Flashback caused by CIVB in a free straight vortex

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1 Introduction

Interaction between vortices and flame has attracted attention of specialists for a long time as a problem of fundamental importance for understanding of flame propagation mechanisms in turbulent flows. A long time, effect of turbulent fluctuations induced by vortices was considered as the main mechanism of the flame propagation enhancement in turbulent flows. Recently, a new interesting mechanism of the vortex-flame interaction was observed in the premixed combustion. It has been revealed that the flame can rapidly propagate along the vortices much faster than in surrounding premixed media [1,2]. This observation can substantially supplement or even change our concepts on mechanisms of flame propagation in turbulent media. It was revealed that the vortices can play a role of flame conductors increasing the flame propagation speed substantially. Later, it was found that this phenomenon, the **Combustion Induced Vortex Breakdown (CIVB)** is not only of pure academic interest, but can take place in various combustion devices. One example is the combustion chamber of gas turbines. Due to progressively more demanding emission limits, stationary gas turbines utilize premixed combustion chambers. The flame in this case is aerodynamically stabilized in a vortex which is forced to break down at a certain location inside the chamber. The practical experience shows that the instabilities in form of flame flashback into the mixing apparatus in front of the combustion chamber may occur and negatively influence the safety of the gas turbine operation. The origin of this phenomenon is the same as the origin of the rapid flame propagation along small turbulent vortices.

2 Object and Methods of Investigation

The aim of the current work is study of premixed flame propagation along an unconfined, straight vortex. The vortex generated by the swirl generator device (see Fig.1 and the description in [3]) was steady and fully turbulent with a strong inner axial flow (swirled jet). The swirl number S, defined by

$$S = \frac{\dot{D}}{\dot{I} R_{ref}} \qquad \text{with} \qquad \dot{D} = \int_0^R 2\pi\rho\, u_{\tan} u_{ax} r^2 dr \qquad \dot{I} = \int_0^R 2\pi\rho\, u_{ax}^2 r dr$$

where R_{ref} is a reference radius and the integral is over some reference plane, which is orthogonal to the vortex axis, e.g. the nozzle exit plane of the swirl generator device, was varied from S = 0 to 2,3.

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The jet consisting a methane-air mixture with a selectable equivalence ratio θ was ejected into the ambient surrounding air.
The premixed medium inside of the vortex was ignited at some distance above the swirl generator either by an electric spark or using a ring burner hold a stationary flame. The flame propagation is recorded by high speed video films and also simultaneous OH-LIF/PIV measurements have been performed.
Since only integral parameters of the flashback event could be retrieved from experiments, numerical simulations were performed to get a deeper insight into the flow physics. The large eddy simulation (LES) technique was applied since it is expected to be generally more accurate and requires less modelling effort than unsteady Reynolds-Averaged Navier-Stokes (URANS) based techniques. All simulations presented below were carried out using the open source PDE solution framework OpenFOAM. The presumed-PDF model based on ILDM reduced chemistry [4] was applied as the combustion model.

3 Results

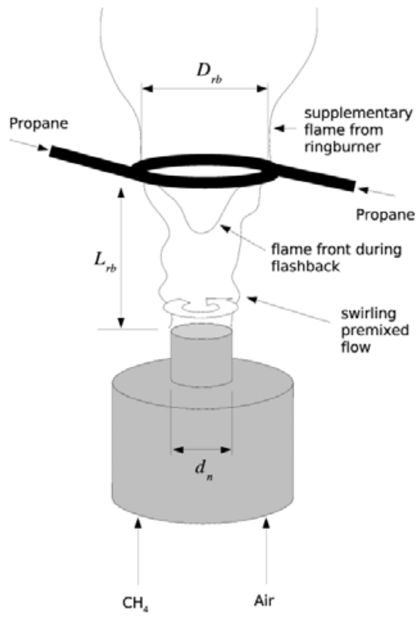

Figure 1: Sketch of experimental setup.

The swirled jet can experience a vortex breakdown even in an isothermal flow if the swirl number high enough. Since the aim of this work is the study of the breakdown caused by pure combustion mechanisms, in the first stage of the investigations a range of the swirl numbers S and volume flow rate V° through the swirl generator were established at which the vortex breakdown and the recirculation inside of the vortex were impossible. It has been done from analysis of PIV measurements performed in the isothermal flow. Further investigations with combustion have been done within this range of S and V°. Details of this study can be found in [3]. To show that CIVB exists in a free vortex, the flame propagation was documented using high-speed camera (125 frames per second) films. The flame propagation against the main flow direction and towards the swirler nozzle was observed under certain conditions. The CIVB at a flow rate of 12 m^3/h is shown in Figure 2 for different time instants. The same trend as in the experiment can be seen in the numerical simulations (Figure 3). The velocity field is shown by contours of the axial velocity. It is recognizable, that there is a spot of negative axial velocity in front of the flame tip. This is a remarkable feature of the CIVB as pointed out in [1].
The flame front in experiments can be detected from the OH field. Figure 4 demonstrates a snapshot of simultaneous measurements of velocity field by PIV and the OH concentrations using LIF. As seen the velocity in front of the flame is much lower than in other parts of the flow above the nozzle. The measurements show that the flashback is a stochastic event and it is hard to quantify the influence of parameters on the propagation velocity because there is also uncertainty in the experimental boundary conditions in a free vortex. The right image of figure 4 shows the flame front clearly seen in the OH-concentration field.

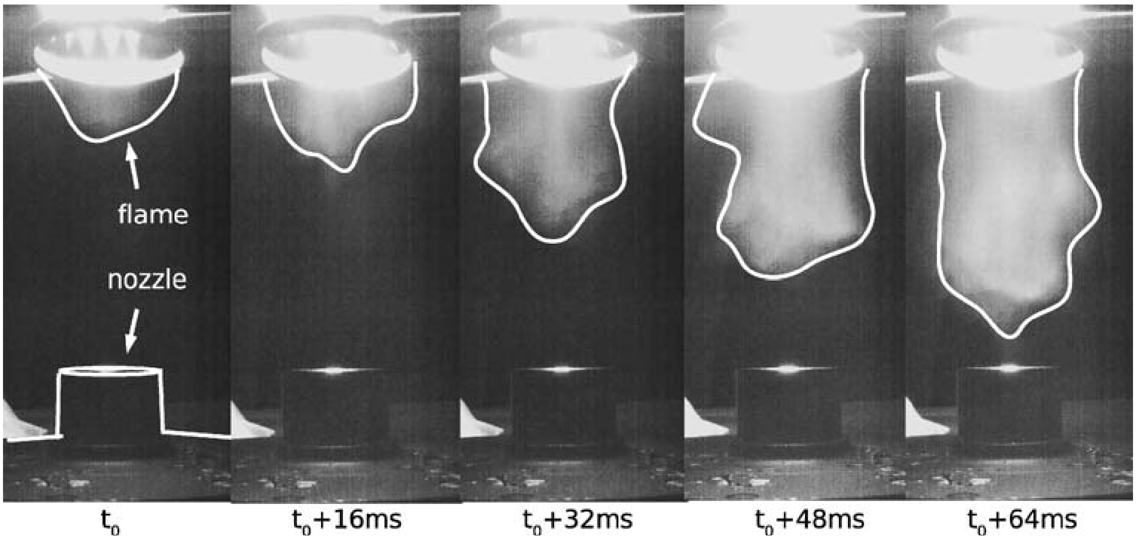

Figure 2: Flame propagation after increasing the swirl number to the critical value

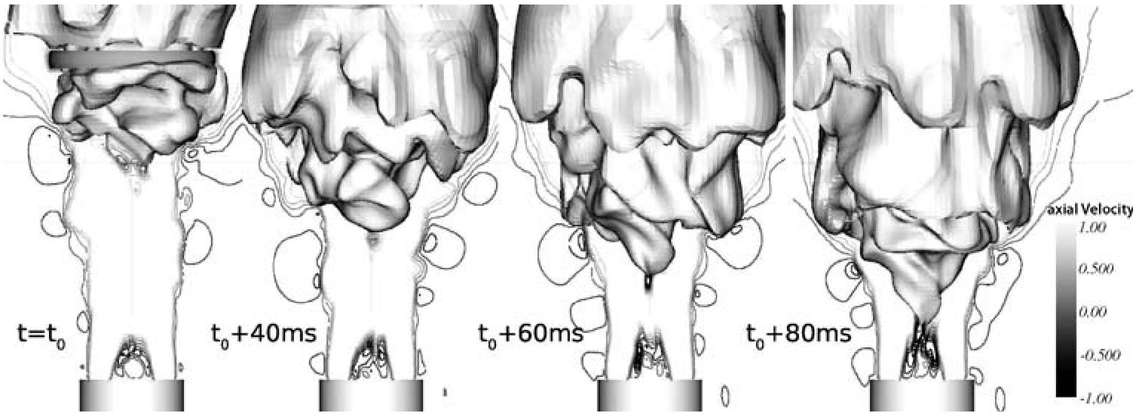

Figure 3: Flame propagation during the LES simulation

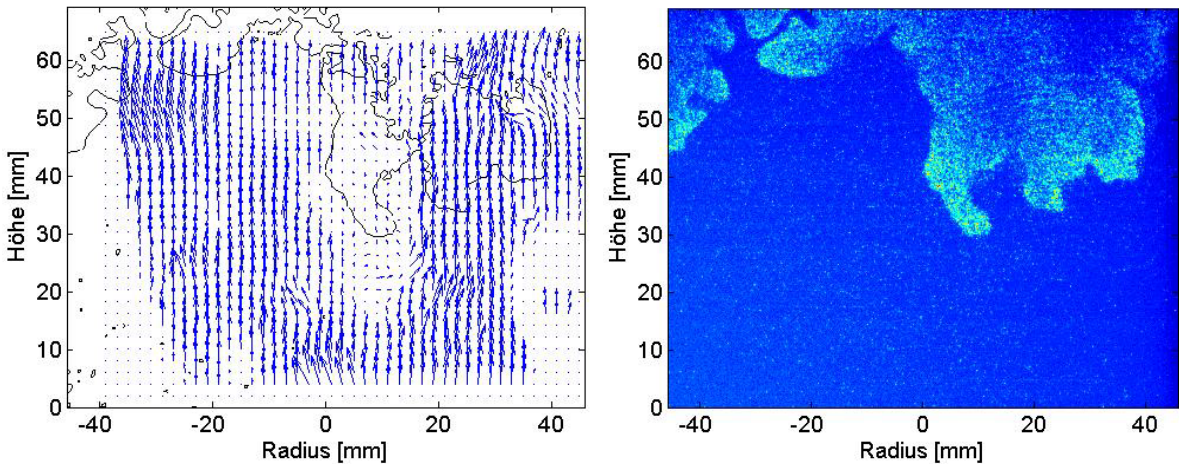

Figure 4: Simultaneous PIV/LIF snapshots of propagating flame during CIVB at V°= 12m³/h and S = 0,49. The left image shows isocontours of OH-concentration together with velocity vectors from PIV. The right image shows the corresponding raw OH-LIF image.

4 Conclusions

Appearance of the Combustion Induced Vortex Breakdown (CIVB) was demonstrated for a free straight vortex formed by a swirling jet. The swirling jet containing the air premixed with methane is injected from the nozzle of a movable block burner into ambient surrounding air. The flow in the vortex is unconfined, steady and full turbulent with an essential inner axial component. Velocity measurements performed in the isothermal flow using the PIV method show that the vortex is stable and the flow inside the vortex has rotational and positive axial components. The vortex breakdown and recirculation flows were not observed. If the jet is ignited by a ring burner at a certain height above the nozzle the flame can propagate along the vortex against the axial flow. Two different sorts of the flame flashback were identified. First, the flame propagates against the main flow direction if the equivalence ratio is increased (the premixed fuel becomes rich). In this case the flame is developing on the boundary of the jet where the axial velocities are negligible. This phenomenon is a common partially premixed combustion and has nothing to do with the CIVB. The CIVB takes place if the swirl number exceeds a certain threshold at a constant value of the equivalence ratio. The flame overcomes the positive axial flow and rapidly propagates towards the jet nozzle. As follows from the analysis of pictures taken by a high speed camera the flame has a conical tip, which is typical for the CIVB. This phenomenon was also simulated numerically using the Large Eddy Simulation. LES simulation clearly shows the appearance of a small area of negative axial velocities in front of the flame tip. This is a remarkable feature indicating the presence of the CIVB. Analysis of the LES data points out that the flame propagation against the main flow occurs mostly by induction effects caused by the circumferential vorticity appearing due to the radial expansion of the vortex tube (see [3],[5]). The expansion causes a strain field spiraling the vorticity field. On the contrary, the vorticity appearing due to the volume expansion caused by the combustion counteracts the flame flashback. Simultaneous measurements of the velocity and the OH concentration fields have been performed using combined PIV and LIF. They can provide new information for a more detailed investigation of the CIVB phenomenon and LES models assessment.

References

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