Interaction of Heat Release and Vortex Breakdown in Swirling Flames

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Abstract The interaction of heat release by chemical reaction and the flow dominates flame transition in swirling flows caused by Combustion Induced Vortex Breakdown (CIVB). The simultaneous application of 1 kHz high speed Particle Imaging Velocimetry (PIV) for the analysis of the flow field and OH Planar Laser Induced Fluorescence (PLIF) for the detection of the flame front is particularly useful for the improvement of the understanding of the observed fast CIVB driven flame propagation. For the first time, the combination of both techniques was successfully applied to confined swirling flows. In the study, the flow field characteristics of an aerodynamically stabilized burner system with CIVB are analyzed in great depth. The influence of geometric parameters of the swirl generator was investigated and conclusions concerning the proper burner design of vortex breakdown premix burners are drawn from the experimental results. In particular, the effect of the vortex core with respect to the stability of the swirl stabilized burner is analyzed. The contribution of combustion to vortex breakdown is shown comparing isothermal and reacting flows. Flame stability as well as the vortex core precession are discussed. The presented data reveals that at the onset of CIVB driven flame transition the azimuthal vorticity leads to the formation of a closed recirculation bubble at the tip of the internal recirculation zone. Once this bubble propagates upstream, the flame is able to follow and to propagate relative to the bulk flow velocity with a velocity far beyond the turbulent flame speed. The interaction of reaction and flow was observed for different volumetric heat releases. The experiments confirm the CIVB theory of the authors, which was initially developed on the basis of a CFD study alone: The volume expansion as well as the baroclinic torque, both have an effect on whether fast flame propagation occurs above a certain thermal power. Whereas the volume expansion caused by the heat release stabilizes the flow field and the reaction, respectively, the baroclinic torque stimulates flame transition. For upstream propagation the flame tip has to have a position downstream of the stagnation point of the bubble. Else, the required transition inducing force is insufficient and the flame remains stable. In case the flame reaches positions too close or even upstream of the stagnation point, the fast propagation is interrupted or even prohibited. The key finding that the relative position of flame and stagnation bubble governs CIVB is discussed on the basis of high speed LIF/PIV data as well as chemiluminescence. Since essentially the same behavior has been observed before in tests of a totally different swirler design and flow field, the conclusion can be made that the root cause for CIVB independent of the special geometry has been found.

1. Introduction

Lean premixed combustion is one of the most successful methods for reducing emissions of burner systems. Unfortunately, this combustion method has a major disadvantage, which non-premixed combustion systems have not to deal with: Transient flame behavior caused by instabilities cause fluctuations of heat release and thus additional emissions or even an undesired increase of flame propagation velocity, which can lead to sudden flame flashback. The latter phenomenon represents the most severe system failure, because of the risk of overheat of upstream positioned burner components and subsequent. For this reason, the transition of the flame has to be avoided for any operational conditions. In reacting flows with swirl Combustion Induced Vortex Breakdown (CIVB) has been identified as one source of sudden flame transition in swirl stabilized combustors, but the root cause of the flow transitions has not yet been fully understood. As previous investigations showed (Duwig and Fuchs 2007, Konle et al. 2007), CIVB is influenced by the interaction of the chemical reaction and the flow field. The contribution of this paper is the detailed
experimental analysis of this interaction not only for the stable case but also for the sudden transition of the reacting flow. Due to the availability of high speed PIV and LIF laser systems, it was possible to observe the transient behavior of the highly turbulent swirling flow field and the flame simultaneously with high temporal resolution. For the first time such measurements were extended to the case of confined swirling flows. The main purpose of the paper is the validation of the theory of CIVB developed by (Kiesewetter et al. 2007) on the basis of a numerical study. The theory will be experimentally confirmed with simultaneously acquired high speed PIV and LIF data. Furthermore, comprehensive data regarding the influence of the reaction on vortex breakdown will be presented.

The following section will explain the fundamentals of the CIVB theory first. Then, the significance of the flame position relative to the stagnation point of the recirculation bubble will be discussed and the influence of heat release on the azimuthal vorticity will be explained. The third section will present the investigated burner geometry and the instruments applied. How high quality data can be successfully acquired in the difficult case of enclosed flows with swirl despite low signal-to-noise ratios is explained in some detail. The fourth section will present the experimental results of the CIVB investigations, before finally conclusions are drawn and an outlook will be given.

2. Background

For compact high efficient combustion, modern gas turbine combustors use high swirl levels. The additional tangential velocity component creates shear and turbulence and provides the recirculation zone downstream of the burner exit plane required for flame stabilization. Burners without fuel lance on the centerline that provide bluff body flame stabilization require an alternative method for flame holding. For this purpose vortex breakdown has been successfully applied. Figure 1 illustrates the basic principle: The closed vortex flow in the burner mixing tube breaks down inside the combustion chamber close to the burner exit. The upstream directed flow creates a zero-velocity-line, which characterizes the bubble boundary. In the premixed and reacting case the flame anchors at the burner axis near the upstream end of this vortex breakdown bubble and is stabilized in a tulip shaped region with velocities in the range of the turbulent flame speed of the flame.

![Fig. 1 Numerically calculated axial flow velocity and scheme of the investigated burner: The isoline for zero velocity illustrates the contour of the vortex breakdown bubble, the colored field illustrates the axial velocity component. The scheme illustrates the geometric parameters (burner exit diameter D, open slot length s of the swirl generator, center bore hole diameter d) and the internal recirculation zone (IRZ).](image-url)
Many burner systems use a central bluff body to produce the required zone of low flow velocity (Hasegawa et al. 2001) and to avoid any upstream propagation of the flame on the burner axis. But even the use of this technique does not guarantee the safe operation concerning the occurrence of CIVB driven flame transition (Noble et al. 2006). However, aerodynamically stabilized burner systems without such flow obstacles in the center are even more sensitive for CIVB. This type of geometry is investigated in this paper (Sect. 3). For low reactivity fuels flame flashback for this burner is in most cases caused by CIVB. The other causes of flame flashback, which are

- turbulent flame speeds which locally exceed the axial flow velocity or
- upstream flame propagation in wall boundary layers or
- strong periodic velocity fluctuations in the burner due to thermoacoustic instabilities

can be more easily avoided by proper design of the combustion system than CIVB. Flame transition caused by CIVB occurs against high flow velocities on the burner axis, far away from any surface and without any pressure fluctuation. Therefore, the appearance of CIVB is fundamentally different from the other three flashback types listed above.

Starting with a stable reaction downstream of the burner exit plane inside the combustion chamber, an increase of equivalence ratio and / or the change of mass flow can provide the necessary conditions for flame transition caused by CIVB (Konle et al. 2008). A stability map of the investigated burner is shown in Fig. 2. The notation of the different geometric combinations includes the burner diameter D, the open slot length s and the center bore hole diameter d in mm (Legend: D s – d).

![Fig. 2 Stability map of the investigated burner: Flame transition due to CIVB occurs after increasing the equivalence ratio above characteristic limits. The increase of swirl and the reduction of the vortex core radius reduce the area of stable operation (Sect. 4). The legend describes the geometric parameters in the form: D s - d (Fig. 1).](image)

The cause of vortex breakdown is the production of azimuthal vorticity (Brown and Lopez 1990). This vorticity component induces axial flow velocity against the main flow direction according to the law of Biot-Savart (Panton 1996). That the vorticity transport equation (equ.(1)) (Darmofal 1993) is best suited for the analysis of the occurrence of CIVB driven flame transition has been shown by (Kiesewetter et al. 2007).
\[
\frac{D\omega}{Dt} = \frac{\partial}{\partial t} (\omega) + (\bar{U} \cdot \nabla)\omega = (\omega \cdot \nabla)\bar{U} - \bar{U}(\nabla \cdot \omega) + \frac{1}{\rho^2} (\nabla \rho \times \nabla p) \tag{1}
\]

This version of the vorticity transport equation includes the terms for the stretching / tilting, the volume expansion and the baroclinic torque and neglects the contribution of dissipation and diffusion. The combustion induced terms of equ.(1), the volume expansion due to heat release (second term on the right hand side) and the baroclinic torque (third term), play an important role for the changes of azimuthal vorticity and the induced axial velocity, respectively (Kiesewetter et al. 2007).

\[\text{Fig. 3 Azimuthal vorticity changes during flame transition from a URANS computation: The snapshot taken during flame transition upstream through the mixing tube illustrates the resulting change of azimuthal vorticity and, separately, the changes due to volume expansion and baroclinic torque. The comparison of the lower two plots shows: The baroclinic torque induces negative vorticity near the centerline and thus stimulates flame transition due to CIVB. However, the production of positive vorticity due to volume expansion can compensate this negative production and thus inhibits any transition, if reaction is sufficiently intense in the zone close to the stagnation point.} \]

Figure 3 shows an example of the azimuthal vorticity changes during flame transition inside the mixing tube analyzed numerically for the investigated burner system. The volume expansion leads to production of positive azimuthal vorticity close to the flame tip (second plot in Fig. 3) and thus to the reduction of the induced velocity against the flow direction. The baroclinic torque generates negative vorticity (third plot in Fig. 3) and increases the upstream directed velocity. The sum of all three terms of equ.(1) (Fig. 3 top) shows that during the upstream transition of the flame a net production of negative azimuthal vorticity occurs near the axis at the flame tip. This leads finally to
the observed sudden upstream propagation of the recirculation zone through the mixing tube.

Stable operation conditions are achieved as long as the central recirculation zone is positioned downstream of the burner exit plane and does not penetrate the mixing tube. However, if the azimuthal vorticity change increases the induced upstream velocity and then leads to the generation of a zone of low velocity upstream of the point of flame ignition, the bubble is finally able to propagate into and through the mixing tube (Kiesewetter et al. 2007). The calculated velocity field in Fig. 1 shows the onset of the formation of such a low velocity zone. Flame transition is linked to the propagation of this bubble. Former investigations (Konle et al. 2007) showed that during upstream propagation the upstream stagnation point of the recirculation bubble and the flame tip are not exactly at the same axial position and that the flame is positioned a small distance downstream of the bubble tip. It has been found that the position and distribution of the heat release relative to the bubble determines the location of the upstream tip of the vortex breakdown bubble in stable operation and also in the onset of CIVB. In order to generate CIVB the distance between stagnation point and flame tip must provide favorable conditions for the generation of high negative vorticity due to the baroclinic torque and at the same time the opposite effect of the volume expansion must not reach the same order. If the reaction starts too close or even upstream of the stagnation point, the volume expansion term at least partially compensates the baroclinic torque. The positive change of the azimuthal vorticity reduces the induced force against the main flow. As the consequence, the upstream motion of the bubble and the flame are stopped and CIVB is inhibited. The important role of the ratio between vorticity changes due to volume expansion and baroclinic torque will be shown in more detail in Sect. 4.

3. Test Rig and Measurement Techniques

The configurations used in the study were derived from the swirler design of Burmberger et al. 2006. The tangential inlet ports for the main air provide the swirl required for the breakdown of the swirling flow downstream of the mixing tube. An additional axial jet is added on the burner axis for tailoring the velocity field (Fig. 1). More details on the influence of the open slot length s on the swirl level and of diameter d of the axial jet on the formation of vortex breakdown are given in Konle et al. 2008.

For the validation of the theory outlined above and the development of design criteria for more reliable burner systems on the basis of the governing mechanisms, the instantaneous positions of the upstream boundary of the closed recirculation bubble and the flame tip had to be simultaneously measured with sufficient temporal resolution. For this purpose the high speed PIV-PLIF combination developed earlier by the research group of the authors was applied. The optical access to the propagating flame was achieved by a mixing tube made of silica glass. From the investigation of open flames reported earlier (Konle et al. 2008) to measurements during transition with confinement the most challenging task was to get a satisfactory signal-to-noise-ratio for the measurements inside this tube. Two severe problems had to be solved, the quick deposition of titanium dioxide particles on the glass tube and the reflections of the PIV- and PLIF-laser pulses at the glass tube surface, superposing the Mie-signal for the velocimetry measurements and the OH*-fluorescence signal for flame front detection.

The wavelength of the LIF-laser 283 nm was suppressed by an optical filter and only the signal of the detected signal at 308 nm was recorded. The problem of PIV-laser reflections was solved by sequent creation of artificial background images. The signal of light scattering at the glass tube as well as the reflected light at the seeding film inside the tube, both could be subtracted from the images by this technique. Figure 4 illustrates the procedure. On the right hand side of Fig. 4 the axial velocity profile for x/D = -2 (i.e. 80 mm upstream the burner exit) is plotted. With background subtraction the expected shape of the velocity profiles was reproduced, whereas processing of the original data delivers large errors, because fixed patterns stemming from the interaction of the laser
light with the glass tube and the deposits cannot be fully suppressed and deliver velocity deficits. Finally, the optimized data evaluation procedure allowed the acquisition of the velocity field inside the tube. More detailed general information about the simultaneous application of particle imaging velocimetry and planar OH laser induced fluorescence are included in (Konle et al. 2008).

Fig. 4 Difficulties encountered during the PIV measurements in the mixing tube: Laser light reflections at the glass surface and at the opaque film of deposited seeding particles inside the tube mask the Mie-signal of the particles suspended in the flow and require post-processing of the raw images (left hand side) before correct velocity profiles of the confined flow are obtained. The right plot displays an example of an axial velocity profile inside the tube at x/D = -2 for the evaluation of original and post-processed images.

The characterization of the flow fields alone and the analysis of the interaction between heat release and vortex breakdown, respectively, required two different procedures:

- Flow field characterization: The analysis of the undisturbed flow field inside the mixing tube was done in two steps. An axial light sheet was used to measure the flow field at stable operation points in the middle plane. Figure 5 illustrates this measurement plane (r₀-plane). In addition, light sheets orthogonally to the burner length axis (Fig. 5 right hand side) were used to measure the tangential velocity component. Figure 5 shows a chemiluminescence sequence of a propagating flame for illustration of the measurements planes. The four snapshots have a time separation of 12.5 ms. The size and shape of the internal recirculation zone as well as of the closed and propagating recirculation bubble are also shown.

- Interaction of reaction and flow field: For the analysis of the interaction between heat release and flow, upstream flame propagation driven by CIVB was initialized by increasing the equivalence ratio (see Fig. 2). The positions of stagnation point and the flame tip were acquired in the middle plane (r₀-plane in Fig. 5). The variation of the volumetric heat release was realized by increasing the equivalence ratio with different rates of change after reaching CIVB prone operation conditions. The bulk flow velocity was unaffected by this procedure.
4. Results

4.1. Flow field characteristics

For the characterization of the flow field inside the mixing tube the axial and the tangential velocity profiles at different positions were measured. In Fig. 6 these profiles are shown for isothermal flow and the configuration 4022-12.0. The mass flow of 1100 l/min and the bulk velocity of 14.5 m/s correspond to the operating point with $P_{th} = 40$ kW thermal power and equivalence ratio $\Phi = 0.625$. The swirl number is $S = 0.5$ for this configuration.

![Fig. 6 Axial and tangential velocity profiles for the configuration 4022-12.0: The illustrated isothermal operation point corresponds to $P_{th} = 40$ kW thermal power and an equivalence ratio $\Phi = 0.625$.](image)

Obviously, the vortex breakdown at the burner exit affects the flow inside the tube. The axial jet is strongly decelerated inside the mixing tube. Already at the position of $x/D = -1.0$, i.e. 40 mm upstream of the burner exit inside the mixing tube, the velocity overshoot in the axial jet is almost completely lost. Further downstream the decrease of the axial velocity indicates that the flow approaches the stagnation point of the IRZ. The tangential velocity profiles (absolute values in Fig. 6, right hand side) illustrate the evolution of the vortex core radius. This characteristic value was defined as the radius of maximum tangential velocity. For the velocity profile at $x/D = -2.5$ (undisturbed region without influence of the vortex breakdown) this radius is about $r_{vc}/D = 0.2$. Its size increases in longitudinal direction up to $r_{vc}/D = 0.3$ at $x/D = -0.5$. This evolution reveals the upstream influence of strong stretching of the streamlines due to vortex breakdown (Kiesewetter et al. 2007) on the flow field.
Fig. 7 Axial and tangential velocity profiles for the configuration 4022-9.0: The variation of the diameter d (Fig. 1) reduces the vortex core radius about 25%.

Figure 7 illustrates the axial and tangential velocity profiles for the configuration 4022-9.0. Compared with the data of 4022-12.0, the most important two observations are that the vortex core radius decreases to $r_{vc}/D = 0.15$ and that the swirler does no longer produce the velocity overshoot in the center of the flow that was clearly visible in configuration 4022-12.0 (Fig. 6). The importance of the vortex core radius is shown in the stability map in Fig. 2: Reducing the central diameter d from 12 mm to 9 mm decreases the critical equivalence ratio and reduces the regime of safe operation without flashback. This shows that the burner stability is influenced significantly by the axial jet on the centerline. Widening the vortex core radius moves the vortex breakdown more downstream and thus increases the critical equivalence ratio required for the penetration of the mixing tube by the transient flame.

The swirl level of the main flow can also be used to tailor the isothermal flow pattern: Reducing the swirl level by increasing the open slot length s leads to a weaker vortex breakdown, shifts the position of the IRZ further downstream and increases the critical equivalence ratio for CIVB (Fig. 2). However, the reduction of swirl increases flame length, an undesired effect in most cases, which does not allow to fully exploit the second measure for burner design.

Although for configuration 4022-12.0 the net production of negative azimuthal vorticity is insufficient to initiate CIVB at the operation point $P_{th} = 40$ kW thermal power and $\Phi = 0.625$ (stability limit $\Phi_{crit} = 0.6$, Fig. 2), the reaction influences the flow field. The axial velocity profile at $x/D = -0.5$ for the isothermal and the reacting cases are compared in Fig. 8. The contribution of the reaction to the vorticity budget has an influence on the flow in the mixing tube near the exit. It decelerates the flow on the axis substantially stronger than for the non-reacting flow, indicating that vortex breakdown is shifted upstream due to heat release. An interesting detail is that this deceleration induces a velocity overshoot at $r/D = +0.2$. 
Fig. 8 Axial velocity profiles at x/D = -0.5: The comparison of the isothermal flow and the reacting case shows the influence of the reaction even for stable operation conditions (same conditions as Fig. 6).

The measurements of the tangential profiles additionally revealed a precessing vortex core (PVC) with a frequency of about 180 Hz. As shown earlier by (Kiesewetter et al. 2007), CIVB as such is a two dimensional effect and not governed by 3-dimensional effects. However, PVC influences the stochastic downstream motion of the flame in the transitional regime. This was already reported by (Fritz et al. 2004, Kröner et al. 2007).

4.2. Influence of volumetric heat release

As explained in Sect. 2, volume expansion due to volumetric heat release changes azimuthal vorticity. In order to analyze the interaction of reaction and flow, in Fig. 9 the simultaneously acquired positions of the flame tip and the upstream stagnation point of the recirculation bubble during upstream propagation are plotted for $P_{th} = 60$ kW and configuration 4022-12.0. Each test sequence started with equivalence ratio of $\Phi_{start} = 0.625$. Then, the volumetric heat release rates were increased with different gradients (Sect. 3).

The left hand side of Fig. 9 represents the upstream propagation of the bubble through the mixing tube at an equivalence ratio close to the critical value $\Phi_{crit} = 0.65$ (very low equivalence ratio gradient). The transition of the bubble initiates the propagation of the flame, the flame anchors at the bubble and follows the bubble tip with a deviation between 0.1 and 0.5 tube diameters. Since both positions are always well separated, no direct interaction between flame and bubble tip takes place.

The right hand side of Fig. 9 presents the macroscopic upstream propagation of the flame through the entire mixing tube for a faster equivalence ratio gradient. Although the upstream propagation due to CIVB is initiated by the same limit $\Phi_{crit}$ predetermined by the geometry and the operation conditions, an equivalence ratio larger than the critical limit ($\Phi > \Phi_{crit}$) is reached during upstream propagation. Thus, the volumetric heat release at the flame tip is higher than for the first case. In the beginning, this results in a direct interaction between flame and bubble tip, the flame propagates closer to the stagnation point and an oscillatory motion is observed. The required time for the upstream propagation is another indication for a stronger interaction of reaction and flow: While the undisturbed transition (left hand side of Fig. 9) passes through the whole observation section of the mixing tube within a time of 28 ms, the stronger interaction slows down the mean propagation speed and the total upstream propagation takes about 40 ms.
Fig. 9 Upstream propagation of bubble and flame: Initial conditions were $P_{th} = 60$ kW thermal power and equivalence ratio $\Phi_{start} = 0.625$ (near the characteristic transition limit of $\Phi_{crit} = 0.65$ for configuration 4022-12.0, see Fig. 2).

CIVB for configuration 4022-12.0 was investigated at $P_{th} = 40$ kW thermal power with even higher equivalence ratio gradients (Fig. 10). For $\Phi \gg \Phi_{crit}$ and thus very high volumetric heat release rates compared to the one at the stability limit, the reaction zone and bubble tip are closely linked together and cannot separate during flame propagation. This slows down the mean propagation speed to a very low level. The total time for upstream propagation increases to 80 ms.

Fig. 10 Upstream propagation of bubble and flame: Initial conditions were $P_{th} = 40$ kW thermal power and equivalence ratio $\Phi_{start} = 0.6$ (near the characteristic transition limit of $\Phi_{crit} = 0.625$ for configuration 4022-12.0). The steep equivalence ratio gradient ($\Phi \gg \Phi_{crit}$) initiates very intensive interaction of bubble tip and flame.

Results of a chemiluminescence signal analysis of propagating flames are illustrated in Fig. 11. This figure displays the propagation speed distribution for thermal powers of $P_{th} = 40$ and 60 kW. Positive propagation speeds indicate downstream shift due to the interaction of the flame front with the bubble tip, which is present at both operation points. While the flame propagates through the mixing tube the upstream motion is frequently interrupted. The measurements show that the mixture mass flow does not influence the interaction. All findings from the chemiluminescence measurements are in line with the results from PIV/LIF.
Fig. 11 Probability density function of flame propagation speed: Distribution of the propagation speed for two operation points (configuration 4022-12.0 at $P_{th} = 40$ kW, $\Phi = 0.65$ and $P_{th} = 60$ kW, $\Phi = 0.69$). The average propagation speed for both cases is negative because of the macroscopic upstream flame propagation.

5. Conclusions and Outlook

The presented study of flame transition caused by CIVB using high speed measurement techniques allowed the analysis of the conditions for the onset of CIVB as well as the investigation of the transient behavior during flame propagation. The following conclusions can be drawn:

- The comparison of axial velocity profiles upstream of the burner exit for the reacting and non reacting cases shows that premixed combustion influences vortex breakdown. The combustion induced production of azimuthal vorticity strengthens the breakdown of the flow. Sufficient net production of this vorticity component leads to the transition of the flow, followed by the propagation of the flame upstream (flashback). Isothermal configurations with stable vortex breakdown inside the combustion chamber do not guarantee general stability for the reacting case.

- As investigated in former studies (Fritz et al. 2003, Burmberger et al. 2006), with an additional core flow on the burner axis the stability of the flow field and the position of vortex breakdown can be influenced via the tailoring of the vortex core radius. An increasing of the axial jet diameter leads to thicker vortex cores and strengthens the axial jet flow on the axis. Accordingly, vortex breakdown is shifted downstream. In summary, the increase of the vortex core radius stabilizes the operation window of burners with flame stabilization by vortex breakdown.

- The interaction of heat release and vortex breakdown is responsible for flame propagation due to CIVB. Under favorable conditions, the azimuthal vorticity production can initiate the formation of a closed bubble and its upstream transition into the burner. Whether this bubble propagates with the flame upstream depends on the flame position and the heat release distribution with respect to the upstream bubble tip.

- The two terms of the vorticity transport equation, which occur only in the reacting case represent the volume expansion and the baroclinic torque, respectively. Both terms compete with each other. Bubble formation and transition requires that the vorticity production due to the baroclinic torque dominates over the volume expansion.

- In summary, all experimental results are in line with the theory Kiesewetter et al. 2007 developed on the basis of a numerical study.
In the next step a numerical analysis of the investigated configurations will be carried out with the main focus on the spatial separation between stagnation point and flame tip.

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References


