

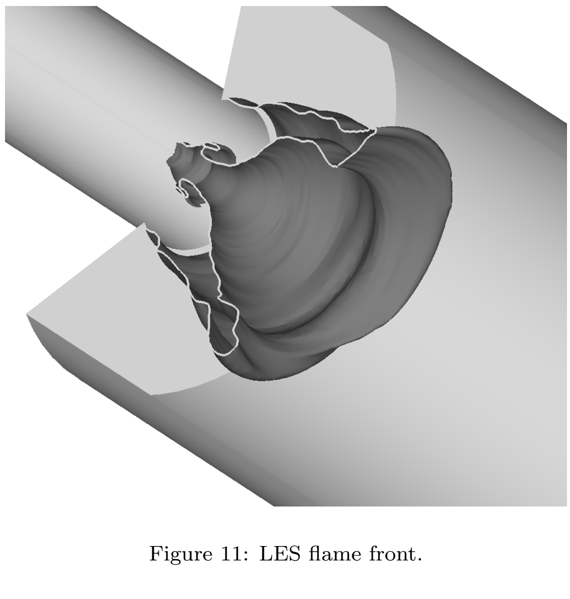

Figure 11: LES flame front.

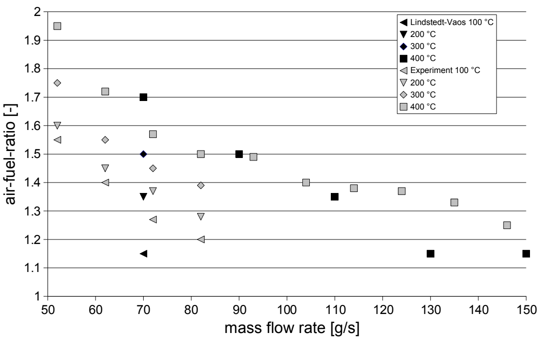

Figure 12: Flashback limits.

CONCLUSIONS AN OUTLOOK

The present work has applied a URANS method and a LES method to a swirl burner geometry simulating the flow in isothermal conditions as well as the reactive case including the flame flashback. In the context of URANS simulations the turbulent premixed combustion was modelled using a model by Lindstedt and Vaos (1999) supplemented with two different quenching models to prevent the flame from propagating along the cold wall. For the LES an artificially thickened flame model was used.
It is shown that the flashback can be reproduced quantitatively even with the relatively simple quasi two-dimensional method. The limits for the flashback were reproduced for several inflow configurations. However this method cannot resolve three-dimensional phenomena like a precessing vortex core. For this reason large-eddy simulations not only of the stable flame but also of the flame flashback are necessary.
Because of its rather strong influence on the interaction between flame and turbulence the artificially thickened flame model might not be the optimal choice for application to the CIVB flashback. In further investigations different combustion models like a flame wrinkling transport model will be used to get closer to the realistic rate of interaction. Further development on the generation of the turbulent inflow boundary conditions also may lead to an improvement of the agreement between simulations and experiments.

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