SELF-EXITED OSCILLATION IN A COMBUSTION CHAMBER DRIVEN BY PHASE CHANGE IN THE LIQUID FUEL FEED SYSTEM

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A new mechanism for the generation of a self-exited oscillation of combustion in a generic combustion chamber typical for aero-engine combustors is described. The cause of the oscillation is the phase change from liquid to vapour which happens when the preheat temperature of the air flowing through the burner exceeds the boiling temperature at the operating pressure and the fuel flow is so low that heat transfer to the liquid fuel causes evaporation within the fuel channels of the burner. Liquid fuel and vapour alternatively enter the airstream of the burner. This leads to an instable situation for the flame. Measurements of chemiluminescence and liquid fuel show nearly complete extinction and reignition for the limit cycle. Prevention of the oscillation is possible by better thermal management on the fuel path.

1 Introduction

Operating cycles of aero-engines lead to combustor inlet temperatures, which are higher than the boiling point of kerosene for a majority of the operating points. For conventional rich-lean combustors, the residence time of the fuel in the fuel lines, if properly isolated from the hot gas path, is small enough to prevent boiling. However for lean combustors, the circumference of the exit of the fuel lines is longer due to the larger size of lean burners having more than twice of the airflow of conventional burners. Since minimal channel heights are imposed for practical fuel systems, the velocity of the liquid decreases, which makes the thermal management more difficult. For internally piloted burners, the use of a central pressure swirl injector as prefilming device is also not possible. This contribution describes a combustion oscillation in a generic experiment, which can evolve when boiling in the fuel lines cannot be prevented.

For the validation of two-phase flow codes, a research burner was built. It is operated in a generic single sector combustor with optical access operating at intermediate pressures with respect to aero-engine cycles. During the commissioning, on the search of a lean operating point representing a part load condition, a combustion oscillation was encountered, that is connected with the heat transfer to the fuel. In the following chapters, the burner and the combustor are described, the measurement techniques are introduced and the experimental evidence is presented. The cause of the instability, the limit cycle and the oscillation frequency are discussed.

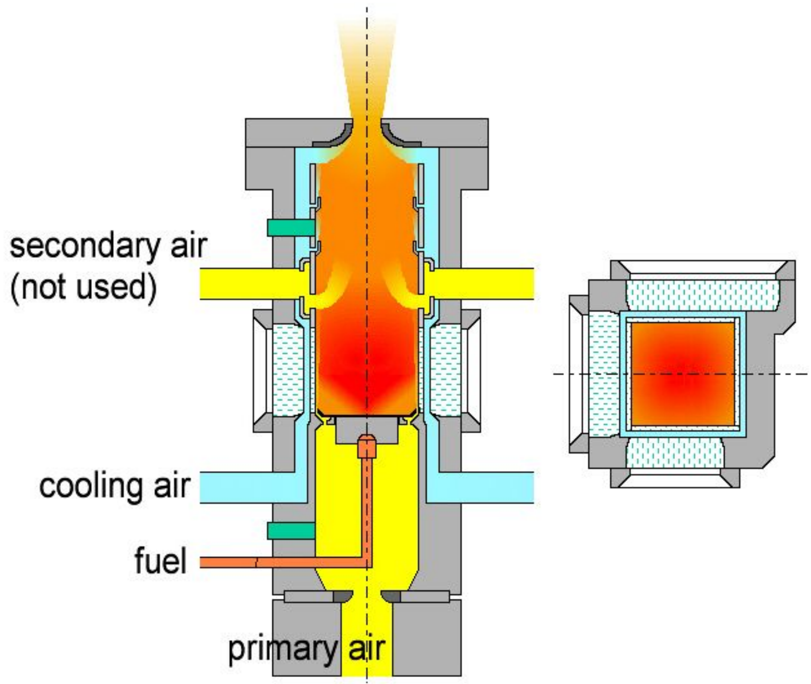


Figure 1: Schematics of the Single Sector Combustor; right: cut through optical section

2 Experimental

2.1 Combustor

The burner was operated in the Single Sector Combustor (SSC). The combustion chamber is schematically shown in Fig. 1. It features a square cross section of 102 x 102 mm and a length of 264 mm. Electrically preheated compressed primary air – shown in yellow – is supplied to the plenum upstream from the combustion chamber through a sonic nozzle, which is used for metering the air mass flow. Additional preheated air is diverted from the primary air supply and guided to the windows for cooling. The secondary air supply shown in the figure was not used in these experiments. Burner and window cooling air are both controlled by sonic nozzles; therefore, the ratio of the air flows was always constant, regardless of the absolute burner air mass flow, which is a function of the variable operating parameters combustor pressure, injector pressure loss and air preheat temperature. According to the sonic nozzle diameters (6.44 mm for burner air, 4 nozzles with 1.72 mm each for window cooling), the air mass flow ratios were: $^{burner}/_{window\ film} = {}^{1}/_{0.285}$; in other words, the fraction of the total preheated air used for window cooling was 22%.

All AFR values mentioned refer to the burner air mass flow, not the total mass flow of preheated air. This definition is somewhat arbitrary as long as the structure of the flow field is not known. If, for instance, the flow should exhibit a pronounced backflow of air, either due to an inner or an outer recirculation zone, entrainment of window cooling air may lead to leaner mixtures near the burner exit; in that case, AFR values based on total air flow might be more appropriate.

The combustor pressure is controlled by another sonic nozzle forming the choked exit of the combustor, along with additional cooling air (blue) which enters the flame tube just upstream from the exit, after cooling the outside of the windows in the optical section. The entire rig is mounted on a three-axes traversing stage which allows positioning with respect to the measuring equipment with an accuracy of

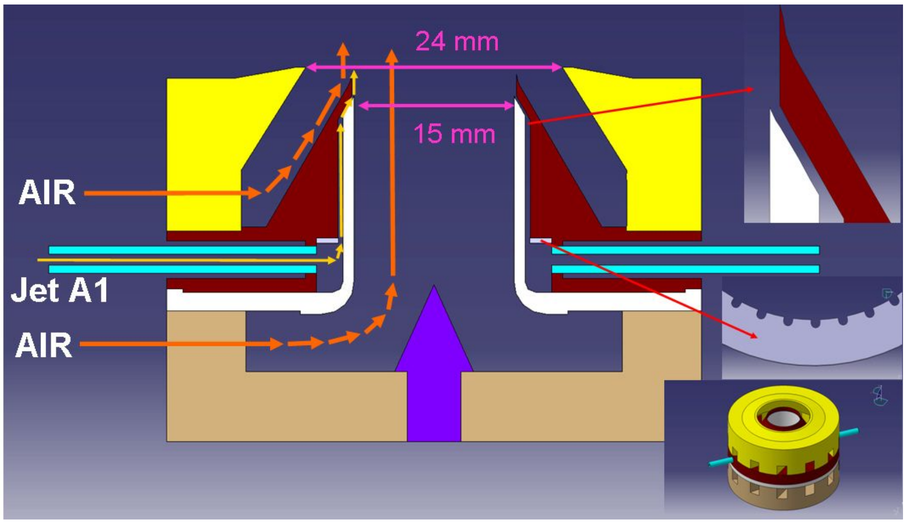


Figure 2: Schematics of the burner. On the right details of the fuel exit slot (top), the metering holes (center) and a 3D view of the assembly

0.1 mm.

The fuel system of the testbed begins at the main kerosene ring line of the media supply of the research site. The fuel is pumped to a manifold, which splits the fuel flow between burner and bypass. The fuel mass flow is measured by Coriolis meters. The fuel mass flow is controlled via the manifold by the SPS control unit of the test bed. Hence the fuel mass flow is held constant irrespective of changes in the pressure losses in the fuel path or changes of the fuel temperature.

2.2 Burner

The burner was built for the purpose of generating a spray that would be representative of aero-engine burners with boundary conditions that should be as well defined as possible. Hence pre-filming air blast atomization was chosen for the fuel injection, as it is the prevailing method in aero-engines. Since ab initio calculation of atomization is not yet possible for the Reynolds number range encountered in practical devices, the measurement of initial conditions with Phase Doppler Anemometry at the nearest possible location to the burner was foreseen. Depending on the codes used, the calculation of the spray could then be started at the outlet of the fuel lines with the film or at the prefilmer lip with a semi-empirical atomization model, the initial measurements providing a first checkpoint of the calculation, or at the location of the measurements. Therefore the design of the burner was to provide a well defined fuel film with respect to temporal and spatial homogeneity as well as some information on temperature.

Figure 2 shows a schematic view of the burner, which was designed and manufactured at DLR, and some of its details. The burner uses radial swirlers. The two air flows are co-rotating. The diameter of the inner air channel is 15 mm, the exit diameter of the outer channel is 24 mm.

Of particular importance to the oscillation are some details of the fuel system, which is therefore described in more detail. Of the two principal variants for prefilming, which are used throughout the industry, the pressure swirl atomizer-swirl cup and the prefilmer supplied from an annular channel between the swirlers, the latter possibility was chosen for a better definition of the initial condition of the film. Earlier research [1] had shown, that for the higher operating conditions of aero-engines, supercritical conditions exist for the film leading to atomization at the wave crests and eventual dry out of the filmer ring. Hence a short prefilmer length is necessary to guarantee that all the fuel is atomized at the prefilmer lip. This is not the case for a pressure swirl injector spraying fuel at the inner wall of a swirl cup, which hits the wall at different places and depending on the angle of incidence can also splash without forming a film.

The kerosene is supplied by two opposite fuel lines to an annular fuel gallery, and from there to a vertical slot through a circular array of 36 orifices with 0.2 mm^2 area each. The pressure drop across these metering holes is so high, that downstream pressure fluctuations of an amplitude that can be tolerated in the combustor, will not result in large changes of fuel mass flow. The pressure drop serves two purposes: it provides a high slope of the mass flow versus pressure relation which is better suitable for a fine control of the fuel mass flux. On the other hand it redistributes the fuel more equally along the circumference from the two opposite fuel entries. The height of the annular slot is restricted to 0.5 mm to minimize the residence time of the fuel. In the middle of the slot height, a thermocouple is embedded in the outer wall to provide an estimate of the fuel temperature at the entry of the air channel. At the end, the slot narrows to 0.2 mm height and is inclined at an angle of 31° which leads the fuel to the filmer lip with a radial momentum small enough to prevent it lifting from the filmerlip, see the detail on the lower right corner of Fig. 2. The purpose of the renewed constriction of the fuel path is the partial isolation of the coaxial fuel slot from the suction of the swirling air flow. Thereby the premature breakup of the film before the opening slot, which was observed in [1] for small film velocities, should be avoided. Apart from the small slot heights, which would not be allowed in a practical injector for reasons of airworthyness, no other means of thermal management were applied.

2.3 Diagnostics

Mean pressures of the plenum and combustor are logged by the data acquisition system as well as the air temperatures in the plenum and the fuel temperature. Two Kistler pressure sensors, one in the plenum and one in the combustor flush with the liner wall monitor unsteady pressures. Unfortunately the measurements of unsteady pressure were not calibrated for the commissioning such that only relative measurements of amplitude of the highest peak in the Fourier spectrum are at hand. The unsteady chemiluminescence is recorded with a photomultiplier, which images the whole flame. It's signal is used as time reference for the oscillation, the positive zero crossing defined as 0°. These time series were the basis for the off-line phase reconstruction [2] of the 2D images of the liquid fuel (Mie scattering) and the reaction zone (OH^* chemiluminescence).

A laser light sheet, generated from the green light of a pulsed Nd:YAG laser, was positioned parallel to and 5 mm above the burner face plate, to monitor the Mie scattering from the spray. The laser sheet was pulsed at a fixed repetition rate of 10 Hz and its time was monitored relative to the oscillation of the OH^* chemiluminescence time series. Because no observation perpendicular to the laser light sheet was possible, the Mie images were taken under an angle of 25° in forward scattering using a intensified CCD camera (LaVision FlameStar2, 384 x 286 pix^2) with a Scheimpflug adapter. In a post-process the images were corrected with respect to the images distortion and intensity distribution within the laser light sheet. Because of the turbulent fluctuations of the combustion, for each test case 900 pictures were taken and sorted afterwards to form groups at fixed phase angles, such that phase averaged 2-dimensional representations of the spray could be generated.

Simultaneously to these Mie images the flame was imaged by chemiluminescence of OH^* as indicator of the heat release. The chemiluminescence was spectrally filtered using an interference filter (315±10 nm) and detected by a second ICCD camera (LaVision FlameStar2, 384 x 286 pix^2), perpendicular to the symmetry axis of the flame. The integration time of 10 μs for a single image is sufficiently short to freeze the motion of all structures within the pixel resolution of 270 μm per pixel. As for the laser light sheets measurements for each test case 900 OH^* chemiluminiscence images were stored for further image processing. After phase averaging using the same method as for the laser light sheets [2], a deconvolution algorithm [3] was applied to the OH^* images to deduce phase and spatially resolved images of the heat release. Additionally films of the chemiluminescence were made with a high speed system from an oblique angle. The high-speed camera system consists of a LaVision HSS6 CMOS camera with pixel resolution of 1024 x 1024 pix^2. With an onboard memory of 8 GB 20 000 consecutive frames could be stored. A high speed controller and the LaVision software tool Davis operate the camera complemented the system and provided a camera timing scheme. The flame luminosity emitted from the combustion chamber was imaged onto the 20 x 20 mm^2 chip by a 85 mm Zeiss objective lens. The viewing angle with respect to the observation window plane of the burner deviated from 90° by 30°.

An aperture of 2.8 was chosen to achieve a depth of focus thick enough to capture the whole nozzle. As

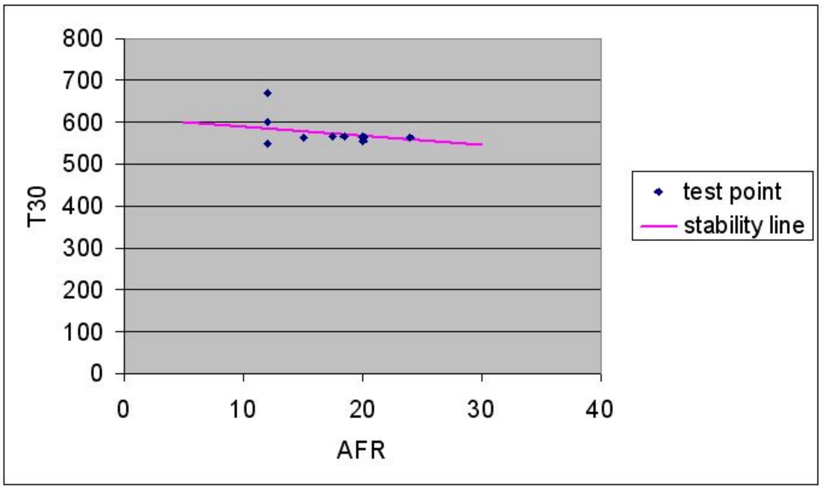


Figure 3: Stability map: Unstable conditions above the line

decreasing the aperture at the same time limits the signal strength, this setting also protects the camera chip from saturation produced by light spots of soot formation.

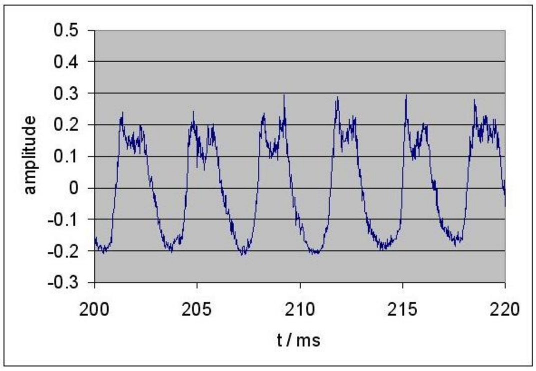
The repetition rate of image acquisition should be adapted to the occurring transient flow phenomena. Since the onboard memory is limited, the selection of the dimensions of the field of view is a trade-off between maximizing the spatial resolution and achieving a repetition rate high enough for the transient flow. A native frequency of the camera was used, enabling the software option to freely adjust the camera chip's region of interest. The aspect ratio of the field of view is adapted to the dimensions of the burning chamber. For the given setup observation windows of 384 x 208 pix^2 can be imaged at 60 kHz repetition rate resulting in 0.26 mm/pix resolution.

3 Results

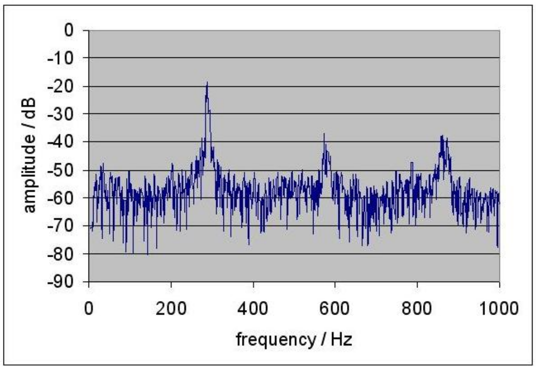
3.1 Operating conditions

For the validation exercise, it was intended to investigate just two operating conditions using the full diagnostic repertoire: One point at low pressure and low preheat temperature, corresponding to idle conditions of an engine, and one at higher pressure, resembling cruise conditions.

For the low pressure operating point, it turned out that both combustor pressure and the spatially integrated OH^* chemiluminescence exhibited strong periodic oscillations with frequencies between 250 and 500 Hz if the pressure was reduced below 4 bar. At 3 bar or below, stable operation could be achieved only under fuel-rich conditions. It was therefore decided to fix the pressure at 4 bar, where stable operation was possible at AFR values up to 20. At this point, also an influence of the preheat temperature was observed: while at 550 K the burner was operating stable, an increase of 20 degrees resulted in noticeable oscillations. An increase of the air temperature from 550 to 570 K results in a wall temperature rise from 450 to 460 K in the vertical fuel slot (see Fig. 2). However, it is known from the properties of kerosene [4], that the vapour pressure of Jet A-1 rises from 0.7 to 4 bar between 460 and 550 K. Since the temperature measurement is not at the end of the fuel path, higher temperatures can be anticipated towards the filmer lip, where significant prevaporization can then take place, introducing an instability in the fuel feed. In any case, the tendency to exhibit instabilities appears to be correlated with the fuel flow: Under conditions where the fuel flow is low, i.e., at low pressures and/or high AFR values, fluctuations occur.



(a)



(b)

Figure 4: (a) Time series and (b) Fourier spectrum of oscillation from OH* at AFR 12 and 670 K preheat

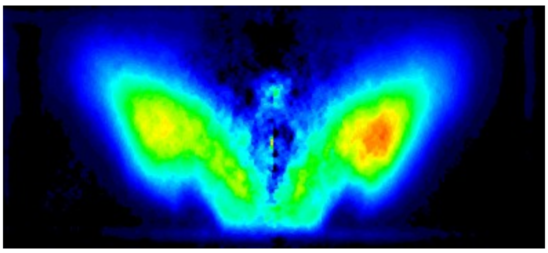
The oscillation was investigated at an air pressure of 4.1 bar, air pressure loss of 3%, AFR's between 12 and 23 and preheat temperatures between 563 and 670 K. In Fig. 3 a stability map is given in a plot of preheat temperature vs. AFR, with the instability above the slightly descending line.

Comparing the fuel temperatures along the stability line for different AFR's provides further evidence for the role of the fuel temperature in the instability: Between AFR 20 at 563 K preheat and AFR 12 at 600 K preheat, the fuel temperature only rises from 460 to 476 K. Considering the nonideal isolation of the thermocouple against the higher temperature of the metal, a nearly constant fuel temperature follows for the boundary to the unstable condition.

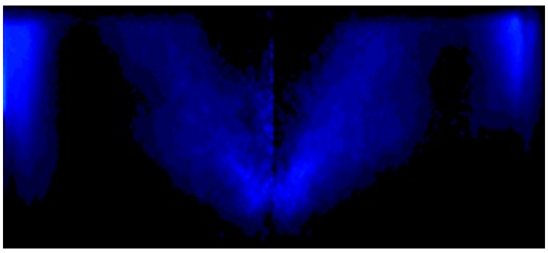
The time series and Fourier spectrum of the oscillation from the OH* chemiluminescence signal at AFR 12 and 670 K are shown in Figures 4(a) and 4(b).

The time series shows a nearly sinusoidal form at the lower half and a ragged top hat at the peak of the heat release curve, always with a hump at the leading edge and sometimes also at the trailing edge. Consequently two harmonics are seen in the Fourier spectrum. The form of the heat release curve is due to the partial extinction and reignition in the oscillation. Here, the high speed video is particularly instructive. It shows, that the flame nearly extinguishes following a nearly complete dry out of the liquid fuel. Some visualization of the phenomenon can be provided by the pictures of the deconvoluted phase averaged OH* chemiluminescence and Mie scattering at the respective minimum and maximum condition.

The frame of Figure 5 is somewhat misleading because the OH* signal extends down to the lower boundary of the picture, which is not identical to the burner face plate but 5 mm above. From the oblique position of the video, a small standoff distance is noticeable also for the max condition. The

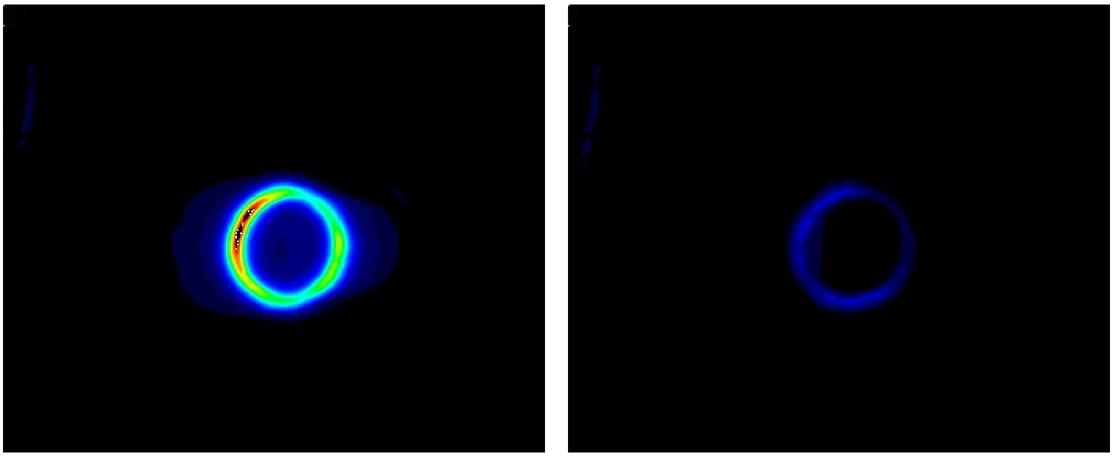


(a)



(b)

Figure 5: Deconvoluted, phase averaged OH* chemiluminiscence at (a) AFR 12, 670 K, and 135° and (b) AFR 12, 670 K and 293°.



(a) (b)

Figure 6: Planar Mie scattering at 5 mm above the burner face plate at (a) AFR 12, 670 K and 22° and (b) AFR 12, 670 K and 225°.

phase difference of 113° between the Mie and OH* at max condition is composed of the convective time for the fuel to reach the flame. There is a different phase delay of 68° for the min condition. This is not astonishing, because two separate processes are at work: The near extinction of the flame depends on the burning velocity and the amount of fuel in the combustor, whereas the minimum of Mie scattering depends on the liquid fuel feed, which should be zero at the injection point, when only prevaporized enters the burner. However the convection times from that point to the plane at 5 mm above the burner faceplate are quite different: the gaseous fuel enters with a higher velocity and some negative radial momentum in the high velocity airstream, whereas the liquid fuel is transported from the injection point to the prefilmer lip with low velocity and must be accelerated by the air flow upon atomization.

The change of frequency of the oscillation with AFR is presented in Fig. 7.

The picture results from a blowout trial, where AFR was continuously lowered. The amplitude shows a steep rise at the onset and a tophat profile up to the point of extinction. The frequency of the oscillation is proportional to the AFR and hence to fuel flow.

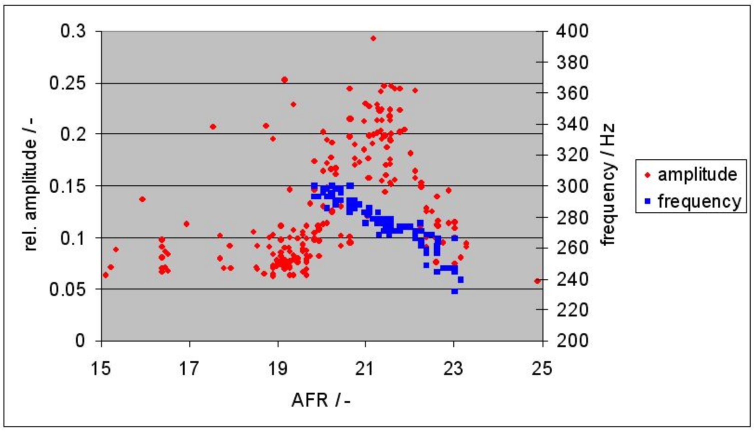


Figure 7: Oscillation frequency and amplitude over AFR.

4 Discussion

From the data presented in the results section it can be rather safely concluded, that the oscillation is connected with a phase change in the fuel line. To transport bubbles of evaporated fuel to the outlet and push them through the final constriction before the swirl channel of the burner keeping up the mass flow, a higher pressure loss is needed. Since the fuel system holds the fuel mass flux constant irrespective of higher pressure losses, the mean pressure loss of the fuel lines downstream of the metering holes rises indeed. The loss occurring if the gaseous fuel flow would be accelerated to reach the mean mass flow rate is on the order of but below the pressure loss occurring at the metering holes. Since the total fuel pressure is rising, this means, that fuel is transported through the metering holes even during phases, when the kerosene bubbles enter the burner. This combination of losses has two effects which are of importance to the oscillation: The gaseous fuel enters the burner with appreciable velocity but with a mass flow lower than the mean value, whereas for the phases when liquid fuel enters the burner, the fuel velocity as well as the mass flow is higher. On the fuel side of the injection point, the phases with gas ejection and lower mass flow rate lead to a higher heat transfer and therefore further enhance the boiling which eventually happens around the whole circumference of the slot. On the air side, the ejection point is in the zone of the smallest area of the gas flow. The higher volumetric flow rate of the gaseous fuel therefore leads to a lower effective area remaining for the air and hence a higher pressure loss for the air, reducing temporarily the air mass flow. This creates the uncommon situation, that a higher pressure loss for the air flow goes together with lower air mass flow. For such conditions, Polifke et al. have formulated an instability mechanism in [5], which is not necessarily thermoacoustic, because the Rayleigh criterion doesn't need to be satisfied for its existence. However since the liquid fuel needs to be transported to the prefilmer lip and therefore encounters a phase delay, the oscillation in air flow rate is accompanied by a oscillation of fuel flow into the combustor, which is not in phase.

For the limit cycle which we observe experimentally, the pressure rise by the reignition and the rising heat release certainly satisfy the Rayleigh criterion. The rising pressure in the combustor reduces the air flow and with it also fuel transport and atomization rate of the liquid fuel, as has been shown for forced oscillation by [6] and [7] for situations with and without combustion. However the effect is limited by the amount of fuel transported during the cycle. Since no velocity measurements nor quantitative values for the fluctuating velocity are available, an upper bound is given by the pressure rise which would be achieved, if the combustion of all the fuel in one cycle would be instantaneous. This value is above the mean pressure loss of the burner, however in the video, where the flame luminescence also lights the fuel spray, remaining fuel flow is seen at least for some cycles. Since on the other hand the fuel inertia can counteract the change of direction of the gas flow, no clear evidence for the complete stop of the gas flow can be obtained.

Fig. 7 showed that the frequency of the oscillation is proportional to AFR. It is not connected to the preheat temperature. Earlier investigations with forced air flow on a burner of similar size in the same rig [8] showed the resonance of the sound room at 324 Hz for 700 K preheat but with a clear dependence on preheat temperature. It is also not connected to an axial mode of the combustor which would be much higher. The time for one oscillation is about 20% lower than the residence time of the liquid fuel in the final constriction for the single phase case. For the higher pressure loss of the 2 phase flow it will be lower. The argument, that the residence time of the fuel in the final passage is connected to the oscillation frequency is rather straightforward, since that is the time that will be needed for liquid fuel to emerge again and reignite combustion once the situation comes up that the whole final passage is dry. Hence the length of the passage also influences the amplitude of the oscillation.

The best and safest way to prevent the type of oscillation seen in this contribution is the prevention of fuel boiling by better methods of thermal management as applied here. One such measure would be the isolation of the fuel path from the hot air stream by materials with lower heat conduction or isolation with air slots. Those methods are routinely used in aero-engines. However as stated in the introduction, lean combustion requires even higher efforts such that it is not always excluded that the conditions described here are avoided at all times.

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