Experimental investigations of ion current in liquid-fuelled gas turbine combustors

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Abstract
This work covers investigations of the static and dynamic behaviour of a confined, co-swirled and liquid-fuelled airblast injection system. The focus lies on the application of ion current sensors for the qualitative measurement of the heat release rate or for flame monitoring purposes in complex technical combustion processes. The ion current sensor is to operate in a feedback control loop in order to react on combustion dynamics in real time. The first part of the work analyses experimental data, which were obtained with different techniques, e.g. dynamic pressure, chemiluminescence, fine-wire thermocouples and ion current. The results show that the thermo-acoustic instability and the precessing vortex core generate an interaction mode. The frequency of this interaction mode is the difference of the other two modes. This has not yet been observed for partially premixed and liquid-fuelled injection systems before and also was not detected by the chemiluminescence of the flame. The ion current measurement technique is able to detect the helical mode of the precessing vortex core as well as the interaction frequency, leading to the conclusion that the chemical reactions are influenced by this helical structure. Contour maps of the frequencies reveal this influence in the outer shear layer. The second part of the study focused on the ion current probe as a method to predict static combustion instabilities, such as lean blowout. According to the results, the ion current is a fast responding method to detect lean blowout, provided that the detector is mounted at a suitable position. Measurements at different positions in the flame were compared with phase-locked chemiluminescence measurements. Precursors in the ion current signal for lean-blowout prediction were found using a statistical approach, which is based on ion peak distance. The precursor events allow for the use of this approach with a feedback control loop in future applications.

Keywords
Combustion dynamics, instability prediction, ion current, lean blowout, spray combustion

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1. Introduction
The sustainable use of energy is a challenging task. Increasing passenger volumes in civil air traffic require a basic approach to minimizing the environmental impact of aircraft pollutant emissions. Modifying the combustion process in a propulsion engine is a promising and challenging method to improve emission characteristics and can be influenced directly by the deployment of new combustor and nozzle designs. For the reduction of nitrogen oxide (NOx) emissions, maximum temperatures in the combustor have to be reduced due to the strongly dominating and temperature-dependent Zeldovich NOx formation mechanism.¹ In the last decades, many efforts of engine manufacturers, education and research institutions were dedicated to novel combustion concepts based on a lean combustion approach. However, lean combustion suffers from instabilities and a very lean operating point close to the extinction limit is associated with the risk of imminent blowout, which has to be prevented. Flame stabilization measures, such as

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recirculating flow fields induced by swirl, have the advantage of generating compact flames and enabling high reaction rates, but they also increase the complexity of the combustion process. Turbulent mixing and chemical reactions take place in parallel and interact with each other. In case of spray combustion, fuel atomization and evaporation have to be considered as well.

Combustion instabilities and the lean blowout (LBO) phenomena are examined separately and denoted as dynamic and static instabilities. In the next sections, several aspects of these processes are discussed for different kinds of flames and an overview is given.

Most investigations of dynamic instabilities of swirled combustion cover premixed conditions and use gaseous fuels, such as methane or natural gas, to reduce the complexity of the process. Lieuwen et al.\textsuperscript{2} and Sattelmayer\textsuperscript{3} focused on the direct relationship between oscillations and the equivalence ratio under atmospheric conditions, while Van Kampen et al.\textsuperscript{4} performed experiments relating to this interaction in a pressurized rig. Other authors like Durox et al.\textsuperscript{5} varied the flow field with the swirl number, while Moeck et al.\textsuperscript{6} studied the influence of the precessing vortex core (PVC), which is a rotating coherent structure induced by the swirl. Extensive reviews of combustion dynamics were presented by Candel\textsuperscript{7,8} and Huang et al.\textsuperscript{9} Syred\textsuperscript{10} published a review on the PVC. Due to the complexity of the parallel processes and the interactions between them, the prediction of instabilities still is a challenging task. Consequently, control of combustion dynamics has also developed to a field of research.

A comprehensive review of combustion control systems and sensors is given in Docquier et al.\textsuperscript{11}

However, only very few studies deal with liquid-fuelled, swirl-stabilized combustion with a recirculation zone. Culick\textsuperscript{12} published an extensive report about combustion instabilities in liquid-fuelled propulsion engines in 1988 and de la Cruz Garcia et al.\textsuperscript{13} investigated the interaction of the spray with two different acoustic modes in a counter-swirled airblast injection system. Mirat et al.\textsuperscript{14} analysed the stability of a swirl spray combustor based on a flame-describing function. The authors observed a sooty and a non-sooty flame type and measured the frequency response of the flames to air flow rate modulations. The results show that the OH* chemiluminescence signal is a good tracer for relative heat release disturbances.

Literature on LBO covers the understanding of the blowout mechanism and behaviour. Similar to the literature about dynamic instabilities, some authors studied the control or rather the prediction of the LBO using sensors and control systems. In general, differentiation between dynamic and static combustion instabilities is not expedient in the context of control systems and sensors, because flame monitoring sensors are supposed to detect unstable flame mode and LBO precursors as well. Operation close to LBO can also induce dynamic instabilities due to local flame extinction. This may result in equivalence ratio fluctuations.

Approaches to predicting blowout of swirled flames are based on the ratio between the residence time of flow and the chemical kinetic time, which results in the Damköhler number. In 2013, Cavaliere et al.\textsuperscript{15} presented an extensive survey of literature about the LBO behaviour of swirled premixed, non-premixed and spray flames with a bluff body. The authors concluded that an LBO correlation based on a Damköhler number, which is valid for premixed conditions is also suitable to predict the LBO limit of the non-premixed and spray cases investigated.

Literature\textsuperscript{16–21} focused on the detection of LBO precursors and combustion control in swirled flames with acoustic, optical and ion current sensors. The authors presented a feedback combustion control circuit and different statistical approaches to detecting LBO precursors based on the signals of the sensors. Muruganandam and Seitzman finally published a study about the fluid mechanics of LBO precursors\textsuperscript{22} for a better understanding of the blowout process proper. Domen et al.\textsuperscript{23} investigated LBO phenomena with the dynamic system theory and focused on the permutation entropy as measure of LBO prediction.

Similar to studies of combustion instabilities, LBO investigations mainly deal with gaseous fuels. Work with liquid fuels and in particular with double-swirled airblast injection systems has hardly been carried out so far. Nair et al.\textsuperscript{20} investigated a single cup swirl combustor fuelled with kerosene and performed LBO experiments with acoustic and ion sensing probes under atmospheric conditions. The results of the extensive statistical analysis show that use of ion current sensors for control purposes is very promising. Researches\textsuperscript{24–26} came to the same conclusion. They integrated an ion current detector into the fuel nozzle and performed experiments in a pressurized combustor, but again with gaseous fuels and under premixed conditions.

This article reports investigations of the static and dynamic behaviour of a confined, co-swirled and liquid-fuelled airblast injection system. Work was aimed at classifying the signal obtained by an ion current probe and evaluating its applicability for flame stabilization control purposes. Using ion current signals as a method for the detection of the heat release rate is a technique that was replaced by modern optical measurement methods, such as chemiluminescence or laser-induced fluorescence (LIF), in the past decades. However, use of ion current sensors for combustion
control purposes reduces costs. Moreover, the sensors are robust in comparison to other devices, such as dynamic pressure transducers. Peerlings et al.\textsuperscript{27} found that the chemi-ionization rate is an alternative to conventional OH* measurement when characterizing the dynamic response of flame to flow perturbations. For this purpose, Peerlings et al. calculated the flame transfer function for a flat Bunsen-type flame. The ion current signals obtained in this work are compared with signals measured by dynamic pressure transducers and with OH* radiation images, with analysis being performed in the time and frequency domains. The following section presents some facts about ion current detection and signal interpretation before the experimental setup and the measurement techniques are explained in ‘Experimental setup’ section. ‘Experimental results’ section presents and discusses the results, while the last section draws a conclusion from the findings presented.

2. Ion current detection and interpretation

The detection of current in flames is based on ions and electrons generated by the chemical reactions during combustion. Lawton and Weinberg\textsuperscript{28} published an extensive summary about the electrical aspects of combustion. They listed the positive ions measured and reported in several publications and finally concluded that the chemi-ionization reaction is the most likely source of primary ions:

\[
CH + O \rightarrow \text{CHO}^+ + e^-
\]  

To measure ion densities in flames, Langmuir probes are the method of choice. Mott-Smith and Langmuir were the first to use them to investigate electric discharges.\textsuperscript{29} The probe consists of a measurement and a reference electrode. The former electrode is very small and can be biased with a positive or negative voltage with reference to the latter one. This reference electrode can be the body of the probe. Its area has to be much bigger than that of the measurement electrode to ensure that the current passing through the electric circuit is limited by the measurement electrode.\textsuperscript{30}

The positive or negative bias voltage allows for the separation of charge carriers and, hence, for the differentiation between ion and electron current. The Langmuir potential of an ion current probe positioned in the combustor is plotted in Figure 1. The data on the negative side are multiplied by \((-1)\) to obtain positive values and enable logarithmic scaling. It can be seen that the current for the applied negative voltages is about two orders of magnitude smaller than for positive voltages. Fialkov\textsuperscript{30} explains this trend by a simplified model: Positive charge carriers are ions, which are comparably huge and slow, while negative charge carriers predominately are electrons moving fast with a small inertia. Thus, the negative potential attracts ions and repels electrons, while the positive potential behaves in the opposite way. This also explains why the zero crossing of the current has to take place at negative voltages.

Wortberg\textsuperscript{31} investigated the relationship of heat release rate, temperature and positive ion concentration of a methane-fuelled flat flame burner. The left hand side of Figure 2 shows that the heat release rate and the positive ion concentration are directly linked in case of a laminar and premixed combustion. Similar investigations were performed by Calcote et al.\textsuperscript{32} for propane flames at low pressures. Some of the results are plotted in Figure 2 on the right. It can be seen that the maxima of the CH*, OH* and C2* concentrations measured with a spectrophotometer are in line with the maximum of the positive ion concentration. However, a slow decay of the ion concentration with increasing distance from the reaction zone in both diagrams indicates potential errors resulting from the interpretation of results obtained from the ion current probes. Apart from that, the ion current and heat release rate are not correlated quantitatively, because parameters, such as the electric field intensity, probe geometry or ion mobility, influence the signal. This gives rise to the question whether the analogy between heat release rate and ion concentration can be transferred to turbulent spray flames. To answer this question, the authors performed investigations and concluded that the heat release rate is reproduced very well by the root mean square (RMS) of the ion current signal.\textsuperscript{33}

Based on the correlation between heat release rate and ion current signal, other scientists, such as Ahlheim,\textsuperscript{34} Hoffmann\textsuperscript{35} or Kohler,\textsuperscript{36} used the ion current signal for the detection of the flame front. Every peak in the time signal is evaluated as a flame front passing the probe. The width and shape of the peaks
allow conclusions to be drawn with respect to the mixing character of the flame at a certain measurement position, while the peak distance correlates with the structure of the turbulence.

3. Experimental setup

3.1. Injection system

The injection system used is based on the Partially Evaporating and Rapid Mixing (PERM) concept that was developed by general electric (GE) AVIO in cooperation with Karlsruhe Institute of Technology (KIT). A schematic illustration of this injection system can be seen in Figure 3. It is composed of two separated co-swirled air flows, which circulate around the lip. A Delavan WDA hollow cone pressure atomizer is installed at the bottom of the primary swirler and injects the fuel at a spray angle of 90° onto the lip. The flow number (FN) of the pressure atomizer is four and given in kg/h√bar:

\[ FN = \frac{M}{\sqrt{\Delta P}} \]  

(2)

At the end of the lip, the two air flows are combined and the resulting highly turbulent shear layer atomizes the liquid phase. Marinov et al.\textsuperscript{37} calculated the overall swirl number of the injection system and found that it amounts to 0.75. Swirl intensity is high enough to generate a vortex breakdown and, hence, an inner recirculation zone (IRZ). The recirculation zone induces a PVC and improves the flame stabilization process. The confinement of flow by the combustion chamber also generates an outer recirculation zone (ORZ). All lengths in this work are scaled to the outer radius \( R_0 \).

Earlier investigations of this injection system by Marinov et al.\textsuperscript{38} focused on the difference between a natural gas and liquid (kerosene)-fuelled configuration. In the kerosene-fuelled configuration, a flame-shaped transition appears at a certain air to fuel ratio (AFR) from a stable and compact flame shape to a semi-stable tornado funnel shape. This flame transition is considered as LBO, because the tornado funnel shape is of no relevance to technical applications and can be treated as flame extinction (Figure 4).

3.2. Experimental facility

Figure 5 displays a schematic drawing of the test facility on the left and an enlargement of the insulated combustion chamber with the attached plenum and injection system on the right. The combustor dome can be moved axially inside the combustion chamber. The air flow is supplied by a fan which is designed to operate under atmospheric conditions and generates...
a maximum relative pressure of 0.7 bar with a maximum volume flow of 1600 m$^3$/h. The air mass flow is measured by a vortex flow meter. Close to the plenum, the air is preheated by a preheater with a maximal power of 17 kW. The pressure in the kerosene supply line is generated by a nitrogen bottle, while the kerosene mass flow is detected by a Coriolis mass flow meter. Close to the injection system, a tube connected to a differential pressure transducer and a thermocouple of type K to control the air preheater are mounted. This allows for the control of the effective area of the injection system to identify and prevent leakages. Investigations requiring optical access were performed by replacing the insulated combustion chamber and the water-cooled jacket by a quartz glass cylinder. The OH* images were taken in sideward direction.

3.3. Measurement techniques

In this work, ion current, dynamic pressure, compensated fast temperature and OH* chemiluminescence measurement techniques are applied and compared. The ion current and fast temperature measurements are point-wise measurement techniques. Hence, the resolution of field measurements depends on the distance between the measurement positions. The radial and axial distances between the measurement positions for the ion current experiments was 10 mm. The positive ion current concentration was detected using a water-cooled Langmuir probe that was inserted into the combustion chamber from the top. A DC power supply provided for a voltage of 150 V to be applied to the platinum sphere at the tip of the probe. The reference electrode is the body of the probe. These two electrodes (measurement and reference) are separated by a ceramic layer. An isolating amplifier was used to measure the voltage at a known resistance. The signal was then sent to a signal analyser and afterwards converted into Ampere using Ohm’s law. In Figure 6, the ion current probe is shown. The probe is bent by 90° to enable insertion from the top. The connections of the water tubes are also visible. The right photograph displays an enlargement of the probe tip. The ceramic material that insulates the probe tip from the body is pulled out to illustrate the function in the photograph.

The temperature measurements were made using fine-wire thermocouples. The thermocouples were inserted radially into the combustion chamber via the opening shown in Figure 5. Axial movement was realized by an axial shift of the combustor dome. The change in combustor length does not affect the combustion process or stability, as was previously verified by LBO experiments. The wire diameter of the thermocouples was 100 µm. Due to thermal inertia, thermocouples behave like first-order lag elements. Hence, the time constant of this lag has to be determined at each measurement position by heating up the wire with an electronic pulse and detecting the cooling curve. This was done 50 or 100 times depending on the intensity of turbulence, which was evaluated using a single cooling curve. Afterwards, the mean value of the decay curves was calculated. The measurements were performed with a data rate of 4 kHz for a duration of 10 s. To reduce the influence of amplified noise, a low-pass filter was integrated into the electric circuit and a correction of heat losses due to radiation was made. The range of the time constants was between 15 and 30 ms and was consistent with other studies. Further explanations of this measurement technique are presented by Wollgarten et al. The radial distance between measurement positions was 5 mm and the axial distance was 6 mm.

The dynamic pressure transducer has a sensitivity of 43.5 × 10^{-9} V/Pa and a resolution of 0.69 × 10^{-9} Pa. As the temperatures in the combustion chamber are higher than the maximum operation temperature of the transducer, a flush-mounted installation of the pressure transducer was avoided. Instead, a water-cooled adaptor was used. This adaptor enables an almost

Figure 4. Left: Photograph of the flame of compact, stable shape; right: Photograph of the tornado funnel, semi-stable flame shape.
flush-mounted installation of the pressure transducer (see Figure 5) and ensures low temperatures around the sensor. The combustion chamber length was fixed to $10^9 R_0$.

The excited OH* species were measured using a LaVision digital high-speed camera of type 'HighSpeedStar 5.1'. The camera was operated at a maximum resolution of $1024 \times 1008$ pixels and a measurement frequency of $4$ kHz. The camera was connected to intensified relay optics and a quartz glass object lens. A filter with a maximum transmittance at $308$ nm wavelength was mounted to the object lens to ensure the detection of OH* radiation.

4. Experimental results

The experimental data were analysed in the frequency as well as in the time domain. Experiments were performed under constant boundary conditions and also during the reduction of the kerosene mass flow leading to leaner conditions. The first section presents an extensive analysis of the results in the frequency domain. First of all, dynamic pressure measurements of the system with and without combustion are discussed to classify dominant frequencies transported via acoustic waves. Under non-reactive (isothermal) conditions, the primary and secondary swirlers also are investigated separately to determine the origin of dominant frequencies. Mode coupling will be identified by the analysis of the spectra obtained from OH* chemiluminescence, ion current and fast temperature data. Table 1 gives an overview of the test cases. The equivalence ratio ($\phi$) of combustion is around 0.5 and normalized to the equivalence ratio of flame extinction. The flame transition described in section 3.1 occurs between

Figure 5. Left: Schematic drawing of the test facility; right: Enlargement of the insulated combustion chamber with attached plenum and injection system.

Figure 6. Left: Ion probe with tubes for water cooling; right: Probe tip with platinum sphere.
$\phi_{LBO}/\phi = 0.85$ and $\phi_{LBO}/\phi = 0.92$. Boundary conditions at $\phi_{LBO}/\phi = 0.85$ are therefore close to the flame transition and, hence, close to the limit of technical relevance.

In the second section of the experimental results, measurements under transient boundary conditions are presented and the ion current technique is evaluated in terms of lean blowout prediction.

### 4.1. Frequency analysis

#### 4.1.1. Dynamic pressure measurements

In this section, results of dynamic pressure measurements are presented for an air preheating temperature of 540 K. Figure 7(a) shows the pressure RMS spectra for 2, 3 and 4% pressure drop under non-reactive conditions for the primary swirler only. The secondary swirler was closed with a heat-resistant tape during the experiments. The spectra show significant peaks at 36 and 1290 Hz for 2% pressure drop, which are shifted towards higher frequencies with increasing pressure drop and, hence, increasing air velocity. The peaks at low frequencies are caused by the coupling of the acoustic mode with the flow field, which leads to an increase with increasing flow velocity. At 340 and 1100 Hz, eigenfrequencies of the combustor and the plenum are detected ($f_c$). The maxima marked by $f_{PVC}$ are the frequencies of the PVC as observed by velocity measurements by laser-Doppler anemometry (LDA) performed by Marinov et al.\textsuperscript{42} LES calculations by Keller et al.\textsuperscript{43} are consistent with the experimental findings relating to the PVC.\textsuperscript{41} In Figure 7(b), the spectra of the secondary swirler are plotted. The PVC frequencies are not present, while flow-dependent hydrodynamic instabilities are detected between 72 and 104 Hz ($f_h$) and eigenfrequencies $f_v$ are identified.

Measurements with both swirlers in Figure 7(c) reveal the combination of the findings explained above. The helical structure of the secondary swirler ($f_h$) and the frequency of the PVC ($f_{PVC}$) are present in the spectra. The maxima between 146 and 208 Hz are the second harmonics of $f_h$. Additionally, the difference of $f_{PVC}$ and $f_h$ exists for each pressure drop with comparably high maxima. The dominant frequency at 1100 Hz in Figure 7(a) and (b) vanishes for the combined measurement and the first eigenfrequency around 340 Hz is coupled with the flow field, which in return causes a dependency of velocity.

Figure 7(d) displays the spectra for the case of stable combustion. The difference of $f_{PVC}$ and $f_h$ is not visible anymore. The dominant frequencies $f_h$ are shifted to higher values, because the acoustic pressure propagates with the velocity of sound, which is proportional to the square root of temperature. The frequencies increase by a factor of 1.65, leading to a temperature of 1470 K. This temperature is far below the global adiabatic temperature of the operating conditions, because the plenum with the preheating temperature reduces the temperature influence caused by combustion.

In Figure 8 on the left, pressure spectra at different equivalence ratios are plotted. At a comparably high equivalence ratio ($\phi_{LBO}/\phi = 0.78$), the peaks of the thermo-acoustic instability ($f_c$) and the coherent structure ($f_{PVC}$) are more distinct. Additionally, an interaction frequency $f_i$ can be found as the difference between the PVC and acoustic eigenfrequency. This phenomenon was observed by Boxx et al.\textsuperscript{44} and investigated intensively by Moeck et al.\textsuperscript{6} The interaction is an indication of a coupling or superposition of the PVC and a thermo-acoustic oscillation. This allows the conclusion to be drawn that the acoustic eigenfrequency is coupled to the heat release rate.

At $\phi_{LBO}/\phi = 0.85$, the thermo-acoustic instability is relatively weak. As a consequence, the interaction with the PVC vanishes. Further leaning of the measurement conditions to $\phi_{LBO}/\phi = 0.92$ causes the flame transition from the compact stable shape to the tornado funnel shape. The spectrum looks totally different: Low frequencies up to 100 Hz increase, while the combustion noise at frequencies higher than 100 Hz is significantly smaller. The frequency of the hydrodynamic instability $f_h$ of the secondary swirler and the thermo-acoustic

### Table 1. Operating conditions and measurement techniques applied in the experiments.

| Measurement technique       | Swirler                  | $\Delta p/p_0$ (%) | $\phi_{LBO}/\phi$ |
|----------------------------|--------------------------|--------------------|-------------------|
| Pressure                   | Primary                  | 2; 3; 4            | Non-reactive      |
| Pressure                   | Secondary                | 2; 3; 4            | Non-reactive      |
| Pressure                   | Primary + secondary      | 2; 3; 4            | 0.85              |
| Pressure; OH*              | Primary + secondary      | 3.5                | 0.78; 0.85; 0.92  |
| OH*                       | Primary + secondary      | 2; 3; 4            | 0.85              |
| Ion current, temperature   | Primary + secondary      | 3.5                | 0.85              |
instability disappear, whereas the PVC as a fluid dynamics-driven coherent structure continues to exist.

The frequency \( f_{i2} \) is the difference between the PVC frequency and the frequency \( f_{c2} \), which results from the primary swirler at around 50 Hz, as can be seen in Figure 7(a). The frequency \( f_{c2} \) is increased to 100 Hz due to the temperature rise. The table on the right of Figure 8 summarizes the dominant frequencies for the case of stable combustion that will be further investigated using the chemiluminescence, ion current and fast temperature measurement techniques.

### 4.1.2. OH* chemiluminescence measurements

Figure 9(a) displays spectra of the OH* chemiluminescence images at different pressure drops and Figure 9(b) at different equivalence ratios. On this basis, the dominant frequencies of the acoustic pressure can be evaluated for the case of combustion. The spectra were calculated by evaluating the intensity of the whole OH* image. The
thermo-acoustic instability is still visible except for the semi-stable flame state ($\phi_{LBO}/\phi = 0.92$), which confirms coupling with the heat release rate. Neither the PVC frequency nor the interaction frequency between thermo-acoustic instability and the PVC exist in any of the spectra. In Figure 9(c), the OH* frequency spectra of the left and right sides of the combustion chamber at 3.5% pressure drop are plotted exemplarily because of the skew-symmetric structure of the PVC. However, the PVC and interaction frequencies are lacking, leading to the conclusion that the OH* chemiluminescence measurement is not sufficient to measure the influence of the PVC on the heat release rate.

4.1.3. Ion current and fast temperature measurements. A Fourier transformation at every measurement position and the isolation of the dominant frequencies summarized in Figure 8(b) enable visualization by contour maps. At the American Society of Mechanical Engineering (ASME) 2015, the authors presented several contour maps of ion current, fast temperature and OH* radiation for varied pressure drops and air preheating temperatures. They concluded that the ion current technique is an appropriate method to display the heat release rate like the OH* radiation. In Figure 10, the frequencies of the thermo-acoustic instability, the PVC and the interaction are plotted based on the ion current (left) and fast temperature (right) measurement results for the stable and compact flame type ($\phi_{LBO}/\phi = 0.85$). The red oval in Figure 10(a) marks the reaction zone. The solid black lines indicate the IRZ and ORZ, while the dashed lines denote the mean spray direction.

Analysis shows that the frequency of the thermo-acoustic instability in (a) is displayed well by the reaction zone and coincides with the OH* spectra. The fast temperature measurements additionally reveal coincidence of frequency peaks with the local signal measured in the inner (ISL) and outer shear layer (OSL). In Figure 10(b), it can be seen that the PVC frequency is detected in the OSL by the ion current measurement technique. This leads to the conclusion that reaction takes place in this area, which is influenced by the motion of the PVC. This is in agreement with the calculations of Keller et al. who investigated the interaction of the spray and the PVC by Large Eddy Simulation (LES). A clear difference exists between the spectra of OH* radiation and the ion current. The
fast temperature measurements reflect the PVC frequency in the OSL and also in the ISL, because this measurement technique is not only related to the heat release rate, but also to the mixing processes of cold and hot gases due to recirculation. In Figure 10(c), the interaction frequency $f_i$ is displayed. It is obvious that this frequency only exists in areas in which both the PVC and the thermo-acoustic instability are detected. Occurrence of the interaction frequency underlines the fact that the ion current technique is suitable for detecting the PVC influence on the heat release rate.

4.2. Transient boundary conditions

As described above, flame transition from the stable, compact flame shape to the tornado funnel shape is treated as LBO. The tornado funnel state suffers from high carbon monoxide and unburned hydrocarbon concentrations and is of no interest to technical applications. The ion current probe was placed at three different positions. Simultaneously, chemiluminescence was measured. In this way, the time response and the probe’s capability of detecting LBO can be determined.

In Figure 11, Abel-transformed images of OH* radiation are displayed for the compact flame shape (left) and the tornado funnel state (right). The white circles with a cross inside mark the three different positions of the ion current probe. To detect the flame transition, the fuel mass flow was decreased during one recording interval of the signals. The diagrams in Figure 11 on the right display the ion current and OH* chemiluminescence trends versus time. The red rectangles denote the change in flame shape. This area is enlarged in the right part of the diagrams. The Abel-transformed images reflect the characteristics of the ion current signals: At position 1, the probe first is located in an area with low OH* radiation. After transition, the signal amplitude decreases significantly, since OH* radiation decreases. The characteristic at position 3 is similar, but even more intense. Position 2 is located in a region where reaction takes place before and after the transition. The change in flame shape cannot be detected clearly. Position 3 is suited best for detecting flame transition. For this reason, the following investigation will focus on this position exclusively. The results show that the response of the ion current probe to the flame transition depends on the location inside the combustor and is not delayed compared to the OH* signal. The probe is fast enough for combustion control with a feedback control loop.

4.2.1. LBO prediction. The ion current time signal shown in Figure 11 exhibits a remarkable number of peaks in regions with a reaction. In literature, each peak is interpreted as a flame front passing the sensor, which results in a high amount of ions and, hence, ion current. These flame fronts are related to the large eddies so that the mean distance between the peaks in the time signal of the ion current can be interpreted as a reacting turbulent time scale. The analysis presented here was performed in the time domain.

Use of the ion current probe as LBO sensor requires calculation of the peak mean distance during operation so as to enable a feedback loop control, as shown by Muruganandam et al. and Keshav et al. for chemiluminescence data. The analysis presented here is done afterwards and focuses on the use of control loops in technical applications. For this reason, the signal is sliced into commensurate parts with a specific interval length $\Delta t$. The calculation has to be applied to each part. As the intensity of the signal depends on the AFR, the original signal is detrended first, as shown in Figure 12. In this figure, the original signal is shown...
on the left, while the detrended signal is shown on the right. Apart from the interval size $\Delta t$, a threshold value has to be defined, which separates the dominant peaks from each other. The blue line in the detrended signal in Figure 12 marks a threshold of 0.33 m$A$. For each interval, the mean peak distance can then be calculated.

The mean peak distances for each interval are plotted in Figure 13 and denoted turbulent time scales $\tau_t$. The diagram on the left has an interval size of 50 ms, while the diagram on the right was generated with an interval size of 125 ms. The LBO has been observed during the experiments after a time period that correlates with the blue line. The results reveal a significant increase of the turbulent time scale due to a lack of peaks or reaction around the large-scaled turbulent structures for both interval sizes when approaching the LBO. The analysis at the higher resolution of 50 ms shows that this increase is stronger before the shape of the flames changes after 3 s. The results reveal a significant increase of the turbulent time scale. The lack of peaks and, consequently, the increased mean peak distance indicate that the LBO will occur. This increase of the turbulent time scale caused by the lack of peaks predict LBO and can be considered as LBO precursors.

In general, a small interval enables a faster reaction to the combustion process in a feedback control loop. The presented data rate of 4 kHz is low, while the fuel
mass flow reduction rate of 6 s is fast. Consequently, investigations were made in the insulated combustion chamber at higher data rates and slower reduction rate of the fuel mass flow by a factor of 2.3. The results are presented in Figure 14. Please note the scaling of the $x$-axis, which goes up to 30 s. The interval for this analysis is 125 ms and the threshold for the peak detection also is 0.33 $\mu$A. Flame shape transition occurs at 16 s. At 4 kHz data rate, a clear increase of the mean peak distance can be found after 6 s. The higher data rate of 16 kHz causes a more constant and slow increase of the mean peak distance. When neglecting the signal-to-noise ratio, the higher data rate might lead to an increased amount of peaks and thus to a faster and more constant increase of the defined turbulent time scale which is favourable for monitoring. The constant values for the turbulent time scales, which can be observed at 4 kHz data rate, result from a low amount of peaks. This suggests that the threshold of peak detection of 0.33 $\mu$A is quite high for these measurement conditions. Precursors can be found for both data rates and clearly indicate the upcoming flame transition. The increased sampling rate does not result in any advantage: Precursors are found closer to the LBO compared to the lower sampling rate.

5. Conclusions
This article presented the results obtained by different measurement techniques in a double swirled airblast
injection system. Analysis first focused on dominant parts in the frequency domain and then on the time domain of the ion current signal for LBO prediction.

Analysis of the frequency domain revealed an interaction frequency of the thermo-acoustic instability and the PVC frequency for flames with spray combustion, as it had been observed for premixed methane flames by Boxx et al. and Moeck et al. Investigation of the heat release rate demonstrated that the ion current technique is capable of detecting the PVC, while the chemiluminescence results reflect thermo-acoustic instability only. Frequency contour maps of the fast temperature and ion current measurements showed that ion generation and, hence, chemical reaction mainly occur in the OSL of the PVC. Due to the point-by-point measurement, the ion current technique is suitable for obtaining frequency maps, if phase information is not needed.

In the second part of this work, the ion current measurement technique was evaluated in terms of LBO prediction. The results showed that the success of this method depends on the measurement position. For the investigated injection system, an advantageous position close to the wall produced excellent results. The ion current system proved to be fast in terms of time response, so that it is possible to use control loops in a technical application. Precursors are needed to enable control mechanisms. They were determined successfully using the mean peak distance of the ion current signal. Three parameters had to be adapted for reliable precursor detection: A threshold value for peak identification, an interval size and a threshold value, which defines extinction moments.

The ion current measurement technique is a promising approach to combustion control and to detection of dominant frequencies in the combustor. Investigations under pressurized conditions are ongoing and will soon enable an application in an annular combustor.

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References
1. Lefebvre AH. Gas turbine combustion. Boca Raton, Florida, USA: CRC, 1999.
2. Lieuwen T and Zinn BT. The role of equivalence ratio oscillations in driving combustion instabilities in low nox gas turbines. Symp Combust 1998; 27: 1809–1816.
3. Sattelmayer T. Influence of the combustor aerodynamics on combustion instabilities from equivalence ratio fluctuations. J Eng Gas Turb Power 2003; 125: 11–19.
4. van Kampen JF and Kok JBW. Characterisation of interaction between combustion dynamics and equivalence ratio oscillations in a pressurised combustor. Int J Spray Combust Dyn 2010; 2: 219–252.
5. Durox D, Moeck J, Bourgouin JF, et al. Flame dynamics of a variable swirl number system and instability control. Combust Flame 2013; 160: 1729–1742.
6. Moeck JP, Bourgouin J-F, Durox D, et al. Nonlinear interaction between a precessing vortex core and acoustic oscillations in a turbulent swirling flame. Combust Flame 2012; 159: 2650–2668.
7. Candel S, Durox D, Schuller T, et al. Progress in swirling flames and annular combustor dynamics. Lund, Sweden: European Combustion Meeting, 2013.
8. Candel S, Durox D, Schuller T, et al. Dynamics of swirling flames. Anna Rev Fluid Mech 2014; 46: 147–173.
9. Huang Y and Yang V. Dynamics and stability of lean-premixed swirl-stabilized combustion. Progr Energy Combust Sci 2009; 35: 293–364.
10. Syred N. A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in swirl combustion systems. Progr Energy Combust Sci 2006; 32: 93–161.
11. Doquier N and Candel S. Combustion control and sensors: a review. Progr Energy Combust Sci 2002; 28: 107–150.
12. Culick FEC. Combustion instabilities in liquid-fuelled propulsion systems. In: AGARD Conference Proceedings 450, Joint Propulsion conference, Boston, USA, 1988.
13. de la Cruz Garcia M, Mastorakos E and Dowling AP. Investigations on the self-excited oscillations in a kerosene spray flame. Combust Flame 2009; 156: 374–384.
14. Mirat C, Durox D and Schuller T. Stability analysis of a swirl spray combustor based on flame describing function. Proc Combust Inst 2015; 35: 3291–3298.
15. Cavaliere DE, Kariuki J and Mastorakos E. A comparison of the blow-off behaviour of swirl-stabilized premixed, non-premixed and spray flames. Flow Turbul Combust 2013; 91: 347–372.
16. Muruganandam TM, Nair S, Neumeier Y, et al. Optical and acoustic sensing of lean blowout precursors. AIAA 2002; 3732: 7–10.
17. Muruganandam TM, Nair S, Scarborough D, et al. Active control of lean blowout for turbine engine combustors. J Propul Power 2005; 21: 807–814.
18. Nair S and Lieuwen T. Acoustic detection of imminent blowout in pilot and swirl stabilized combustors. GT 2003; 38074: 16–19.
19. Nair S, Muruganandam TM, Olsen R, et al. Lean blowout detection in a single nozzle swirl cup combustor. In:
20. Nair S, Rajaram R, Meyers A, et al. Acoustic and ion sensing of lean blowout in an aircraft combustor simulator. In: 43rd AIAA meeting papers, Reno, Nevada, USA, 2005, pp.3627–3634.

21. Prakash S, Nair S, Muruganandam TM, et al. Acoustic sensing and mitigation of lean blow out in premixed flames. AIAA 2005; 1420: 2005.

22. Muruganandam TM and Seitzman JM. Fluid mechanics of lean blowout precursors in gas turbine combustors. Int J Spray Combust Dyn 2012; 4: 29–60.

23. Domen S, Gotoda H, Kuriyama T, et al. Detection and prevention of blowout in a lean premixed gas-turbine model combustor using the concept of dynamical system theory. Proc Combust Inst 2015; 35: 3245–3253.

24. Benson K, Thornton JD, Straub DL, et al. Flame ionization sensor integrated into a gas turbine fuel nozzle. J Eng Gas Turb Power 2005; 127: 42–48.

25. Chorpening BT, Huckaby ED, Morris ML, et al. Flame ionization distribution and dynamics monitoring in a turbulent premixed combustor. In: Proceedings of turbo expo, Barcelona, Spain, 2006, GT2006-90879, pp.8–11.

26. Chorpening BT, Thornton JD and Benson KJ. Flame ionization sensor testing in a pressurized combustor. In: IEEE sensors, Orange County, Irvine, California, USA, 2005, p.4.

27. Peerlings LBW, Kornilov VN, de Goey P, et al. Flame ion generation rate as a measure of the flame thermo-acoustic response. Combust Flame 2013; 160: 2490–2496.

28. Lawton J and Weinberg FJ. Electrical aspects of combustion. Vol. 1, Oxford: Clarendon Press, 1969.

29. Langmuir H and Mott-Smith I. Studies of electric discharges in gases at low pressures. General Electr Rev 1924; 27: 449, 538, 616, 762.

30. Fialkov AB. Investigations on ions in flames. Progr Energy Combust Sci 1997; 23: 399–528.

31. Wortberg G. Ion-concentration measurements in a flat flame at atmospheric pressure. Symp Combust 1965; 10: 651–655.

32. Calcote HF, Kurzius SC and Miller WJ. Negative and secondary ion formation in low-pressure flames. Symp Combust 1965; 10: 605–619.

33. Wollgarten JC, Zarzalis N, Turrini F, et al. Ion current measurements as a method for the detection of the reaction front in combustion with swirl stabilized airlub injection systems. In: Proceedings of turbo expo, 2015, GT2015-42357, Montréal, Canada, pp.8–11.

34. Manfred Ahlheim. Reaktionsstruktur einer turbulenten Diffusionsflamme hergeleitet aus Ionisationsmessungen. PhD Thesis, Karlsruhe, Germany, 1981.

Notation

- f Frequency (1/s)
- $L_t$ Integral length scale (m)
- $M$ Mass flow (kg/h)
- $p$ Pressure (kg/(s^2\cdot m))
- $q$ Volumetric thermal load (kg/(s^3\cdot m))
- $R_0$ Nozzle outlet radius (mm)
- $t$ Time (s)
- $\phi$ Equivalence ratio (–)
- $\tau$ Time scale (s)