Large-Eddy Simulation of Combustion-Induced Vortex Breakdown in an Unconfined Vortex

Eike Tangermann[1], **Michael Pfitzner**[1], **Hannes Kröger**[2], **Egon Hassel**[2]

[1]Institut für Thermodynamik, Universität der Bundeswehr München, Neubiberg, Germany

[2]Lehrstuhl Technische Thermodynamik, Universität Rostock, Germany

1 Introduction

Recent development in gas turbine combustion has lead to lean premixed combustion as a promising way to reduce NOx emissions. However, a major issue of lean combustion still is its stability. Lean blowoff and flame flashback are limiting factors to the operational range of the air-fuel-ratio.

Several flashback mechanisms have been identified. A very complex one is the combustion-induced vortex breakdown (CIVB) which has been investigated experimentally [1, 2] for confined vortices. Numerical studies in RANS context [3, 5] and with Large-Eddy-Simulations [4] also have been carried out. It is likely to occur in swirl-stabilised combustors if certain conditions of the flow field and of the mixture are fulfilled.

However, the CIVB does not only occur in confined vortices like in the gas turbine application but also in free vortices [6]. In the present study the CIVB has been simulated using Large-Eddy-Simulation for a burner configuration with unconfined swirling flow. Two different combustion models have been applied, a presumed PDF model and an flame surface density model, to investigate the sensibility of CIVB to the combustion model.

2 Burner Configuration

The configuration of the burner [6] is shown in figure 1. It allows to observe the CIVB of a methane flame in an unconfined vortex. Premixed gas enters through a swirl generator and a nozzle with a diameter of $d_n = 42mm$ into the unconfined combustion region. From the sides air is mixed into the swirling flow. Unlike in gas turbine-like combustors there is no state of stable operation. Instead only blowoff and flashback occur right after the ignition.

The isothermal flow field depends on the swirl intensity and the mass flow rate. The swirl is characterised by the swirl number S which represents the ratio of swirling momentum to axial momentum. For the same swirl number the flow field is similar at different mass flow rates. This allows to scale the inlet profiles for different operational conditions. In isothermal operation a vortex breakdown occurs at a swirl number $S > 0.49$. The formation of a recirculation zone starts at swirl numbers $S > 0.61$.

The numerical domain covers a cylindrical volume of $6.66d_n$ in the diameter and $4.7d_n$ in axial direction. The grid consists of 600000 cells with cell sizes of approximately $1mm$ in the combustion region.

Correspondence to : eike.tangermann@unibw.de

The swirl generator is not resolved numerically. Instead mean velocity profiles with superimposed fluctuations are used as inlet boundary conditions in the nozzle exit plane. The fluctuations are generated by the method of turbulent spots [7] and the mean profiles result from auxiliary simulations of the swirl generator validated with experimental data.
To achieve a reaction the mixture is ignited 120mm above the nozzle exit plane. Under certain conditions a CIVB is generated causing a flame flashback up to the nozzle. The existance of CIVB depends on the flow field, i.e. on the swirl number and the mass flow rate and on the equivalence ratio of the mixture.

3 Modelling

The flame flashback by CIVB is a highly unsteady and three-dimensional process. To resolve the full structure of the phenomenon methods offering a high spatial and temporal resolution like Large-Eddy-Simulation are necessary. The LES have been carried out using open source code OpenFOAM.
Governing equations are the filtered, Favre averaged conservation equations for mass and momentum for a compressible newtonian fluid. To take the variability of the enthalpy into account an equation for the enthalpy also is solved. The numerical schemes are of second order. As a subgrid-scale turbulence model for the closure of the equations the dynamic Smagorinsky model is used. For the open boundaries total pressure conditions are applied.
Two different models have been used to reproduce the combustion. A rather simple model based on an algebraic expression for the flame surface density [8] and a more sophisticated presumed PDF/ILDM approach. Thus the influence of the combustion modelling on the formation of CIVB could be investigated.
The basis for the presumed PDF/ILDM model is a progress variable Y defining the position of the chemical state on the low-dimensional manifold. A transport equation is solved for the Y-variance which is closed by presumed beta-PDFs. Due to its time consumption the PDF integration is not performed for every cell and every time during the solver run but only once in advance. The results are stored in a multi-dimensional lookup table. The chemistry table is generated using the Flamelet Generated Manifolds (FGM) method. Computation of the laminar, plane flamelets was done using CANTERA. No flame strain was taken into account. As a progress variable the CO_2 mass fraction was used.
The second combustion model is based on an expression for the flame surface density (FSD) developed in [8] from analysis of a DNS of a flame in isotropic and homogeneous turbulence. A transport equation is solved for the reaction progress variable $\tilde{c}$. To account for the entrainment of fresh gas a regress variable $\tilde{b} = 1 - \tilde{c}$ is also introduced. The reaction source term $\bar{\dot{\omega}}$ then is calculated from the density of the unburnt mixture ρ_u, the laminar flame propagation velocity s_l^0 and the flame surface density σ according to $\bar{\dot{\omega}} = \rho_u s_l^0 \overline{\Sigma}$. The flame surface density is expressed by $\overline{\Sigma} = 4\beta \frac{\tilde{c} \cdot \tilde{b}}{\overline{\Delta}}$ with the filter width $\overline{\Delta}$ and a modelling constant β. The approach features no explicit subgrid-scale modelling. The subgrid mixing in the flame is expressed by the length scale $\overline{\Delta}/4\beta$. It has to be calibrated for each application depending on the turbulence properties. For the current flow a value of $\beta = 1.0$ has been selected as best fit to experimental flashback results.

4 Computational Results

Two operating points have been investigated numerically using the PDF-model. The swirl number for both is $S = 0.39$. The gas flow rate for the first case is $\dot{V} = 12m^3/h$, for the second case it is $\dot{V} = 20m^3/h$. The second case also has been simulated with the FSD combustion model. In all cases the ignition position is $120mm$ above the nozzle exit plane.
To achieve an initial flow field for the flashback simulations the isothermal flow has to be simulated first. For a successful reproduction of the flashback the isothermal flow has to be validated. Data from PIV

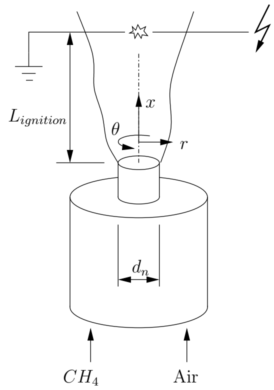

Figure 1: Investigated burner configuration

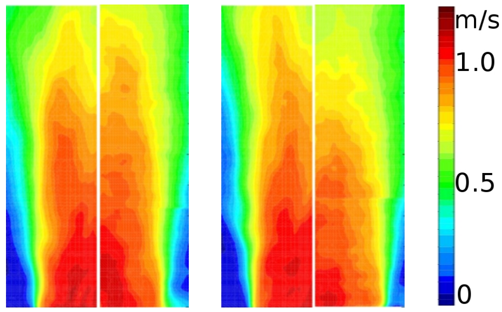

Figure 2: Axial velocity from LES (left half) and PIV (right half). $S = 0.39$, $\dot{V} = 12m^3/h$ (left), $\dot{V} = 20m^3/h$ (right)

measurement [6] are available for the validation. Figure 2 shows plots of measured and computed axial velocity for the two cases. The agreement for mean swirl numbers generally is good. The axial jet and the onset of the vortex breakdown are predicted well.

The flashback simulations have been performed starting with an air equivalenve ratio $\lambda = \frac{1}{\phi} = 1.0$. After the ignition a CIVB flashback occurs in both cases. The expansion of the hot gas in the center of the vortex leads to a vortex breakdown with a recirculation zone. The recirculation pulls the hot gas upstream inducing the breakdown even further upstream. During the flashback the flame always stays attached within the recirculation zone. Its tip is located close to the maximum upstream velocity. Figure 3 shows the flow field during CIVB with the recirculation zone marked by an isoline of zero axial velocity and the flame front is marked by the isosurface $\tilde{c} = 0.5$. The upstream propagation finally is stopped close to the inlet boundary where the flow field is fixed by the inlet boundary conditions.

In the next step simulations at leaner conditions were performed until the ignition did not lead to a flashback any more to determine the limiting equivalence ratio for the CIVB. If the mixture is lean enough the flame is blown out of the computational domain and the combustion extinguishes after the ignition is turned off.

Figure 4 shows the limiting values of the air equivalence ratio from simulation and experiments. The uncertainty of air flow rate and equivalence ratio is shown by error bars. The computational points for both models are marked with downward pointing triangles marking a flashback and upward pointing triangles marking a simulation without flashback. The computed limits fit the experimental results within the range of uncertainty. However, the model constant of the FSD-model had to be tuned for the proper fit. Other applications might require different tuning.

The behaviour of the flame tip during a flashback has been investigated in detail for the case $S = 0.39$, $\dot{V} = 20m^3/h$, $\lambda = 1.0$. Though the axial velocity of the isothermal flow field changes with the distance from the nozzle exit the flashback takes place at a rather constant propagation velocity. The flame tip velocity determined with the PDF-model is $u_{tip} = 0.78m/s$, the FSD-model results in a velocity of $u_{tip} = 0.42m/s$. For other operational cases the PDF-model tends to overestimate the experimentally determined propagation velocity by a factor of two. However, the flashback is a stochastic process and several simulations with high computational expense would have to be averaged for a more meaningful result.

5 Summary and Conclusions

Flame flashback by combustion induced vortex breakdown has successfully been simulated in a free straight vortex using Large-Eddy-Simulation with two different combustion models. After the ignition

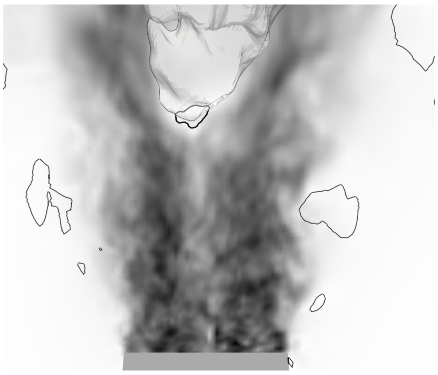

Figure 3: Snapshot during a CIVB flashback. Contours of velocity magnitude, recirculation zone marked with an isoline of zero axial velocity and flame front marked by the surface of $\tilde{c} = 0.5$.

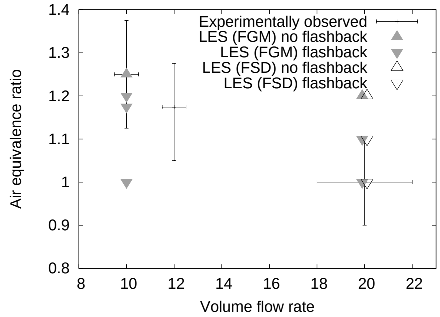

Figure 4: Simulated and experimental flashback limits

above the nozzle exit at a sufficiently rich mixture the flame induces a vortex breakdown whose recirculation zone pulls the flame upstream. The limits of the air equivalence ratio for which a flashback occurs have been determined and good agreement with experimental limits has been found.
The combustion models differ in the reproduction of the flashback process. The upstream propagation takes place faster with the PDF-model than with the FSD-model. However, the propagation velocity from the FSD-model depends on the modelling constant. Future work will focus on the subgrid modelling for the FSD-formulation to gain more independence from the model tuning.

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