Flashback in a Swirl Burner With Cylindrical Premixing Zone

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Flame flashback from the combustion chamber into the mixing zone is one of the inherent problems of lean premixed combustion and essentially determines the reliability of low NO_x *burners. Generally, flashback can be initiated by one of the following four phenomena: flashback due to the conditions in the boundary layer, flashback due to turbulent flame propagation in the core flow, flashback induced by combustion instabilities and flashback caused by combustion induced vortex breakdown. In this study, flashback in a swirling tubular flow was investigated. In order to draw maximum benefit from the tests with respect to the application in gas turbines, the radial distribution of the axial and circumferential momentum in the tube was selected such that the typical character of a flow in mixing zones of premix burners without centerbody was obtained. A single burner test rig has been designed to provoke flashback with the preheating temperature, the equivalence ratio and the mean flow rate being the influencing parameters. The flame position within the mixing section is detected by a special optical flame sensor array, which allows the control of the experiment and furthermore the triggering of the measurement techniques. The burning velocity of the fuel has been varied by using natural gas or hydrogen. The characteristics of the flashback, the unsteady swirling flow during the flame propagation, the flame dynamics and the reaction zones have been investigated by applying high-speed video recordings, the laser Doppler anemometry and the laser induced fluorescence. The presented results show that a combustion induced vortex breakdown is the dominating mechanism of the observed flashback. This mechanism is very sensitive to the momentum distribution in the vortex core. By adding axial momentum around the mixing tube axis, the circumferential velocity gradient is reduced and flashback can be prevented.* [DOI: 10.1115/1.1473155]

Flashback in Premixed Combustion Systems

In order to achieve low NO_x emissions, the lean premixed combustion is often used in stationary gas turbines. Because of their excellent flameholding, burnout and emission characteristics swirling flames are almost exclusively used in gas turbine combustion systems. The superior performance of swirling flames stems from the high turbulence level in the mixing zone and the generation of a radial pressure gradient in the burner exit, which leads to a stable recirculation zone with strong backflow of hot gases. Since both effects depend upon the swirl intensity, gas turbine burners are usually high swirl designs. An important upper limit for the aerodynamic design of the swirl generator is given by the transition of the vortex breakdown from the combustion chamber into the burner with the formation of recirculation zones in the mixing chamber. According to the usual design practice, the swirl number and the radial swirl distribution is selected such that for the nonreacting flow a sufficient margin against the propagation of the vortex breakdown in the core flow into the burner is obtained. The feedback of the chemical reaction on the flow field is usually not considered in the basic aerodynamic phase of the design procedure.

First of all, the reliability of swirl burners is determined by its capability to prevent flashback in normal operation. In addition, fail safe designs must be able to recover from flashback without damage due to thermal overheat. To date, a detailed understanding of the governing mechanisms for flashback in turbulent swirling flows has not been established, although the precise description of the limits is a prerequisite for the design of reliable premix burners operating under severe pressure and temperature.

In general, four flashback causes can be distinguished:

- flashback in the boundary layer,
- turbulent flame propagation in the core flow,
- flashback due to combustion instabilities, and
- combustion induced vortex breakdown.

Flashback in the Boundary Layer. Low flow velocities in the boundary layer promote the upstream flame propagation whereas the heat loss to the wall can cause flame quenching. For laminar flows, Lewis and von Elbe [1] balance the velocity gradient g at the wall with the laminar flame speed S_L divided by the quenching distance d_q as the flashback criterion.

$$g=-\left.\frac{\partial u}{\partial r}\right|_R=\frac{S_L}{d_q} \tag{1}$$

According to Eq. (1) a critical velocity gradient $g<S_L/d_q$ leads to upstream flame propagation near the wall. In order to generalize the experimental results, a dimensionless relation was proposed as a flashback criterion ([2]). In this framework, the balance of the downstream convective transport and the upstream flame propagation with heat loss to the wall is expressed in terms of Peclet numbers. The velocity gradient is replaced by an average velocity and a characteristic length scale. Although the theories can also be formally applied to turbulent boundary layers, it is known that the same criteria do not apply in the turbulent case. The critical velocity gradient is much higher than the laminar one ([3]), since the axial turbulent diffusion above the laminar sublayer increases the flame speed.

This type of flashback is often predominant in nonswirling low-turbulence flows.

Turbulent Flame Propagation in the Core Flow. If the turbulent burning velocity exceeds the local flow velocity in the core

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Contributed by the International Gas Turbine Institute (IGTI) of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS for publication in the ASME JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER. Paper presented at the International Gas Turbine and Aeroengine Congress and Exhibition, New Orleans, LA, June 4–7, 2001; Paper 01-GT-054. Manuscript received by IGTI, December 2000, final revision, March 2001. Associate Editor: R. Natole.

flow, flashback is the consequence. The turbulent burning velocity depends on the chemical kinetics and the turbulence structure, i.e., the length scales and the local velocity fluctuations. Many studies on the correlation of the turbulent burning velocity with the turbulent velocity fluctuations in the flow have been published (e.g., [4–7]). However, the results obtained from different correlations scatter widely and the proper determination of turbulent flame velocities remains a challenging task because of the complex interaction of turbulence and chemistry.

Swirling flames have a highly wrinkled and corrugated structure, which increases the flame surface considerably above the surface of a laminar flame. Mainly this effect is responsible for the increase of the turbulent flame speed above the laminar value. Whether distributed reaction zones or even well stirred local zones are of strong significance under gas turbine conditions could not be demonstrated yet. If these effects exist, they have an additional effect on the turbulent flame propagation. Turbulent burning velocities show a correlation with the laminar flame speed. This implies that, while burning fuels with high laminar burning velocities, burners with a low turbulence level are more appropriate than high swirl designs in order to receive a sufficient margin against flashback ([8]).

For stable fuels like natural gas at moderate mixture temperatures, flashback in the core flow is less critical even in highly turbulent flows due to the low laminar flame speed. A simple design rule for the optimum safety against flame propagation in the main flow is to avoid local zones of low axial flow velocity and wake regions ([2]) in the mixing zone.

Flashback due to Combustion Instabilities. Combustion instabilities can be responsible for the upstream flame propagation, both in the boundary layer ([9]) and in the core flow. The driving force for noise and pulsations in gas turbine combustion systems is the fluctuating heat release of the reacting mixture in the primary zone. Four different mechanisms can contribute to the noise spectrum peaks ([10]). First of all, the turbulent noise produces a background noise level. This broad-band excitation can be considerably amplified at the eigenfrequencies of the combustion system so that they produce distinct pulsation. Swirling flows particularly tend to form natural coherent flow structures like precessing vortex cores ([11]) or vortices generated near the transition from the mixing section into the combustion chamber. This second physical phenomenon can result in flow oscillations at specific Strouhal numbers even in the isothermal flow and leads to an amplification of the combustion noise if the excitation meets an eigenfrequency of the system. The third driving mechanism are forced coherent flow structures. They are observed if the flow instabilities respond to the triggering by velocity perturbations with subsequent phase-locking. The classical mode of unstable self-excitation is the fourth potential cause of pulsations.

High amplitudes of periodic flow velocity fluctuations at the burner exit, as a result of the mentioned instability mechanisms, lead to a periodic displacement of the reaction zone. The consequence is a periodic variation of the burner pressure loss, which again incites the oscillations. This feedback loop finally leads to periodic flashbacks. Pulsation initiated flashback requires a high pulsation level to occur, which is far beyond the acceptable noise levels of combustion systems. This kind of flashback can be interpreted as the final terminating step of a highly unstable combustion process after sufficient amplification.

Combustion-Induced Vortex Breakdown. Many gas turbine burner designs follow the basic philosophy to stabilize the flame in the combustion chamber and to avoid reaction within the burner. Burners with a centerbody or fuel lance provide a recirculation zone on the axis even without swirl. However, imposing swirl on the main flow leads to a strong amplification of the backflow of hot gases and a better flame stabilization. An advantage of designs with centerbody is that the swirl can be selected in a wide window, which is primarily limited by the propagation of the vortex breakdown upstream and the formation of a recirculation zone around the centerbody.

The experimental flashback study is focused on burners without fuel lance in the center of the mixing zone. The design of swirlers without centerbody requires a thorough tailoring of the swirling flow, since the flameholding capability depends entirely on the vortex breakdown without the aid of a bluff body. It can be shown that in tubular flows axial profiles with a jet on the axis are required for a stable transition of the vortex flow into its annular form in the combustion chamber. It is well known that a reduction of the swirl around the vortex core by friction or an abrupt change in the cross section leads to a pressure rise on the axis. The positive pressure gradient reduces the axial velocity in the vortex core, which at the same time effects an radial transport of angular momentum. Therefore the vortex core grows and again supports the positive pressure gradient ([12]). These effects govern the transition of the vortex from its closed into its annular form.

The formation of the vortex breakdown strongly depends on the geometry and the distribution of the axial and circumferential velocity. If the swirl number exceeds a critical value, the recirculation zone is able to extend itself throughout the entire mixing section. It is shown subsequently for the first time that even if the swirl number is well adapted to prevent this effect in the isothermal flow, the chemical reaction can nevertheless lead to a breakdown of the flow, combined with an upstream flame propagation. This effect could be observed in the present work as a characteristic flashback mechanism in swirling flows and henceforth will be called combustion-induced vortex breakdown.

Experimental Facility

The experimental facility, as sketched in Fig. 1, is essentially made up by three parts, the fuel/air premixing section (A), the swirl generator followed by a mixing tube (swirl burner B), and the combustion chamber (C).

The combustion air is preheated by electrical air heaters. To avoid any influence of equivalence ratio fluctuations or the fuel/air mixing quality on the flashback behavior, a multistage premixing section has been installed. Gaseous fuel, natural gas or hydrogen, is added to the air in a swirl mixer and the mixture subsequently passes a static mixer for fine scale mixing. For the laser Doppler anemometry, scattering particles (TiO_2) can be added upstream of the fuel injector, in order to achieve an optimum dispersion of the seeding in the flow.

A swirler generates the desired flow profile with an axial jet. The actual object of interest, the cylindrical fused silica quartz glass mixing tube, is fixed between the swirler and the combustion chamber. The optical access to the mixing tube exit zone is pro-

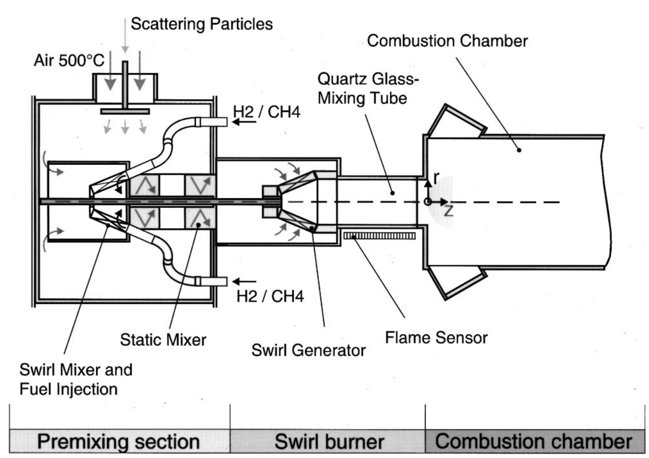

Fig. 1 Premixing section, swirl burner, and combustion chamber

vided by quartz windows. The combustion chamber itself is watercooled and protected by ceramic flame tubes inside.

The rating of the experimental facility is as follows:

air mass flow:	0.15 kg/s
pressure:	atmospheric
mixture temperature:	30°C–500°C
rated thermal power:	200 kW
fuel:	natural gas, hydrogen

In the tests, flashback was initiated by a continuous increase of the fuel mass flow at a constant air mass flow, starting from a stable operating point. The increase of the equivalence ratio allows for the control of the density ratio over the flame front. Moreover, the turbulent burning velocity is influenced indirectly via the increase of the laminar flame speed. Both effects are of importance for the flashback limits of gas turbine burners. The position of the flame in the mixing tube is detected by an optical flame sensor which is described in detail below. After the flashback has propagated through the entire mixing tube, the sensor shuts off the fuel supply. With natural gas as the fuel, flashback could not be observed as long as the flow speed and the equivalence ratio were selected in the typical range of gas turbine burners. For this reason, the equivalence ratio in the tests had to be considerably increased over engine values in order to provoke flashback.

Optical Measurement Techniques

To classify the observed phenomena with respect to the mechanisms listed above, it is of prime importance to obtain simultaneously experimental data of the flow field and the flame front position. In addition, to avoid any impact on the flow and the reaction in the mixing tube during the flashback non intrusive optical methods were applied.

Laser Doppler Anemometry (LDA). The laser Doppler anemometer used in the present experiments (two-dimensional Dantec LDA with BSA enhanced processors, 6 W Coherent Innova 90 argon ion laser, three-dimensional traverse system), was set up to measure coincidently the axial and circumferential velocity components in a horizontal plane through the mixing tube axis with high spatial and temporal resolution. To reach a high flexibility, it was employed in its off-axis forward-scattering arrangement. The receiving optics could be adapted to the refraction conditions at the cylindrical interfaces dependant on the radial measuring point and a small effective measuring volume as well as a sufficiently high signal to noise ratio could be achieved. Unlike the laser beams, for the axial velocity component, the refraction of the laser beams for the circumferential velocity component depends on the radial position of the measuring volume. Both, the fringe spacing and the real measuring volume position are altered. To take this into account, a correction factor published by Broadway and Karahan [13] can be applied. With the described setup the stationary flow fields as well as the unsteady flow behavior during the flashback were obtained from the LDA measurements.

High Speed Video. A Kodak Ektapro Motion Analyzer 4540 high speed video camera was applied to visualize the unsteady flame propagation and to get the current flame front position and shape. The recordings have been made at a frame rate of 4500 pictures per second. In case of firing natural gas, the natural fluorescence, mainly emitted by the CH radicals in the flame front (blue-violet range), produce sufficient light for CCD chip recordings.

When combined with LDA measurements, the strong scattered laser light from the scattering particles deposited at the mixing tube wall makes the precise evaluation of the video sequences very difficult. For this reason it was necessary to improve the imaging technique. A major improvement was achieved through filtering the visible light using a Schott UG11 filter. In addition, a two-stage image intensifier (Proxitronic) was attached to the high speed Camera. With this approach, effects of the scattered laser light and seeding could be completely eliminated and the natural flame fluorescence from the OH radicals could be recorded.

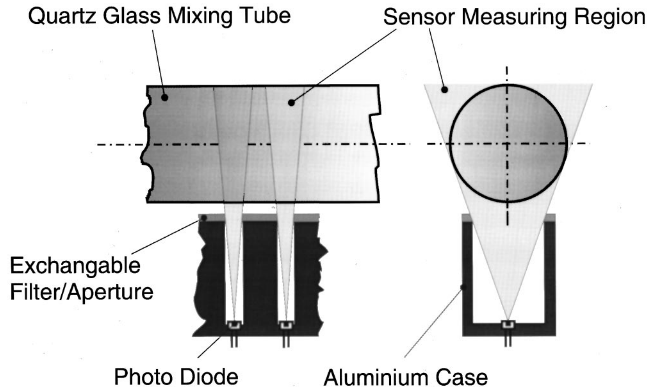

Fig. 2 Optical flame sensor for flashback detection

A software was developed to identify the flame front position automatically. Different digital image processing filters generate a binary picture from each video picture. For further data analysis, the flame front is identified and stored both as a function of the radial coordinate and time ([14]).

Optical Flame Sensor. The high speed video recordings give detailed information about the flame propagation, but unfortunately only over a limited time range of about 225 ms. For this reason, an optical flame sensor was developed for the observation of the flame dynamics over a longer measurement cycle with data rates up to 100 kHz (Fig. 2).

A row of photodiodes is placed along the mixing tube. The chosen photodiode is sensitive to radiation from the near UV to the blue-violet visible light. The analog output signals of all diodes are summed up to an analog signal, which is a measure for the current flame position. The sensor is calibrated by means of simultaneous recorded high speed video sequences. Furthermore the signal of each diode can be separately used to trigger other measurement techniques.

Laser-Induced Fluorescence (OH-LIF). The information provided by the high speed video recordings subsequently presented is always integrated over the depth of the mixing tube and this integration leads to a loss of the local flame structure. In order to obtain a better insight into the local structure of the flame during flashback, a triggered light sheet technique was applied in addition, which offers a spatially high resolution in two dimensions. The planar laser-induced fluorescence of the OH radicals in the reaction zone was selected to characterize the reaction zones of the flashback in great detail. The radicals were excited by a XeCl-excimer pumped dye laser (Lambda Physics EMG 201 and Scanmate 2 with Coumarin 153 dye) tuned to the $Q_1(6)$ line (283 nm) using the $A^2\Sigma^+ \leftarrow X^2\Pi(1,0)$ transition. This excitation has a better signal to noise ratio in comparison with the excitation in the region of 248 nm (KrF-excimer laser). This is of particular importance, since laser light scattering at the cylindrical mixing tube surface is difficult to avoid. The LIF images are recorded by an intensified CCD camera (LaVision Flamestar II). Laser light is cut off by a band pass mirror filter adjusted to 310 nm. During the OH-LIF measurements subsequently presented, the light sheet was located at an axial position of $-1.45D_i < z < -1.9D_i$. Therefore, a section of the flame front is depicted with a high optical resolution.

In the tests, either LDA or LIF have been combined with the optical flame sensor and the high speed camera in order to investigate the interaction between the flow field and the flame or between the structure of the flame front and the flame propagation, respectively.

Results and Discussion

Steady Swirling Flow Field. As will be shown later, it is advantageous to transfer the pressure loss of the swirler into a high axial velocity on the burner axis in order to prevent flashback. A special swirling flow with this attribute and a high circumferential velocity gradient in the vortex core has been used (burner configuration BC I, reference geometry). Figure 3 shows an example for the mean axial and circumferential velocity profile within the mixing tube (coordinate system see Fig. 1). The swirl generator is equipped with a variable orifice on the centerline, which allows the injection of an axial jet. As it is shown in Fig. 3, the axial and swirl momentum distribution near the axis can be influenced by opening the orifice (burner configuration BC II). This configuration leads to a lower mean circumferential velocity gradient in the vortex core. Simultaneously the axial momentum becomes slight higher at the axial position $z=-0.59\,D_i$. The r.m.s. values of the velocity fluctuations u' and w', normalized with the average velocity $\overline{u_a}$, show the high intensity of the turbulence in the swirling flow (Fig. 4). The abrupt increase of the velocity fluctuations towards the axis cannot be directly interpreted as turbulent fluctuations because of other influences such as the precessing vortex core. In the tests, the flashback limits of both configurations were investigated.

The velocity field was measured at different axial locations in the mixing tube. Figure 5 reveals a common characteristic property of tubular swirling flows: The changes of the velocity profiles in longitudinal direction is relatively weak, although a deterioration of the axial jet due to friction is clearly visible. From the axial velocity profile data, it can be seen in addition that the vortex breakdown in the isothermal flow is exactly located in the exit plane of the mixing tube.

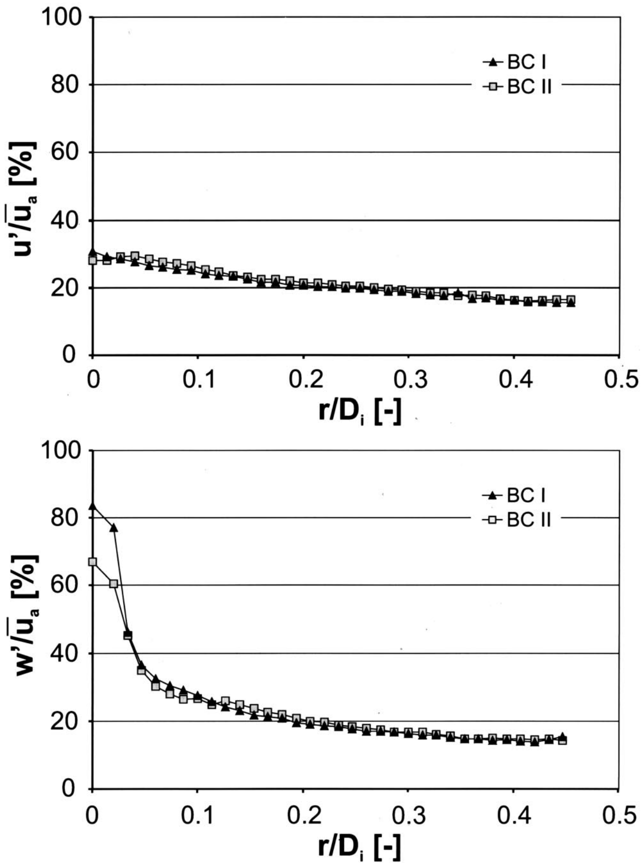

Fig. 4 Nondimensional r.m.s. of fluctuating axial and circumferential velocities $u'/\bar{u}_a$ and $w'/\bar{u}_a$ at $z=-0.59D_i$

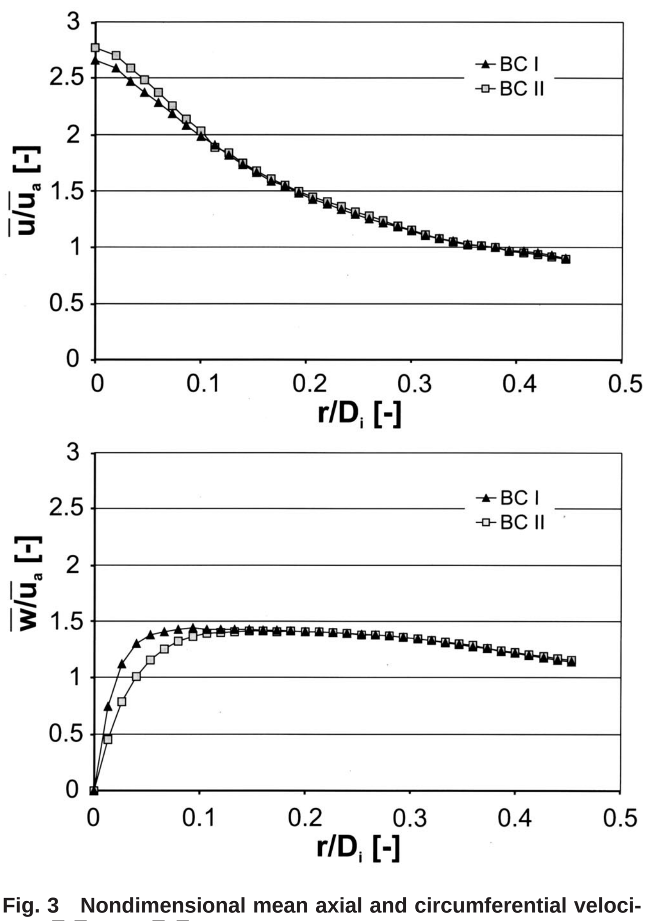

Fig. 3 Nondimensional mean axial and circumferential velocities $\bar{u}/\bar{u}_a$ and $\bar{w}/\bar{u}_a$ at $z=-0.59D_i$

Flashback Characteristics. Subsequently, the flashback behavior of burner configuration BC I will be discussed first. The data acquired by the simultaneous application of the optical flame sensor and the high speed video camera is especially qualified for illustrating the flame propagation process. The sensor signal in Fig. 6 shows the development of the flame position over a period of 900 ms. Obviously not a single flashback but rather numerous shiftings of the flame front characterize the flashback behavior. The extracted video sequences, presented in Figs. 7, 8, and 9 (cf. figure 6) show the flame propagation in the core flow with a high temporal resolution.

The propagation of the flame against the main flow direction starts with the formation of a flame needle near the axis. This needle penetrates the counterflow with a precessing motion (Figs. 7 *B*, *C*, *D* and 8 *B*, *C*). In some cases, vortices in the flow passing slightly off axis form a mushroom shaped flame tip (Fig. 8 *D*). This vortex interaction with the flame can lead to a separation of the flame tip from the downstream reaction zone (Fig. 8 *E*).

During the following flame evolution, a hot plug filled with combusting media is formed (Figs. 7 *G*, *H* and 8 *G*, *H*) and the flame propagation upstream either comes to rest or undergoes a further transition to a wedge shaped flame, which then propagates further upstream (Fig. 9). In the case of stagnation, the further process is not fully predetermined. The first mode is the repetition of the described process, which finally leads to a flashback through the entire tube. In contrast to this process, the second mode leads to the quenching of the reaction by the flow and to a

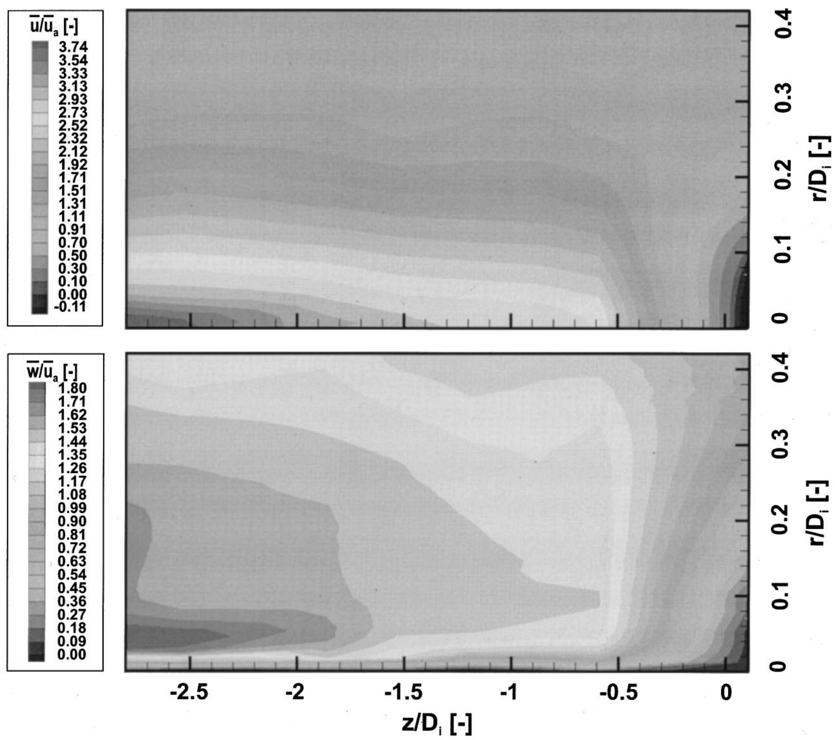

Fig. 5 Mean axial and circumferential velocity field $\bar{u}/\bar{u}_a$ and $\bar{w}/\bar{u}_a$ (BC I)

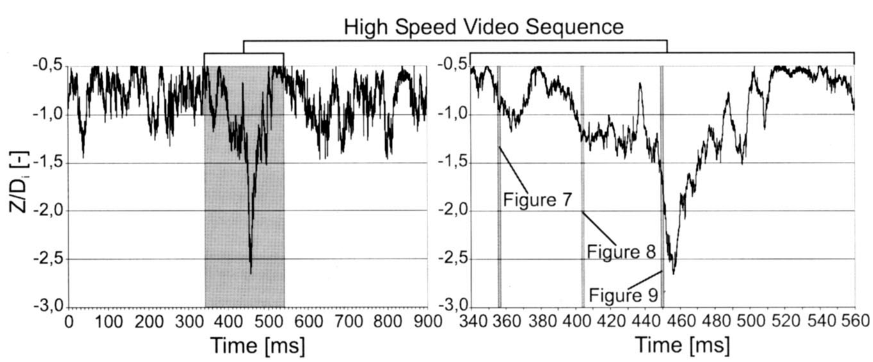

Fig. 6 Optical flame sensor signal during a flashback experiment. Methane-air mixture, $\phi=0.83$, $T=300°C$, Re=54763.

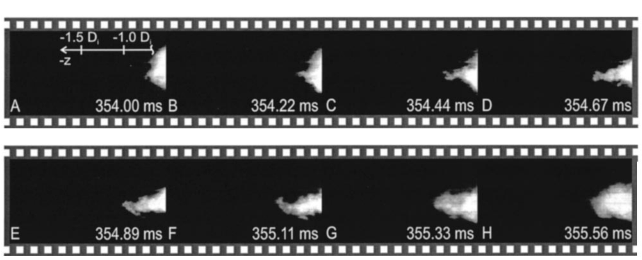

Fig. 7 UV-intensified high speed video sequence. Upstream flame acceleration by forming a flame needle (cf. Fig. 6)

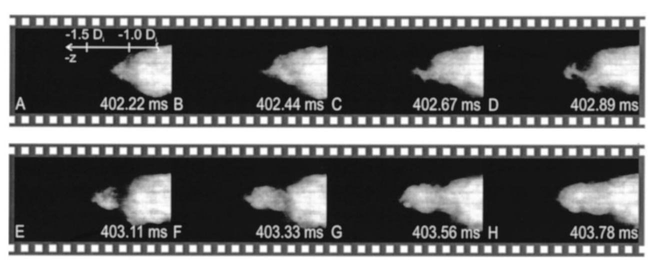

Fig. 8 UV-intensified high speed video sequence. A mushroom-shaped flame tip evolves a separated reaction zone (cf. Fig. 6).

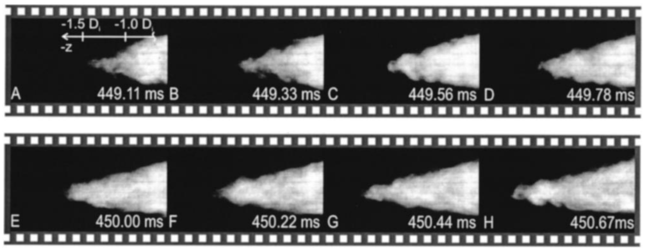

Fig. 9 UV-intensified high speed video sequence. Fast upstream moving wedge shaped flame (cf. Fig. 6).

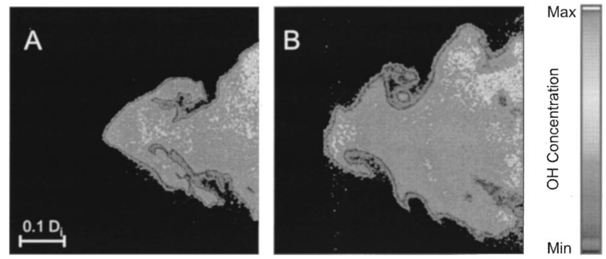

Fig. 11 OH concentration distribution during upstream flame propagation-wedge shaped flame. $\phi=0.83$, $T=300°C$, Re=54763.

subsequent shift of the flame back into the combustion chamber. This again leads to a recurrent flashback process as depicted in Fig. 6.

Due to the complicated dynamics of the flashback, it is insufficient to define the flashback limits as the point at which the flame propagates through the entire mixing tube. A statistical analysis of the signal of the optical flame sensor provides a better insight into the nature of the process. In Fig. 10 the histogram shows the influence of the equivalence ratio ϕ on the probability of the flame position. Starting with $\phi \leq 0.718$ the flame is stabilized at the combustion chamber inlet. For higher equivalence ratios ϕ, the probability of the flame appearing further upstream in the mixing tube increases. At $\phi \approx 0.83$ the flashback can partially propagate through the mixing tube up to $z=-2.25\,D_i$. The lower probabilities of flame tip positions for the same case at $z>-0.25\,D_i$ indicate that there is the tendency of a flame stabilization in the mixing tube. A further increase of the equivalence ratio leads to a final flashback throughout the entire mixing tube.

The experimental finding that the direct flashback through the entire mixing tube can be prevented within a very small window of the equivalence ratio can be explained by the higher jet velocity near the swirler (cf. Fig. 5).

The OH concentration distributions measured by LIF for selected cases fully support the findings obtained from the high speed video sequences. Of particular interest is the detailed information concerning the flame structure and the distribution of reactive species. An upstream propagating flame forms a sharp wedge or mushroom-shaped flame front (Figs. 11 and 12). The measurements reveal zones of high OH concentrations without distinct structures in the combusting sections downstream of the flame front. From the measurement it can be concluded that these zones are intensely stirred and represent a volume reaction zone.

At the outer envelope of the flame, vortex structures are clearly visible. In some cases the flame tip almost completely detaches itself from its body (Figs. 13 *A*, confer 8 E). The transition from a fast upstream propagation into a temporarily constant flame position or even a reversal to a downstream propagation is mostly characterized by the breakdown of the volumetric reaction zone (Fig. 13). At the same time, flame structures suddenly appear, the flame becomes increasingly corrugated and quenched.

Unsteady Flow During Flashback. High speed sequences have shown that the upstream propagating flame tip is restricted to a region near the mixing tube axis. On the other hand, the profiles of the mean axial velocity (Fig. 3) show the highest values on the centerline and the velocity fluctuations are not high enough to explain the upstream flame propagation in the vortex core. Obviously, a feedback between the reaction and the velocity field must be present, in order to explain the observed phenomena qualitatively.

In this context, the unsteady flow near the mixing tube axis is of special interest and might provide the key for a better understanding of the flow-chemistry interaction. Hence, the high speed camera, the laser Doppler anemometer, and the optical flame sensor have been simultaneously applied in the flashback study to correlate the velocity data with the flame position data.

The right part of Fig. 14 shows a 900 ms sequence of the optical flame sensor signal, which was extracted from a longer 5 s measuring interval, in order to capture one single flashback. The sudden upstream flame propagation is clearly visible. The left part shows a magnified view of the flame position data during the flashback at $t=600-640$ ms as well as the transient velocity data for one location slightly off the axis. An additional LDV measure-

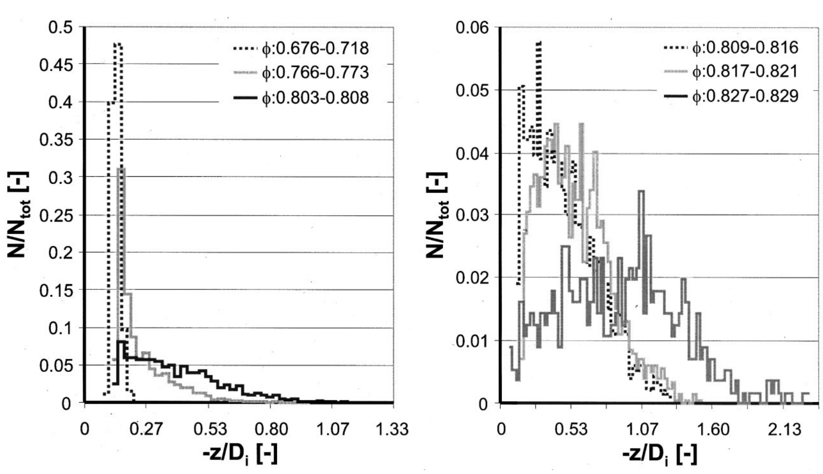

Fig. 10 Probability for flame position with equivalence ratio ϕ as parameter. Histogram at $T=250°C$, Re=73031.

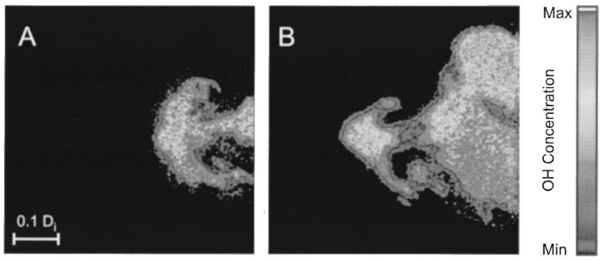

Fig. 12 OH concentration distribution during upstream flame propagation-mushroom shaped flame. $\phi=0.83$, $T=300°C$, Re=54763.

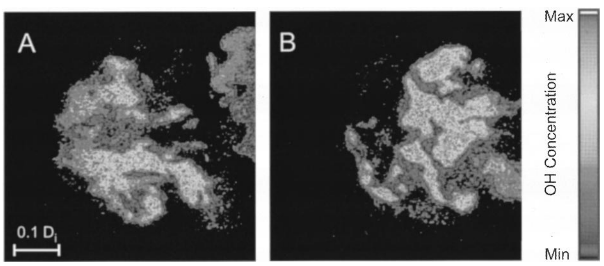

Fig. 13 OH concentration distribution in stagnating flames. $\phi=0.83$, $T=300°C$, Re=54763.

ment (Fig. 15) provides data concerning the relationship between the velocity right on the axis and the flashback position. From the velocity data, it can be clearly seen that the upstream flame propagation is associated with a significant reduction of the axial velocity and with a distinct reverse flow on the axis. According to Fig. 15, the axial flow on the axis totally breaks down, before the flame tip reaches the LDA measuring volume. The location where the axial jet on the axis breaks down moves in counterflow direction, while the flame propagates upstream. It is of particular interest to note that the breakdown point is near to the position of the flame tip.

In the example shown in Fig. 15, the strong forward flow breaks down within approximately 2 ms. Within this extremely short time a significant reverse flow in the order of $1.5\overline{u_a}$ is developed. This leads to a very quick upstream transport of reaction products and intermediates. Since the characteristic time for this process is of the order of the characteristic time for the chemical reaction, the recirculation zone in the mixing tube appears as a highly stirred region (Fig. 11). Further LDA measurements at higher radii show that the extremely strong breakdown can only be observed near the mixing tube axis. At an off axis position of $r=0.13D_i$ (Fig. 14) for example, the decrease of the axial velocity is much weaker and does not approach negative values. The deceleration and the heat release near the axis leads to a radial transport of an angular momentum, which leads to a significant reduction of the circumferential velocity. Near the mixing tube wall the flow in the axial direction is accelerated during flashback.

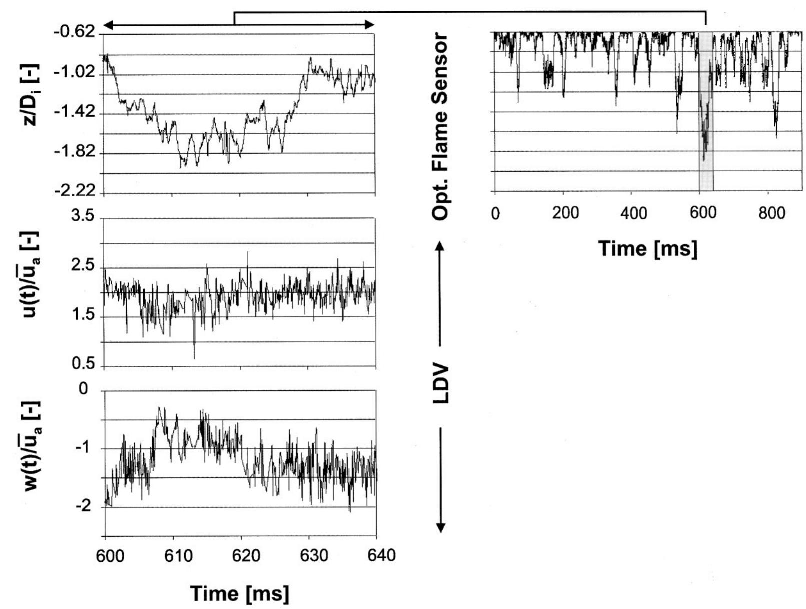

Fig. 14 Flame position and unsteady flow during a flashback. $\phi=0.83$, $T=300°C$, Re=54763, measuring position $r=0.13D_i$, $z=-1.55D$.

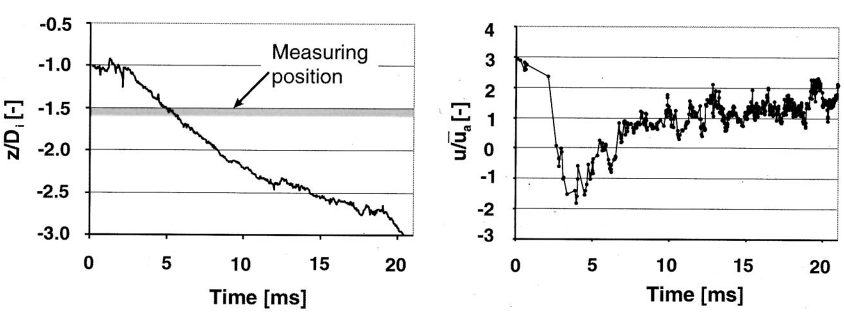

Fig. 15 Flame position (left) and unsteady flow during a flashback. $\phi=0.83$, $T=300°C$, Re=54763, measuring position $r=0$, $z=-1.55D_i$.

From aerodynamic testing of tubular swirling flows, it is well known that small and lengthy cylindrical recirculation zones on the axis can be generated if the swirl number exceeds a certain maximum, if the radial distribution of the axial and tangential momentum is not properly tailored, or if the flow on the axis experiences a loss in total pressure during inflow through the swirler or due to the dissipation of kinetic energy in the vortex core. In the latter case, the loss of total pressure leads in a second step to lower axial velocities and a lower axial momentum on the axis. In our case, an analog effect occurs because the pressure distribution in the burner exit plane is influenced by the chemical reaction in the combustion chamber. For constant total pressure upstream of the swirler, the pressure on the axis rises at the burner exit with increasing thermal power. Consequently, this pressure rise leads to a reduction of the jet velocity near the burner outlet until the breakdown begins to propagate upstream. The associated shifting of the flame position with increasing equivalence ratio is depicted in Fig. 10.

Interestingly, the burner configuration II (cf. Fig. 3) showed a completely different flashback behavior, despite the relatively moderate differences of the two flow fields. Even with stoichiometric mixtures of natural gas and air, only a periodic displacement of the reaction was measured with the optical flame sensor. The flame did not propagate further upstream than to a position of $z=-0.8D_i$. Even in additional tests with hydrogen instead of natural gas, flashback could not be observed although the turbulent flame speed was much higher.

Apparently, the small additional overshoot of swirl free mixture around the axis can prevent the upstream propagation of vortex breakdown. The tests with hydrogen reveal in general that the combustion induced vortex breakdown is governed by additional parameters besides those responsible for the other flashback phenomena mentioned in the Introduction.

Concluding Remarks

From the experimental study on flashback in tubular swirling flows the following conclusions can be made:

• High speed video recordings and OH-LIF measurements show an upstream flame propagation in the core flow near the centerline. A flashback in the boundary layer could not be observed.

• The axial velocity of the steady flow field is too high to allow a turbulent flame propagation in the core flow without any additional driving forces. Therefore, flashbacks in the core require a breakdown of the axial velocity to occur first. This effect could be illustrated by LDA measurements.

• The propagation of the vortex breakdown into the mixing tube is obviously induced by changes of the pressure boundary condition at the combustion chamber inlet due to the chemical reaction. This propagation is the prerequisite for the start of the observed flashback process. The flame propagation is governed by the feedback between the chemical reaction and the flow in the mixing tube and vice versa.

• With small modifications of the axial and circumferential momentum in the vortex core, the flashback resistance can be considerably improved.

• The investigated burner configurations are able to arrest the flame within a narrow margin of the equivalence ratio. This can be explained by the increasing axial jet towards the swirler.

• Current paradigms concerning the appropriate swirl level of gas turbine burner should be reviewed, since designs with lower swirl exhibit advantages from the viewpoint of flashback safety.

Acknowledgment

It is gratefully acknowledged that the work presented in this paper has been supported by Alstom Power (CH) AG. The authors wish to thank T. Ruck and C. Steinbach for the useful discussions and their support.

Nomenclature

D_i = inner mixing tube diameter (m)
d_q = quenching distance (m)
g = velocity gradient (1/s)
u = instantaneous axial velocity (m/s)
$\overline{u}$ = mean axial velocity (m/s)
u' = r.m.s. of fluctuating axial velocity (m/s)
$\overline{u_a}$ = mass mean axial velocity in the mixing tube (m/s)
w = instantaneous circumferential velocity (m/s)
$\overline{w}$ = mean circumferential velocity (m/s)
w' = r.m.s. of fluctuating circumferential velocity (m/s)
Re = Reynolds number
r = Radial coordinate (m)
S_L = laminar burning velocity (m/s)
T = fuel/air temperature in the mixing tube (°C)
t = time (s)
z = axial coordinate (m)
ϕ = equivalence ratio

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