VORTEX BREAKDOWN CONTROL FOR REDUCED COMBUSTION PRESSURE PULSATIONS

C. O. Paschereit, P. Flohr, W. Geng, E. Gutmark[‡]
ALSTOM (Switzerland) Ltd, CH-5405 Baden, Switzerland
[‡]Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221, USA

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Abstract

Flame anchoring in a swirl-stabilized combustor occurs in an aerodynamically generated recirculation region which is a result of vortex breakdown (VBD). The characteristics of the recirculating flow are dependent on the swirl number and on axial pressure gradients. Coupling with downstream pressure pulsations in the combustor affect the VBD process. The present paper describes combustion instability that is associated with vortex breakdown. The mechanism of the onset of this instability is discussed. Passive control of the instability was achieved by stabilizing the location of vortex breakdown using an extended lance. The reduction of pressure pulsations for different operating conditions and the effect on emissions in a laboratory scale model atmospheric combustor, in a high pressure combustor facility and in a full scale land-based gas-turbine are described. The flashback safety, one of the most important features of a reliable gas turbine burner, was assessed by CFD, water tests and combustion tests.

INTRODUCTION

Modern design of low emission combustors is characterized by swirling air in the combustor's dome coupled with distributed fuel injection to maximize mixing. This design results in efficient combustion with extremely low emissions. The fuel distribution and mixing with the air stream play a critical role in the combustion process and in the performance of the system. Various flow dynamics processes control the mixing between fuel and air in diffusion flame configurations and the mixing between the fresh fuel/air mixture and hot combustion products and fresh air in premixed combustors. They include large-scale vortices that evolve in a separating shear layer downstream of a sudden expansion or bluff body flame holders, and swirling vortices that undergo vortex breakdown in swirl-stabilized combustors. Interaction between these vortices which are related to flow instabilities, acoustic resonant modes in the combustion chamber and the heat release process was shown to cause undesired thermoacoustic instabilities in combustors [7].

The burner tested here stabilizes the flame near the burner outlet utilizing the sudden breakdown of the swirling flow, called vortex breakdown (VBD). The swirler consists of two halves of a cone, which are shifted to form two air slots of constant width [2]. This design produced a swirler which is a hybrid of radial and axial swirlers. Gaseous fuels are injected into the combustion air by means of fuel distribution tubes comprising two rows of small holes perpendicular to the inlet ports of the swirler. Complete mixing of fuel and air is obtained shortly after injection.

The characteristics of combustion stabilization by vortex breakdown are controlled by the flow dynamics associated with this particular flow phenomenon. Vortex breakdown is defined as a flow instability that is characterized by the formation of an internal stagnation point on the vortex axis, followed by reversed flow. Two major factors play a role in the vortex breakdown phenomenon, the swirl ratio and the presence of an adverse pressure gradient [1], [8]. Performing experiments with vortices in tubes, Leibovich and others have shown that as the swirl ratio is increased, the location of breakdown moves upstream. Rusak and Lamb have developed a criterion based on the swirl ratio for axisymmetric vortex breakdown. The swirl ratio, based on the maximum circumferential velocity over the maximum axial velocity, should be equal to 0.58 +/- 0.03 at the point of breakdown. Any value greater than this will result in breakdown. Experimental data has shown good agreement with the theory [5], [4]. The sensitivity of vortex breakdown to pressure gradients can cause coupling between pressure perturbations in the combustion chamber and the heat release from the flame which is anchored at the recirculating region produced by the breakdown, thus forming a feedback loop that may lead to combustion instability and a change in pollutants formation [6]. Free stream flashback is another inherent feature of swirl-stabilized premixed combustion that is closely related to vortex breakdown due to the low velocity or even reversed flow caused by this phenomenon [3].

The present paper describes combustion instability that is associated with vortex breakdown. The mechanism of the onset of this instability will be described. Passive control of the instability was achieved by stabilizing the location of vortex breakdown using an extended lance. The reduction of pressure pulsations for different operating conditions and emissions in a laboratory scale model atmospheric combustor and in high pressure combustor facility are described. The flashback safety, one of the most important features of a reliable gas turbine burner, was assessed by CFD, water tests and combustion tests. In addition an analysis assuming potential flow was performed.

EXPERIMENTAL SETUP

Atmospheric Combustion Facility

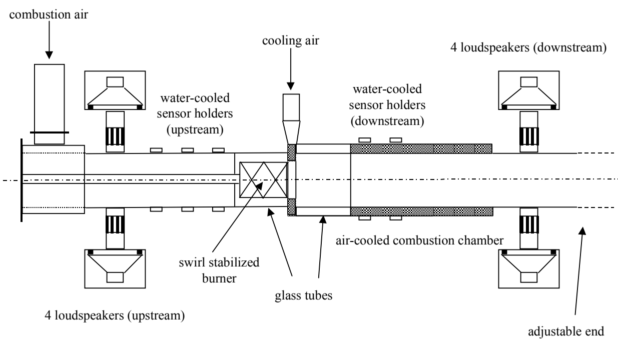

Fig. 1 Schematic of the atmospheric test facility

The atmospheric combustion facility is shown in Fig. 1. The test rig consists of a plenum chamber upstream of a swirl-inducing burner and a combustion chamber downstream of the burner. The plenum chamber contains perforated plates to reduce the turbulence level of the flow. The circular combustion chamber consists of an air cooled double wall quartz glass to provide full visual access to the flame. The exhaust system is an air-cooled tube with the same cross-section as the combustion chamber to avoid acoustic reflections at area discontinuities. The acoustic boundary conditions of the exhaust system can be adjusted from almost anechoic (reflection coefficient $|r| < 0.15$) to open end reflection.

Pressure fluctuations were measured using Brüel & Kjær water-cooled microphones. The wall-mounted water-cooled 1/4" condenser microphones were placed at an axial distance of $x/D = 0.69$. The holders consisted of a small orifice ($d = 0.5$ mm) open to the combustion chamber. The microphone diaphragm was placed in a small cavity and was heat radiation protected. The resonance frequency of the holder was larger than $f_{res} > 20$ kHz. Using condenser microphones rather than piezoelectric pressure probes gave the advantage of highly accurate phase and amplitude data which is necessary for acoustic measurements. The frequency response of the microphones in probe holders were compared against standard B&K microphones and showed good agreement. To compare pressure pulsations in the different test configurations one microphone at $x/D = 2.5$ was used.

The operating conditions of the burner have been maintained by analyzing the exhaust gas composition using a physical gas analysis system. CO and CO_2 have been analyzed by using nondispersive infrared spectroscopy. The nitric oxides NO and NO_2, combined in NO_x have been detected with a chemiluminescence analyzer. The detection of the remaining O_2 in the exhaust gas was made utilizing the paramagnetic properties of oxygen in the analyzing device. Carbon and oxygen balances were continuously computed and agreement within 0.2% was assured.

High pressure combustion facility

The process of burner development and improvement includes combustion tests under 10 bars pressure. The facility is shown in Fig. 2. It allows quick, cost effective and therefore extensive testing of single machine burners. The test rig consists of a plenum chamber upstream of the burner, two water cooled tubular pressure vessels and the rectangular chamber liner. The hot exhaust gases are quenched before the pressure reduction throttle and then discharged through the exhaust. The operating conditions of the burner have been maintained as in the atmospheric test rig by analyzing the exhaust gas composition.

The combustor liner is convectively cooled to prevent contamination of actual burner emissions by introducing additional film cooling air into the combustor and to avoid introduction of unrelated acoustic damping effects. Direct optical observation of the flame is provided by a video system mounted downstream of the burner. In addition, optical observation of the mixing zone through the burner slots is possible by a video system mounted upstream of the burner in the plenum.

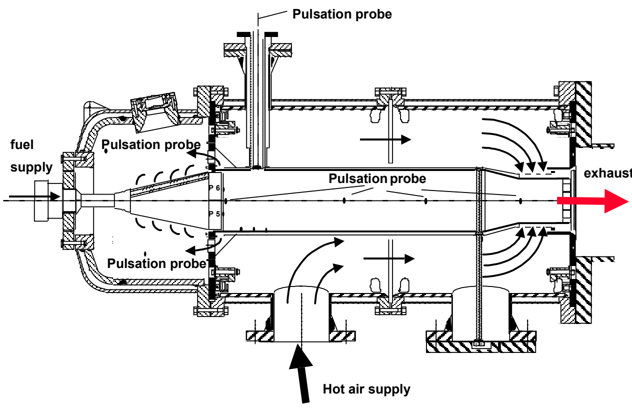

Fig. 2 Schematic of the high pressure test facility

RESULTS AND DISCUSSION

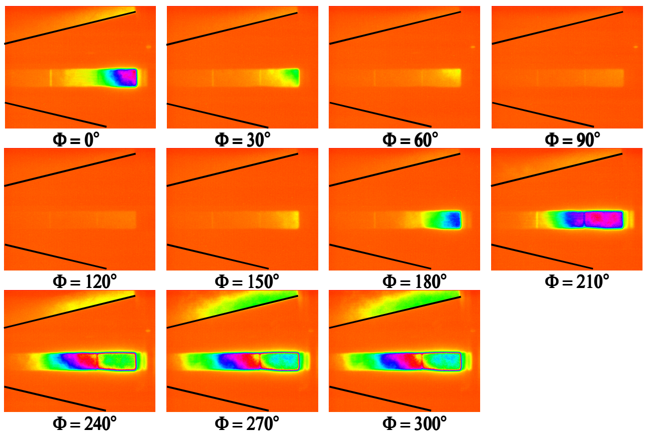

Fig. 3 Flame motion in and out of the burner during a pilot instability cycle. Phase averaged pictures taken through a glass window in the burner are shown at intervals of 30 deg.

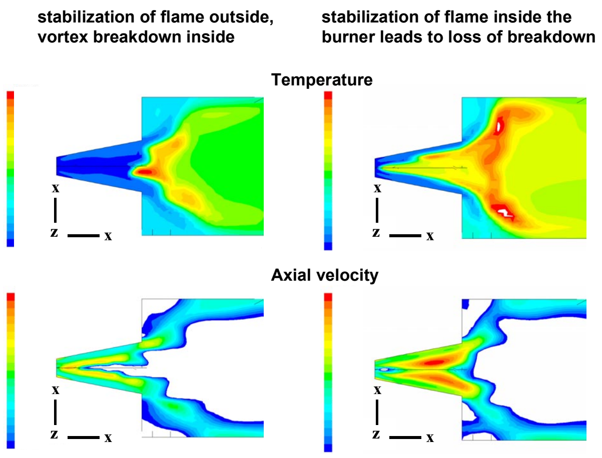

Fig. 4 CFD simulation of the pilot instability

Instability Mechanism

Combustion instability was observed during a simulated startup operation of the burner using the pilot stage of the burner at flame temperatures $T/T_n > 0.8$, where T_n is the nominal flame temperature of the burner. Instability was also observed during switchover to premix fuel. Lower amplitude instabilities, reaching 30% of the peak levels in pilot and mixed operation, were also observed under simulated premix operation. The instability was related to the fluctuating pilot flame position which occurred when the flame temperature was increased above $T/T_n > 0.8$, (Fig. 3). CFD simulations showed that the oscillations in flame location were related to the behavior of the vortex breakdown. When the flame was stabilized outside the burner, initiation of vortex breakdown was observed to occur inside the burner. When the flame was pushed into the burner by a increased pressure in the combustion chamber, the decreased density resulted in the prevention of the vortex breakdown (Fig. 4). Subsequent to the disappearance of the swirl-based stabilization mechanism, the flame exited the burner, stabilizing at the sudden expansion. The vortex breakdown was thus re-established and the instability cycle repeated itself.

Passive Control of Instability

In order to prevent the instability mechanism associated with large amplitude movement of the vortex breakdown location and the resulting flame oscillations in and out of the burner, passive control was applied to stabilize the vortex breakdown location. This stabilization was achieved by extending the pilot fuel lance into the burner. The concept was initially tested in an atmospheric combustor rig operating in piloted mode. Extension of the pilot fuel lance into the burner as shown in Fig. 5 resulted in a significant reduction of the pressure pulsations. The tests were performed using a fuel lance with an adjustable length which could be extended axially in order to determine an optimal length.

The tests showed that the optimum suppression of the pulsations occured when the lance extension length was $x/L \approx 0.7$, where L is the length of the burner (Fig. 6). However, variation of length was possible by $\pm 25\%$ without significant increase in pulsations. With 5% fuel injection through the long lance the oscillations were reduced by over 12 dB. It was imperative to ensure that the improvement of the operation in pilot mode will not result in degradation of the premixed operation. Atmospheric test rig results indicated no increase in NO_x emissions and pulsations during premixed operation (Fig. 7). Added pilot fuel injection through the extended lance resulted in increase in NO_x emissions. However, 5% fuel injection, which yielded a substantial decrease in the instability level, yielded acceptable penalty in NO_x production due to the extremely low level at baseline conditions.

The main pulsation reducing mechanisms are:

1. Stabilization of the vortex breakdown in the recirculation zone of the extended pilot lance

2. Prevention of the periodically changing

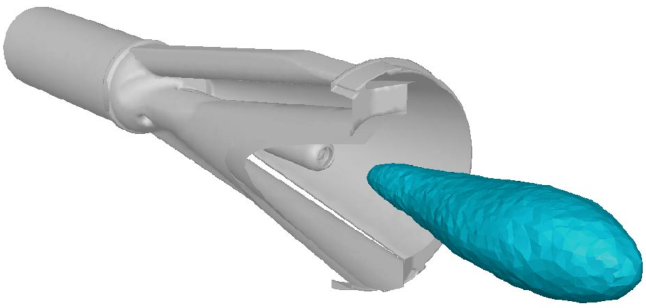

Fig. 5 Burner with extended lance

stabilization location of the pilot flame

3. Introduction of streamwise vorticity to suppress the spanwise coherent structures which are the source of one of the mechanisms that drive thermoacoustic oscillations

The main advantage of extending the lance into the burner was the improved performance during startup. Without the extended lance an increase of pulsations was observed when the burner power was increased at a constant flame temperature, and when the flame temperature was increased at a constant power (constant burner velocity) (Figs. 8 and 9). The typical normalized instability frequency at these conditions was $St = fD/U = 0.6$, where f is the frequency of the instability, D the burner diameter and U the burner exit velocity. Excitation of pressure oscillations was completely eliminated during start up with pilot operation.

FLASHBACK SAFETY

An important feature of a reliable gas turbine burner in addition to its efficiency, emissions, flame stability, lean extinction limits and pulsation behavior is its flashback safety. The effect of the extended lance on the flashback safety of the burner was assessed by using CFD simulations and by performing combustion tests at atmospheric and high pressure.

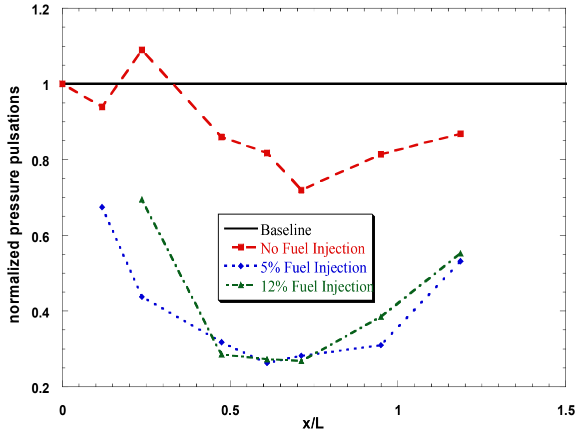

Fig. 6 Suppression of pressure pulsations for different lance lengths

In addition an analysis based on potential flow was performed. The flashback safety margins were assessed based on the stability boundaries of annular vortex breakdown to occur upstream of the lance tip. If an annular VBD was to propagate upstream of the lance tip it would have caused flame propagation into the burner and damage to the lance and the burner's structure.

Analysis of annular breakdown

The stability of the flow, inside the burner with extended fuel lance, near the lance tip was analyzed for the simplified configuration shown in Fig. 10. The analysis was based on potential flow approximations.

It was assumed that annular breakdown occurs near the lance tip. Upstream of this point the flow was assumed to be appropriately described by two concentric potential vortices, superimposed on a double plug-flow (see Fig. 10). The effect of the axially changing flow inside the double cone burner was neglected. While this assumption may seem to be a strong simplification when the entire flow inside the burner is considered, it should be appropriate for an analysis that is localized at the lance tip.

Figure 11 presents results for the generic

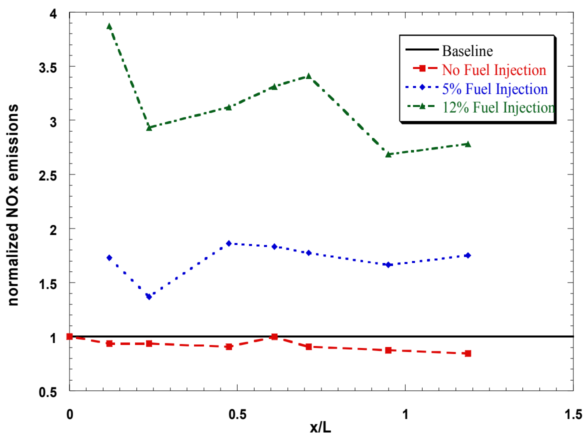

Fig. 7 NO_x emissions for different lance lengths

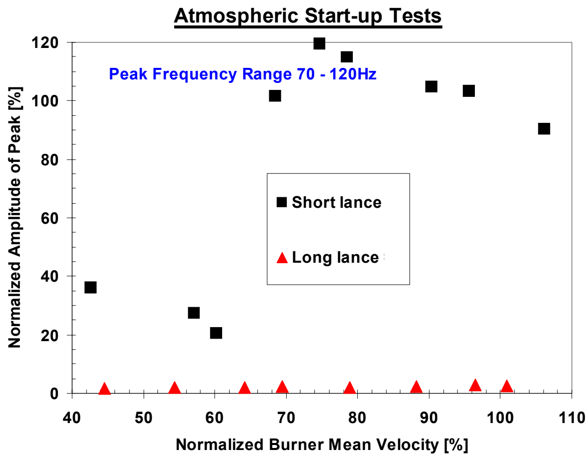

Fig. 8 Atmospheric startup test. Power variation.

(and strongly simplified) situation for which the annular flow around the lance can be described by a single potential vortex which is superimposed on a plug jet flow. The effect of swirl and variation in lance diameter (assuming a fixed outer diameter) was analyzed for this configuration. Fig. 11 shows that increasing the swirling component in the flow has a destabilizing effect while an increase in lance diameter has a stabilizing effect. Fig. 13 depicts results from water tunnel measurements. The flow parameter β, as well as the geometric parameters r_L, and r_T/r_L can be estimated from analysis of the flow at the lance tip. The results indicate that the design for the standard lance is well below the critical level for which annular breakdown could be expected.

CFD and water tunnel simulations

CFD calculations were performed to investigate the position of the vortex breakdown as well as to check for recirculation regions along the extended lance to verify the burner's flashback safety. These calculations were performed for the case without combustion. The purpose was to ensure that there are no locations along the extended lance where the flame could stabilize. Fig. 12 shows good agreement between the axial velocity profiles calculated using CFD and the water tunnel measurements. The flow field was mapped between the extended lance and the burner's walls. The flow was shown to be positive in the entire measurement and computational regime indicating that annular vortex breakdown did not occur, as predicted by the potential flow analysis in the previous section. CFD simulations and water tunnel measurements were also performed downstream of the extended lance tip (Fig. 13). The figure shows the comparison between CFD and water tunnel measurements of the axial and the absolute value of the tangential velocity components. The position of the vortex breakdown was identified to be well downstream of the tip of the extended lance where the axial velocity was reversed. This vortex breakdown location prevented the flame from being stabilized close to the lance tip with possible lance overheating. The CFD calculations of the highly turbulent swirling flow were in good agreement with the measurements in the water tunnel simulation and showed no recirculation regions at the lance.

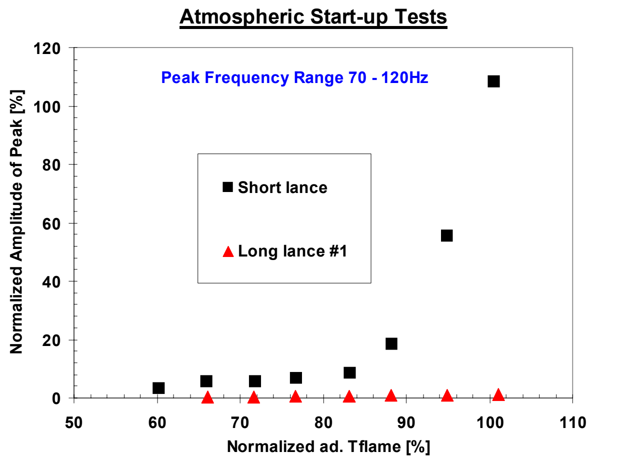

Fig. 9 Atmospheric startup tests. Flame temperature variation.

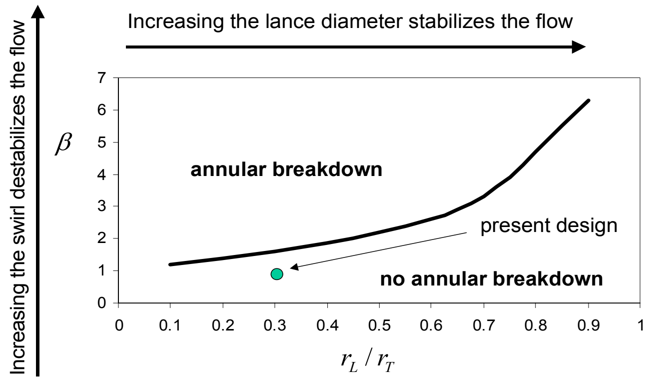

Fig. 11 Critical swirl for a single vortex ($w_1 = u_1$). Present design shown to be in stable region.

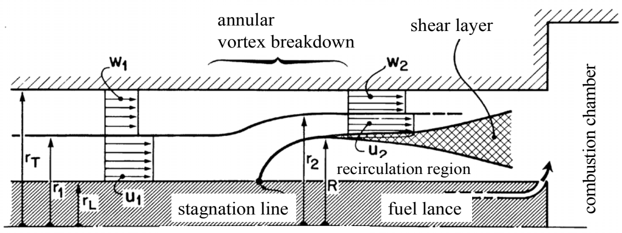

Fig. 10 Schematic of the configuration used for annular breakdown analysis.

Combustion tests

The results of the atmospheric flashback safety tests were confirmed by tests conducted in the high pressure combustion rig. As the CFD and water tests indicated in atmospheric pressure conditions without combustion, the flame did not stabilize on the lance tip or upstream of it during high pressure combustion (Fig. 14).

Flashback safety tests were performed by adding gaseous fuel with high laminar flame speed (hydrogen) to the main fuel which was natural gas. The percentage of the additional fuel at the point when flashback occurs was a measure of the flashback safety of the tested burner. The resulting value was compared to the baseline flashback safety level of certified commercial burners. The burner is acceptable as 'flashback safe' if the test results are within the margins allowed for certified burners. The flashback safety margin for certified burners is at 80% of the design target.

A number of different variants in terms of the extended lance length have been tested and compared against a design target defined for a standard burner. The results are summarized in Fig. 15. The tests were conducted at atmospheric conditions. The position that ensured flashback safety was also effective in suppression of pressure oscillations. All variants tested achieved the design target of 100%.

A forced atmospheric flashback test, in which a hydrogen igniter was mounted in the slots at the upstream part of the burner, confirmed the flashback safety of the burner (Fig. 16). The forced flashback tests proved flashback safety over a wide power range ($0.39 \leq P/P_n \leq 1$) and flame temperature range ($1 \leq T/T_n \leq 1.06$). When the igniter was switched on, the flame was forced to move into the burner. With the igniter switched off the flame was always pushed outside of the burner, again indicating the flashback safety of the extended lance.

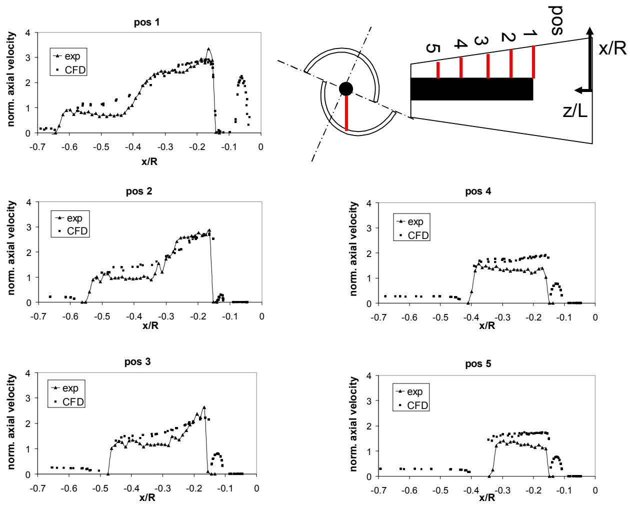

Fig. 12 CFD calculations of the axial flow field around the extended lance compared with water tunnel measurements.

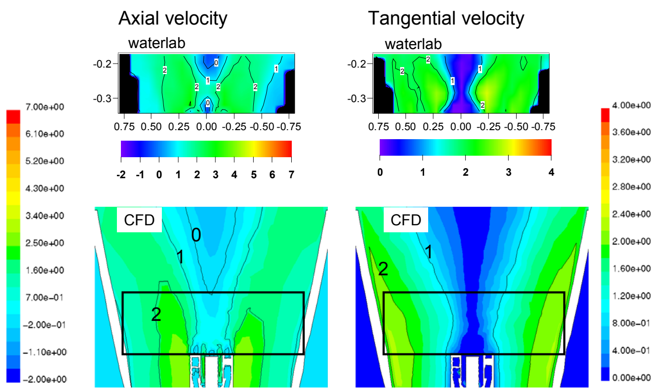

Fig. 13 CFD calculations of the flow field downstream of the lance compared with water tunnel measurements.

ENGINE IMPLEMENTATION

The operating behavior of the burner with the long lance was verified in a test engine. The main improvement of the long lance could be seen in the startup procedure. With the original burner high pulsation levels were observed during startup at a normalized RPM range between 0.68-0.85 (Fig. 17). Using the long lance the startup procedure was smooth and the pulsation levels were reduced by 90% (Fig. 18).

CONCLUSIONS

This paper describes the source of combustion instability that is associated with vortex breakdown and a passive control method developed to suppress it. The tests were performed in an atmospheric combustor and were verified in combustion tests at 10 bar pressure and in a commercial engine.

The mechanism exciting the instability was investigated using CFD simulations. The simulations showed that the pressure oscillations were linked to fluctuations in the flame location, which were in turn affected by changes in the vortex breakdown characteristics. When the flame stabilized outside the burner, initiation of vortex breakdown could be observed inside the burner. When the flame was pushed by increased combustion pressure into the burner, the decreased density resulted in the elimination of vortex breakdown. Subsequent to the disappearance of this swirl-based stabilization mechanism, the flame exited the burner, stabilizing downstream of the burner's exit at the sudden expansion. As the burner temperature dropped and density increased, the internal vortex breakdown was re-established and the instability cycle repeated itself.

In order to prevent the instability mechanism which was shown to be associated with large amplitude movement of the vortex breakdown location and the resulting flame oscillations in and out of the burner, passive control was applied to stabilize the vortex breakdown location. The stabilization was achieved by extending the pilot fuel lance into the burner. The concept was demonstrated in an atmospheric combustor rig. Extension of the lance into the burner eliminated the high pressure pulsations observed in mixed and purely piloted operation. The optimal extended lance length was approximately 70% of the burner's length. The pressure pulsations were sup-

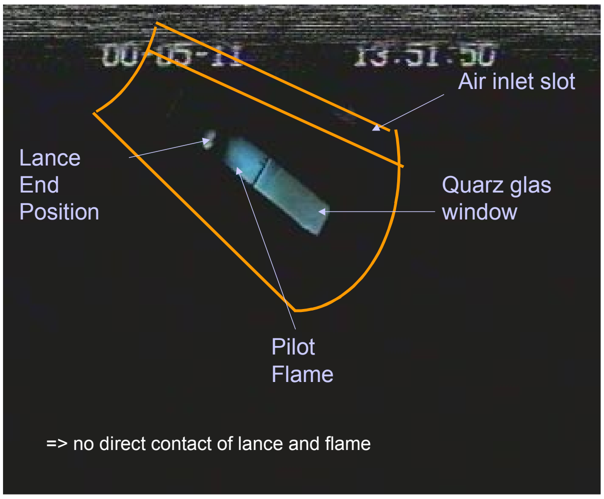

Fig. 14 Video image of combustion in the high pressure rig, indicating that the flame is stabilized downstream of the extended lance

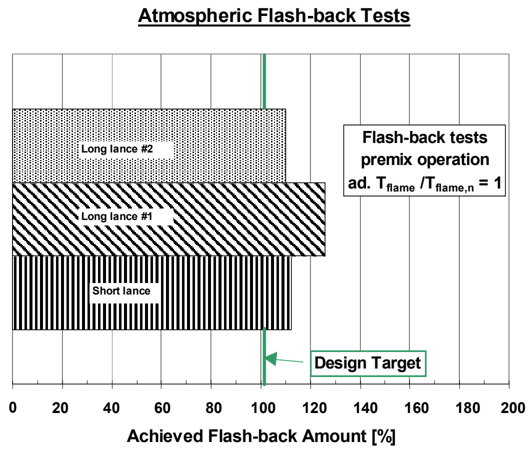

Fig. 15 Atmospheric hydrogen flashback tests

pressed by more than 12 dB in piloted operation. The improvement of the operation in pilot mode did not result in degradation of the premixed operation. Atmospheric test rig results indicated no increase in NO_x emissions and pulsations.

The extended lance improved performance in the atmospheric test rig. Without the extended lance an increase of pulsations was observed when the burner power or the flame temperature were increased. The extended lance completely eliminated excitation of pressure oscillations for start up conditions with pilot operation.

Other concerns associated with the extended lance were possible internal stabilization of flame on the lance and flashback safety. Potential flow analysis established criteria for the occurrence of annular vortex breakdown. Velocity measurements showed that the present conditions were subcritical and predicted that such breakdown will not occur. CFD simulations and water tunnel measurements showed that the position of the vortex breakdown was well downstream of the tip of the extended lance. This vortex breakdown location prevented the flame from being stabilized close to the lance tip with possible lance overheating. Hydrogen flashback tests confirmed that the extended lance did not adversely affect the flashback safety.

The stable operation of the burner with the long lance was verified in an high pressure test rig as well as in a test engine. The main improvement of the long lance could be seen in the startup. With the original burner high pulsation levels were observed during startup while the long lance yielded smooth startup procedure and the pulsation levels were reduced by 90%. Flashback safety was verified in the high pressure tests in which the flame was shown to stabilize downstream of the lance tip.

The instability suppression by the extended lance was attributed to the following mechanisms: the stabilization of the vortex breakdown in the recirculation zone of the extended pilot lance, prevention of the periodical change in the stabilization location of the pilot flame, and the introduction of streamwise vorticity that suppressed the spanwise coherent structures which were one of the mechanisms that drove thermoacoustic oscillations.

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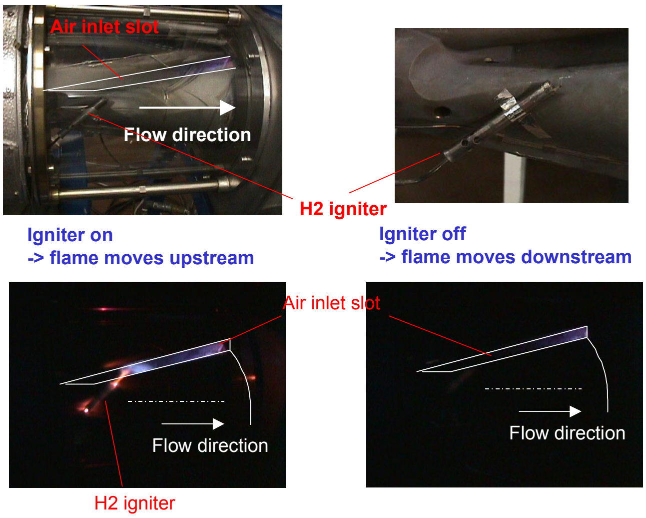

Fig. 16 Forced atmospheric hydrogen flashback test

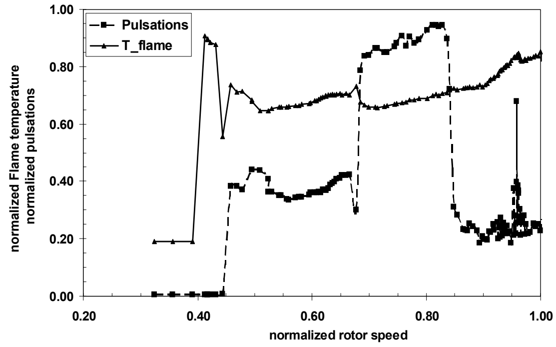

Fig. 17 Baseline startup test in the test engine with the original burner configuration.

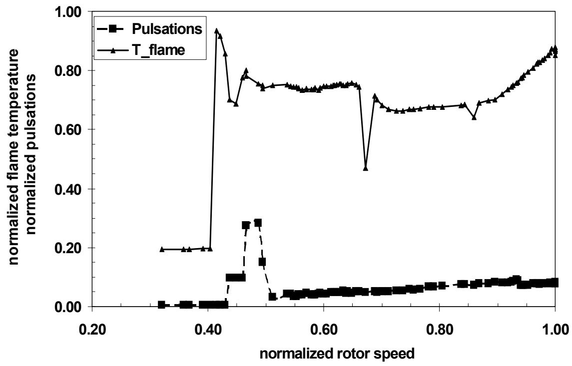

Fig. 18 Reduced pulsations in a startup test in the test engine using the long lance.

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