



EXPERIMENTAL INVESTIGATION OF THE THERMO-ACOUSTIC INSTABILITIES COUPLED WITH WALLS VIBRATIONS

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In order to fulfil requirements regarding emission of harmful gases to the atmosphere, the gas turbine technologies had to develop into clean techniques for energy generation. Lean premixed combustion of natural gas is one of them. Since during this process excess of air is used, the total combustion temperature is relatively low. In consequence fewer NO_x pollutants are produced. The major drawback of this process is high sensitivity to thermo-acoustic instabilities. Inside the combustion chamber interaction between several phenomena takes place. Three of them, i.e. combustion, acoustics and the combustion chamber walls vibration may be coupled together into a closed feedback loop that might finally lead to gas turbine failure. The destruction process has an origin in flame intrinsic instabilities. When those are promoted by coupling the heat release fluctuations with acoustic field perturbations, the unsteady self-excited oscillations of the pressure field inside the combustion chamber grows in amplitude and exert significant forces on the chamber walls called liner. The liner is a critical component since it has to operate reliably at extremely high temperatures. This has a significant negative influence on the liner performance and its material properties. Additional pressure forces acting on the walls surface due to unstable combustion reduce significantly the life time of the liner and gas turbine itself.

In this paper the thermo-acoustic instabilities are investigated in combination with liner vibrations. The investigations are done at the combustion test rig which may operate with maximum power of 500 kW and absolute pressure equal to 5 bar. In order to observe influence of the wall configuration on the overall instabilities two liners constructions i.e. stiff or flexible are taken into account. Both liners are investigated at various pressure levels. Finally, the relation between perturbations upstream of the burner and system response in form of the flame transfer function is obtained.

1. Introduction

The main drawback of the lean premixed combustion of natural gas is high sensitivity to thermo-acoustic instabilities. Inside the combustion chamber interaction between three phenomena, namely combustion, acoustics and the vibration of the combustion chamber walls take place. Each flame has intrinsic instabilities which lead to noise generation. Two types of the noise generated by the flame can be distinguished: the autonomous noise which comes from the instabilities in the flame only and coupled noise which is a result of mutual interaction between flame and acoustic waves inside the combustion chamber. The latter is of a great importance in the gas turbine industry as it can lead to thermo-acoustic instabilities and later to damage of the combustion system. The unsteady heat release by the flame is an acoustic source and induces the pressure waves in the acoustic resonator. These acoustic waves travel downstream of the chamber and after reflection from the boundaries return to the flame. As a result of the impinging acoustic wave, the instabilities within a flame are enhanced and the flame fluctuates even stronger. High amplitudes of pressure oscillations lead to high forces on the liner surface. When the thermo-acoustic instabilities are not present in the system, the amplitude of vibration is relatively small and the turbine can work for a desired long time without any maintenance. However, in case when self-excited instabilities arise in the system, especially when their frequency is nearby, or even match with the resonant frequency of the combustion chamber walls, the life time of the chamber is reduced significantly. The acoustic loads exerted with the frequency matching the resonant frequency of the liner can lead to high vibration amplitude. This behaviour can lead to the self-excited oscillations of such high amplitude that fatigue damage of the structural parts occurs.

2. Combustion setup

The combustion setup under investigation can work with a maximal thermal power equal to 500 kW at 5 bar absolute pressure. The investigated flame is a natural gas lean premixed flame. To decrease the overall temperature of the structural parts exposed to flame and hot gases, between the liner and pressure vessel a cooling air flow is present. The combustion test rig consists of three modular parts: combustion, structural and cooling section. The cross-section of the combustion test rig together with its modular parts and location of data recording points is presented on Figure 1, where P and Ps are dynamic and static pressure sensors respectively, T are thermocouples, LDV is Laser Doppler Vibrometer and CCD stands for the camera for chemiluminescence measurements.

The combustion section is located just behind the burner mouth. In this section the combustion process takes place. The flame is self-sustained and stabilized by recirculation regions of hot gases which ignite the fresh mixture. To make observations of the flame and measurements the setup is equipped with a system of windows. The windows are mounted in the liner and pressure vessel. Chemiluminescence and Planer Laser Induced Fluorescence (PLIF) can be used to gather information about in-flame composition.

The structural section is the part of the combustion test rig where the vibrations of the liner are measured. To make the liner more sensitive on the pressure changes inside the combustion chamber, part of it has a smaller thickness with comparison to the overall wall thickness. Thus any variations in the pressure pattern inside the combustion test rig are immediately translated to changes in the vibration amplitude and frequency of the flexible section. In order to obtain information about the liner vibrations amplitude and frequency, the flexible section must vibrate freely without any damping. Non-invasive techniques are used for data collection and all thermocouples and pressure transducers are placed at some distance from the flexible section. That is why comparison of the liner vibrations and acoustic pressure is done at different positions. Since the Laser Doppler Vibrometer is the technique employed for vibration data collection, it is necessary to have access to the vibrating liner via transparent windows in the pressure casing. For the liner configura-

tion presented here, the structural modes in the investigated frequency range show mostly the one-dimensional shape. Therefore, liner vibrations are measured through a slit window.

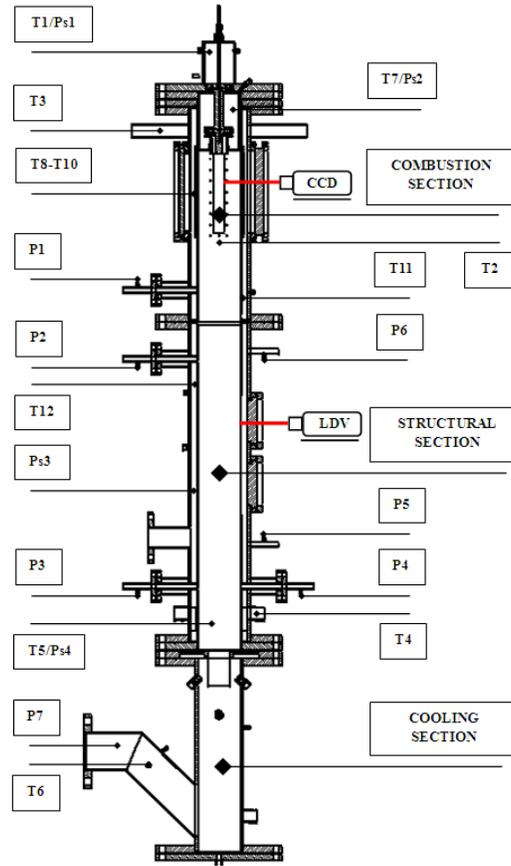


Figure 1: Combustion setup configuration

Two liner configurations with different thickness and length of the flexible section are under investigation. The overall size of both is the same, 150x150x1813 mm and 4 mm thickness of the stiff part. The difference lies in the dimensions of the flexible part. In the configuration called Desire, the flexible section thickness is equal to 1.5 mm and length of 400 mm, whereas in the Fluistcom configuration, the flexible part has thickness equal to 1 mm and length equal to 680 mm. Both names i.e. Desire and Fluistcom come from the names of the EC projects during which the liners were manufactured. The influence of liner configuration on the thermo-acoustic instabilities is investigated with the combustion process at various operating conditions, see Table 1. For measurements with pulsating equivalence ratio a MOOG valve is used. The MOOG valve perturbs the mass flow of fuel in a controlled way. The frequency and amplitude of pulsation is controlled by a Siglab device which sends a signal in form of a voltage change to the MOOG valve.

Table 1: Investigated operation points

Operating point	Thermal power [kW]	Absolute pressure [bar]	Air factor [K]	Mass flow rate [g/s]	Preheating temperature [K]
15.7	125	1.5	1.8	75.53	300
20.8	187	2.3	1.8	113.00	300
30.5	250	3.0	1.8	151.07	300

In the cooling section the temperature of exhaust gases is reduced by mixing first the hot flue gases with the cool air from the cooling passage and then by a water spray. The second task of the cooling section is to provide a uniform pressure distribution in the combustion chamber and cooling

passage. Otherwise, high mechanical stresses can occur in the thin liner walls and finally they might lead to liner fatigue damage. To equalize pressure on both sides of the liner, the cooling passage is connected with the cooling section by four steel bypass hoses. Since the cooling section is also connected with the combustion chamber only minor pressure difference in the combustion chamber and cooling passage are visible. Furthermore, at the place where the structural section is connected with the cooling section a sudden contraction of the combustion chamber exists, see Figure 1. This contraction combined with water spray from the cooling section forced most of the acoustic wave to reflect back inside the combustion chamber.

3. Pulsating flow

In this section results of the experiment performed with fluctuating mass flow rates of fuel are presented. Fluctuations are done with frequency equal to 300 Hz and amplitude of 8.5% of the mean equivalence ratio.

The pressure spectra of pressure transducers P1-P3 present similar behaviour. The forcing peak is located exactly at 300 Hz and the thermo-acoustic instabilities are placed in the vicinity of the second acoustic mode (located around 440 Hz), see Figure 2. The Fluistcom liner configuration shows instabilities at lower frequency with respect to the Desire geometry. The main instabilities are visible at 431 Hz, whereas for the Desire configuration, they are placed at frequency of 439 Hz. This behaviour is confirmed by a series of experiments for the same operating point, where depending on the instantaneous temperature profile inside the combustion chamber and cooling passage, the thermo-acoustic instabilities vary slightly (405-431 Hz for Fluistcom and 433-458 Hz for Desire geometry). At a frequency of 614 Hz for the Fluistcom and 640 Hz for the Desire liner configuration the secondary instabilities appear. They are nearby the third acoustic mode located around 612 Hz. This behaviour presents a strong correlation between thermo-acoustic instabilities and acoustic natural frequencies of the combustion chamber. In case of pressure transducer P1, the peaks around the third and fourth acoustic frequency are even more significant than the main instabilities. This could be an effect of the pressure node located somewhere nearby location of the pressure transducer P1.

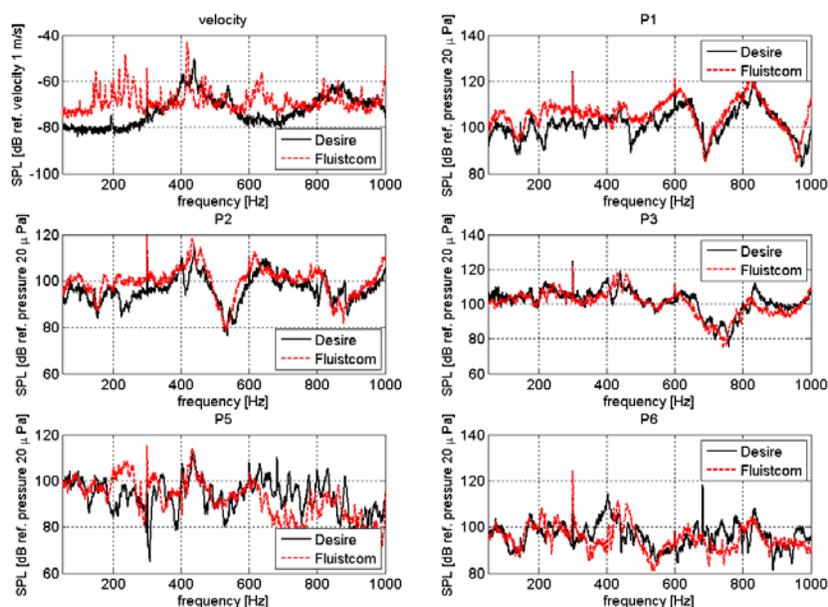


Figure 2: Results of experiment with pulsating flow

The velocity spectrum presents the coupling between acoustic pressure fluctuations and structural vibrations. The strongest coupling is with the second acoustic mode, where the thermo-

acoustic instabilities are visible. The Fluidcom configuration presents coupling with all acoustic modes. However here, the main frequency of liner vibrations is moved from frequency of 431 Hz to 417 Hz. Modal analysis performed in the FEM code in addition to the experiment discovered that at a frequency equal to 420 Hz there exists a structural mode which includes not only the flexible part of the liner but the whole liner. A similar mode is observed for the Desire configuration at frequency equal to 402 Hz. In this case the main vibration frequency is not shifted but the velocity peak occurs at this location.

The main trend of the pressure signal in the cooling passage (P5-P6) resembles more the pressure observed in the combustion chamber than the flexible liner part vibrations. The Fluidcom geometry induces some additional pressure fluctuations in the cooling passage due to the very flexible section (especially visible around 200-250 Hz). The Desire liner due to its high stiffness hardly influences the pressure field inside the cooling passage. Therefore, most likely the noise from the combustion chamber is transmitted to the cooling passage via vibrations of the whole walls and not only due to vibrations of the flexible section. The remaining peaks visible on the cooling passage spectrum come from the acoustic eigenfrequencies of the passage combined with the wall vibrations and turbulences induced by flow around connection for the pressure transducers, thermocouples, bypass connection etc. These obstacles make the signal in the cooling passage more undulating.

4. Flame transfer function

The FTF is studied in numerous papers for passive and active flames, see e.g. [1] and [2], respectively. However, most of the studies are performed for atmospheric pressure conditions. In this article the flame transfer function is investigated at elevated pressure (1.5 bar – 3 bar) for operating points depicted in Table 1. The FTF is obtained entirely with the use of experimental data and thermodynamic relations for two different geometries of the combustion chamber. To retrieve the flame transfer function, steady and pulsating conditions are used. The main sources of the instabilities in the lean premixed turbulence flame are fluctuations in the equivalence ratio, see [3]. Therefore the mass flow rate of the fuel is perturbed by the MOOG valve. Since the instantaneous rate of volume integrated heat release by the flame is not trivial to measure directly, the flame transfer function is divided on several, relatively to measure relations, see Eq. (1). The layout of the techniques employed to reconstruct the FTF is presented in Figure 3.

$$H_f = \frac{\overline{\dot{m}}_f}{\overline{\dot{Q}}} \cdot \frac{\dot{Q}'}{\dot{m}'_f} = \frac{\overline{\dot{m}}_f}{\overline{\dot{Q}}} \left[\frac{\dot{Q}'}{M'} \cdot \frac{M'}{p'_{meas}} \cdot \frac{p'_{meas}}{\delta'} \cdot \frac{\delta'}{\dot{m}'_f} \right] \quad (1)$$

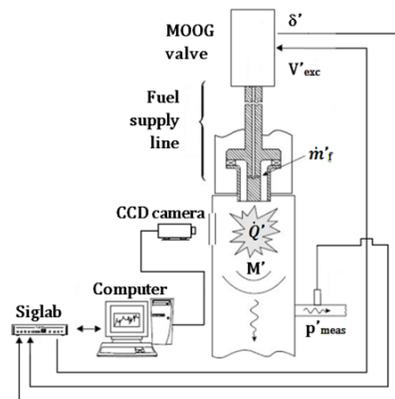


Figure 3: Scheme of the main components used to retrieve the FTF

The dynamic measurements are done for the frequency fluctuation in range from 40 Hz to 400 Hz and amplitude of pulsation equal to 7.5% of the mean equivalence ratio. For the frequency

change a sweep-sinusoidal signal generated by the Siglab is used. The resultant transfer function is saved with frequency interval equal to 5 Hz. To distinguish the correlated flame response from the flow noise, only results with coherence equal to 0.85 and above are taken into consideration. Both dynamic and steady flow data is averaged over 20 loops. Measurements of CH* intensity are performed with sampling frequency equal to 1000 Hz which limits the CH* spectrum to 500 Hz. Since the air factor, preheating temperature and mean flow velocity in all cases are the same, the influence on the flame transfer function spectra is limited to the liner geometry and absolute pressure.

The first ratio in the bracket in Eq. (1) is known from the thermodynamics as $\frac{\dot{Q}'}{M'} = \frac{c_0^2}{\gamma-1}$. It is evaluated at adiabatic flame temperature and is assumed to be constant over the flame, see [4].

The second factor i.e. $\frac{M'}{p'_{meas}}$ represents the transfer function between acoustic mass flow and local pressure perturbation. This function characterise the acoustic behaviour of the combustion system. Since the concentration of CH* radicals is linearly proportional to the rate of heat release in the flame, see [4], the spectral shape of the acoustic source is determined from the chemiluminescence measurements of the light emitted by excited CH* radicals. For the spectral shape of pressure oscillations, auto-spectrum of pressure transducer P1 is used. The transfer function between acoustic flow and local pressure perturbation presented for the Desire and Fluistcom configuration on Figure 4 (left) show a similar results profile. In all cases two peaks in the spectrum are visible around frequencies of 50 Hz and 150 Hz. They might appear due to acoustic modes of the whole setup, however their magnitude is most likely overestimated since the flow noise in the low frequency region has higher impact on the results than in the high frequency region. In the chemiluminescence spectrum see Figure 4 (right) the thermo-acoustic instabilities are present in the frequency range 410-460 Hz. This agrees well with the signal obtained from the pressure transducers and presented on Figure 2. The remaining part of the spectrum presents a shape typical to the turbulence noise with a few peaks around the acoustic eigenfrequencies.

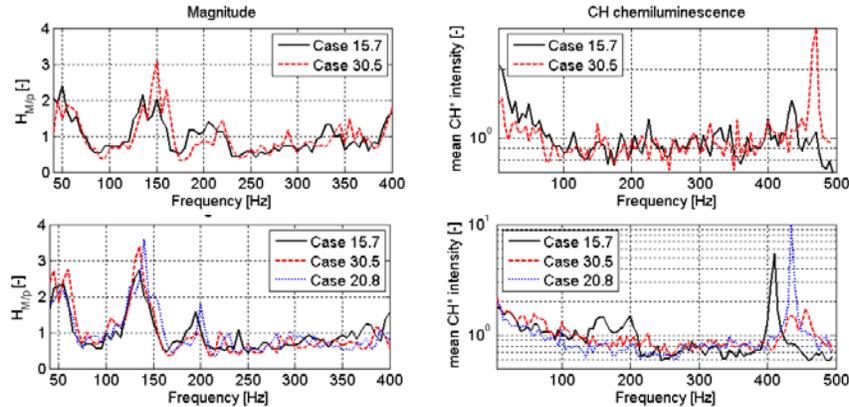


Figure 4: Transfer function $\frac{M'}{p'_{meas}} / \frac{\bar{M}}{\bar{p}_{meas}}$ (left) together with CH* spectrum (right) obtained during investigation of the Desire (top) and Fluistcom (bottom) configuration

The next factor $\frac{p'_{meas}}{\delta'}$ is obtained from the dynamic combustion experiment. The ratio between cross-spectrum and auto-spectrum is taken to determine the transfer function between pressure fluctuations at position of pressure transducer P1 in the combustion chamber and MOOG valve displacement. The magnitude profile of the $\frac{p'_{meas}}{\delta'}$ transfer function is alike for all measurements, see Figure 5. Only minor differences in the amplitude of peaks are observed. Introduction of the flexible liner structure and higher absolute pressure introduce minor dissimilarities between the profiles. The phase spectrum investigated during various conditions presents almost linear behaviour with no clear distinction between investigated operating points and geometries. For all spectra exists a constant time delay between system excitation and response.

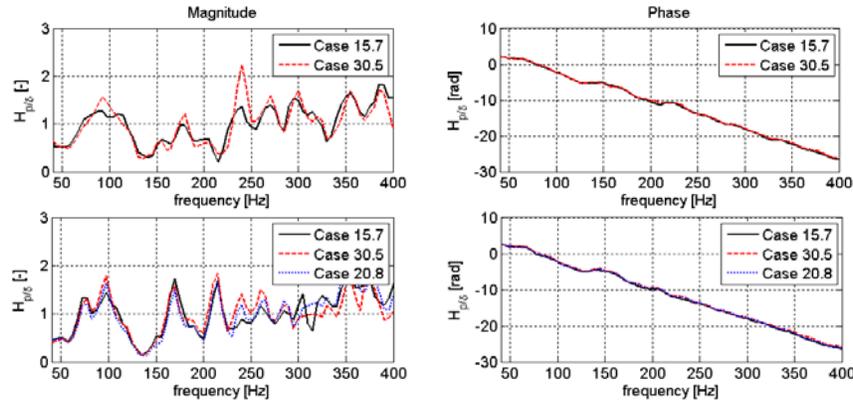


Figure 5: Transfer function $\frac{p'_{meas}}{\delta r} / \frac{\bar{p}_{meas}}{\bar{\delta}}$ of Desire (top) and FluiSTCOM (bottom) investigation

The last transfer function $\frac{\delta r}{\dot{m}'_f}$ represents the quality of the signal transmitted from the MOOG valve to mass flow rate of the fuel, as presented on Figure 6. This data is received from separate experiment performed and described by Kleinlugtenbelt in [5].

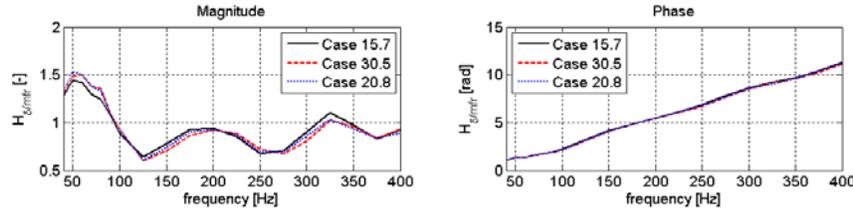


Figure 6: Complementary transfer function $\frac{\delta r}{\dot{m}'_f} / \frac{\bar{\delta}}{\bar{m}_f}$ for both liner configurations

The combination of all aforementioned transfer functions results in the flame transfer function of the investigated combustion setup presented on Figure 7.

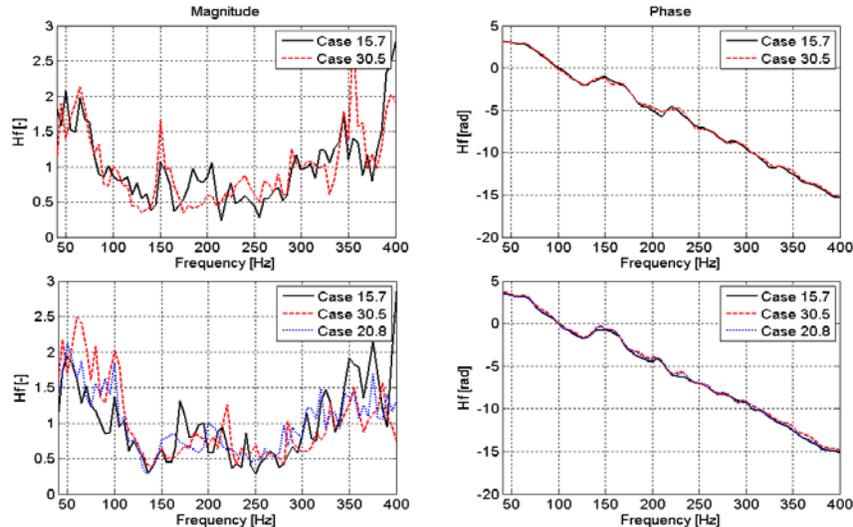


Figure 7: Flame transfer function of the Desire (top) and FluiSTCOM (bottom) configuration

Here only small differences are observed in the magnitude spectrum. All five transfer functions show the same three main peaks, around 70 Hz, 180 Hz and 400 Hz. This behaviour is in a good agreement with typical behaviour of transfer function obtained for combustion systems see e.g. [4] or [6]. The phase spectrum shows an almost linear dependence between phase change and

frequency. Again, there is no major difference noticed for all five investigated cases. Constant convective time delay can be calculated for each spectrum by fitting the linear function. For the Desire liner configuration and operating point 15.7 the predicted time delay between mass flow rate fluctuations and flame response is equal to 8.29 ms, whereas for the operating point 30.5 it is 8.19 ms. The same operating points investigated with the use of Fluistcom liner show time delays equal to 8.36 ms and 8.31 ms respectively. In case of the investigation with operating point 20.8, the time delay is equal to 8.32 ms. From this results it appears that in case of the stiff liner configuration the signal travels faster from the location near the MOOG valve to flame front than in case of the Fluistcom geometry. The same behaviour is also observed when experiments are done at higher pressure levels. This suggests that for the high absolute pressure and stiff liner configuration the flame is located closer to the burner mouth than during the remaining investigated cases. Nevertheless these discrepancies, it can be concluded that for constant mean velocity, air factor and pre-heated air temperature, the effect of pressurizing the combustion chamber and increasing liner flexibility is not significant. In all investigated cases, the magnitude and spectrum of the flame transfer function stays almost unchanged.

5. Conclusions

The experimental results of the combustion process under pulsating flow conditions are presented here. Two liner configurations and several operating points are investigated. The influence of the liner geometry on the vibration level and the acoustic wave inside the combustion chamber and cooling passage is observed. Furthermore, the flame transfer function at various elevated absolute pressures is retrieved. The relation between flow perturbation and heat released by the flame is reconstructed from the transfer functions measured at various locations in the test rig.

The result of the pressure fluctuations inside the combustion chamber and cooling passage are similar for both liner configurations. The thermo-acoustic instabilities in case of the flexible liner configuration (Fluistcom) are shifted slightly to the lower frequency region with comparison to the stiff liner geometry (Desire). The same behaviour is observed in case of the velocity peak. Due to small stiffness of the Fluistcom liner, the vibrations are also well visible at acoustic eigenfrequencies. This is not always the case for the Desire geometry. The pressure signal in the cooling passage resembles the acoustic profile visible in the combustion chamber. Therefore, the sound is transmitted from the combustion chamber to the cooling passage through entire liner vibrations.

The experiments show minor influence of the liner configuration and pressure level on the obtained flame transfer function. All observed spectra have similar profiles of magnitude and phase. There is an almost linear correlation between phase change and frequency. These results translated on time delay show that the Desire liner configuration and higher absolute pressure reduce slightly the time delay necessary to transfer disturbances from the source to the front of the flame.

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