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MEASURING THE FLAME TRANSFER FUNCTION OF TURBULENT NON-PREMIXED SYNGAS FLAMES

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Abstract

Syngas is a fuel, obtained from gasification of coal or other heavy hydrocarbons. It is used to fire gas turbines. Syngas consists of hydrogen (H_2), carbon monoxide (CO) and some inert components like nitrogen (N_2) or water vapour (H_2O). Sometimes methane (CH_4) is present. It has shown in practice that syngas fired gas turbines can suffer from thermo acoustic instabilities. In case of such an instability, pressure oscillations couple with the combustion process. This can lead to extreme noise and structural damage. At the laboratory of Thermal Engineering of the University of Twente, a lab scale syngas combustor is built to measure the thermo acoustic properties of syngas flames. The passive noise of the combustion process was measured as well as the response of the flame to perturbations on the mass flow of the fuel. With the latter measurements, the so-called flame transfer function was determined. The flame transfer function is an important parameter in studying the thermo acoustic behaviour of flames. In these experiments, the flame transfer function is defined as the relation between the heat which is released by the flame and the fuel mass flow.

INTRODUCTION

Coal is an abundant source for power generation. By gasification, a combustible gas is produced (syngas) that can be used for clean combustion in gas turbines. Syngas is a mixture of carbon monoxide, hydrogen and an inert component. Methane can be present. Normally, the syngas produced by the gasification process is diluted with steam or nitrogen. Otherwise, the adiabatic flame temperature becomes too high and will lead to unacceptable high NO_x emission.

Usage of syngas fired power plants shows that some combustion regimes can cause acoustic problems. Acoustic problems usually can be divided into two separate phenomena:

1. Autonomous noise: The flame acts as an acoustic source and does not couple with the acoustic domain. As the combustion process is dominated by turbulent mixing, so will the acoustic source be [1]. Noise basically arises from pressure fluctuations due to unsteady heat release and is therefore strongly dependent on the structure of eddies in the mixing region. But the noise not only arises from the the mixing, also from the fluctuation in the flame surface area during combustion [2].

2. Coupled acoustics: An interaction between the source (the flame) and the acoustic properties of the domain (air line, fuel line, combustor and exhaust) leads to a thermoacoustic instability [3]. When the acoustic boundary conditions are appropriate, this can lead to resonant frequencies of the system and sometimes to a growth of the amplitude in time.

An experimental setup was built in order to gain insight in the mechanisms playing a role in establishing thermoacoustic instabilities.
When the combustion is premixed, the flame transfer function, describes the relation between an equivalence ratio perturbation and the rate of heat release [4] and [3]. In non-premixed flames this is not possible. Bohn et. al defined a flame transfer function for non-premixed flames [5] as the ratio between the rate of heat release and a perturbation in the air mass flow. However, Klein [1] shows in his dissertation that, in case of non-premixed syngas combustion, perturbations on the air side have no significant influence on the rate of heat release of the flame. For that reason, the flame transfer function for non-premixed syngas combustion in this study is defined as the ratio between fluctuations of the heat release and perturbation of the fuel mass flow:

$$H_f(\omega) = \frac{Q'}{m'_f} \ , \tag{1}$$

According to Klein [1], the reason of the air side having no influence is that air is always present in abundance.
This paper will describe the experiments on measuring the flame transfer function and the results of those experiments .

EXPERIMENTAL SETUP

Burner

The burner is designed and manufactured at the University of Twente in the framework of the EU project HEGSA. Two identical burners are manufactured. One is in use at the Verbrennungsinstitut of DLR Stuttgart and one at the Laboratory of Thermal Engineering at the University of Twente.
The burner, shown together with the fuel and combustion air supply system in figure 1, is designed for fuels in the calorific range between 5 and 8 MJ/kg. These are typical calorific values for syngas. The burner is a two channel generic syngas non-premixing burner. The syngas is combusted in a non-premixed mode to prevent flashback due to the presence of hydrogen.

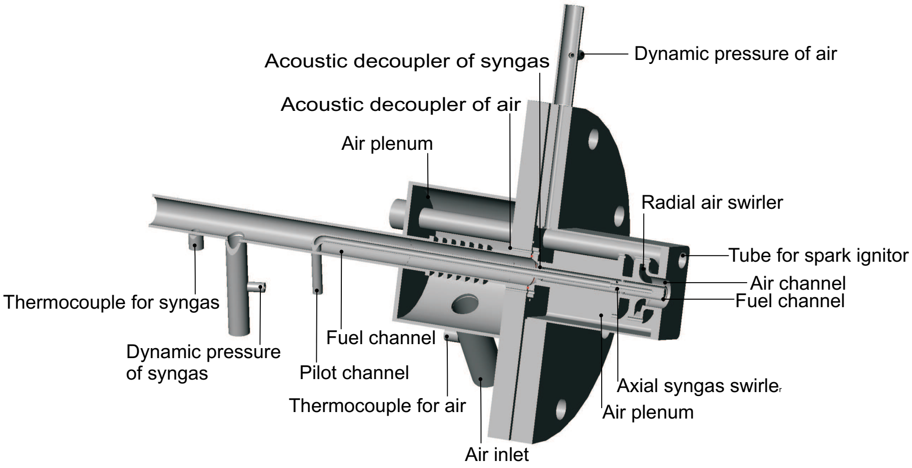

Figure 1: Cross-section view of supply system of the setup

Both air and fuel are swirled. The air is fed to the burner from a plenum. From the plenum the air flows into the radial swirlers. It is swirled in radial channels by triangular blocks. The fuel flows through an annular tube and is swirled by axial vanes.

Setup

The setup can roughly be divided into three sections. All sections are presented in figure 2. From top to bottom there is the supply section, the combustion section and the cooling section. The combustion section consists of a liner and a cooling channel. The liner is 750 mm in length and has a square diameter of 94 mm. The cooling channel surrounds the liner and is fed with cold air. Here, the fuel and air mix and combust. The flame stabilises on the recirculation zone of the swirling flows. The combustion section ends with an acoustic decoupler, which is a round hole of 27 mm in radius. This supplies a refelctive acoustic boundary.
The hot product gases and the cooling air come together in the cooling section. In this section, water fed spray nozzles cool down the mixture below a temperature of 600 K.
The combustion and cooling air are supplied by a screw compressor with drying and inter cooling . All components of the fuel are bottled. For all flows, a mass flow controller is available. The experimental setup is equipped with eight thermo couples. The static pressure is measured at the end of the combustion chamber.
The mass flow controllers, the thermo couples (indicated as TC1-TC8 in figure 2) and the static pressure transducer (P_S) are all read and controlled by a LabView interface.
To withdraw the acoustic information from the combustion system, dynamic pressures need to be measured. This is done by four Kulite dynamic pressure transducers (P1-P4 in figure 2). The measuring points all consists of semi-infinite tubes with ordinary loudspeaker damping material to avoid reflections. The pressure transducers are mounted at different distances from the setup in those semi-infinite tubes. The signals of the Kulites are processed by a SigLab analyser. This SigLab analyser processes the time dependent data into power spectra and transfer functions between the measuring points by using Fourier transforms.
As indicated with equation 1, the flame transfer function is the ratio between the heat release

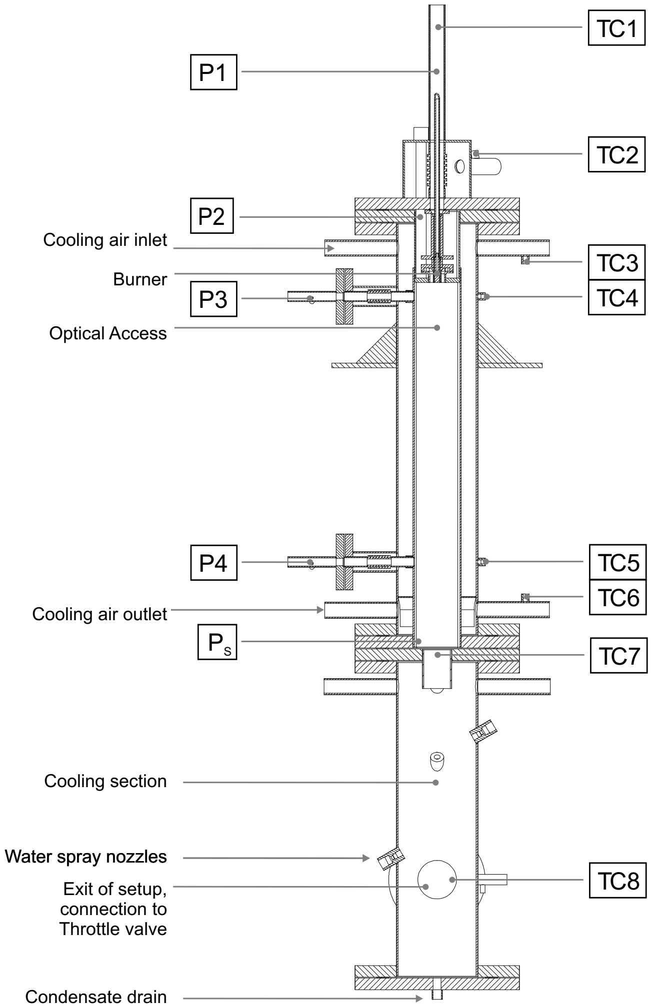

Figure 2: Section view of the experimental setup; P1-P4 are dynamic pressure transducers, TC1-TC8 are thermo couples and P_s is a static pressure transducer

of the flame and a perturbation in the mass flow of the fuel. For this perturbation, several techniques can be applied. Some use a simple loudspeaker [1] and others use a siren [3, 4, 6]. Loudspeakers and sirens can excite up to high frequencies. But the shape of the excitation spectrum of sirens is determined by the sirens geometry [7]. In this setup, a MOOG exciter is applied. Other authors describe this device [7, 8].

RESULTS

Four cases were defined to investigate on the experimental setup. Two types of fuel and two different temperatures for the combustion air. The pressure is ambient for all cases and the excess air factor λ = 2. The MOOG valve excites the fuel mass flow from 5 Hz to 400 Hz. The transfer function which can be measured during combustion is $\frac{p'_{meas}}{p'_{fuel}}$, see figure 3. The

case	$T_{air,inlet}$[°C]	fuel	CO	H_2	CH_4	N_2	LHV [MJ/kg]
DLR 1	20	syngas 6	31.1	1.5	0.0	67.3	5.0
DLR 3	20	syngas 7	29.2	1.5	6.2	63.1	7.8
DLR 5	150	syngas 6	31.1	1.5	0.0	67.3	5.0
DLR 5	150	syngas 7	29.2	1.5	6.2	63.1	7.8

Table 1: Four investigated cases

transfer function we want to know is $\frac{Q'}{m'_f}$. Hence, several steps to reconstruct the desired flame transfer function need to be taken. Equation 2 shows the transfer function that can be measured ($\frac{p'_{meas}}{p'_{fuel}}$), the desired flame transfer function ($\frac{Q'}{m'_f}$) and all other transfer functions that need to be known to reconstruct the flame transfer function.
Figure 3 shows all the elements that play a role in the reconstruction of the flame transfer function in a graphical manner.

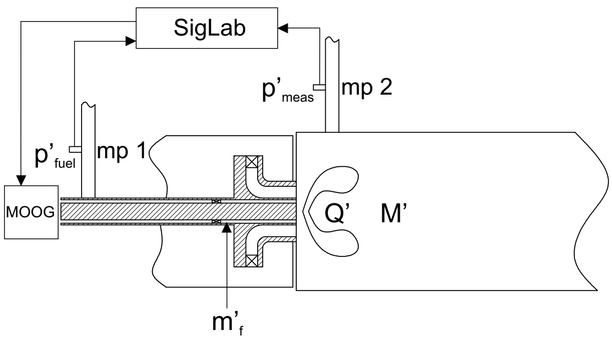

Figure 3: Integration of the SigLab system in the experimental setup

$$H_f = \frac{Q'}{m'_f} \approx \frac{p'_{meas}}{p'_{fuel}} \cdot \frac{p'_{fuel}}{p'_{burner}} \cdot \frac{p'_{burner}}{m'_f} \cdot \frac{Q'}{M'} \cdot \frac{M'_{model}}{p'_{model}} \ , \tag{2}$$

The first unknown transfer function is the burner transfer function: $\frac{p'_{fuel}}{p'_{burner}}$. This is the relation between the pressure at measuring point 1 (mp1 in figure 3) p'_{fuel} and the pressure at m'_f in figure 3. Figure 4 shows the burner transfer function. This transfer function is determined by an acoustic model and during experiments using several excitation methods. The model is in good agreement with the experimental results.
The second unknown element in equation 2 is $\frac{p'_{burner}}{m'_f}$. This is assumed to be a constant, the local speed of sound.
The third unknown transfer function is $\frac{Q'}{M'} = \frac{c_0^2}{\gamma - 1}$ shows how the amount of released heat (Q') is related to the acoustic source (M'). Van Kampen [7] shows that this is a good estimation for the transfer function between the heat fluctuation and the sound source.
The last transfer function of equation 2 is $\frac{M'_{model}}{p'model}$. As the combustion chamber confines the

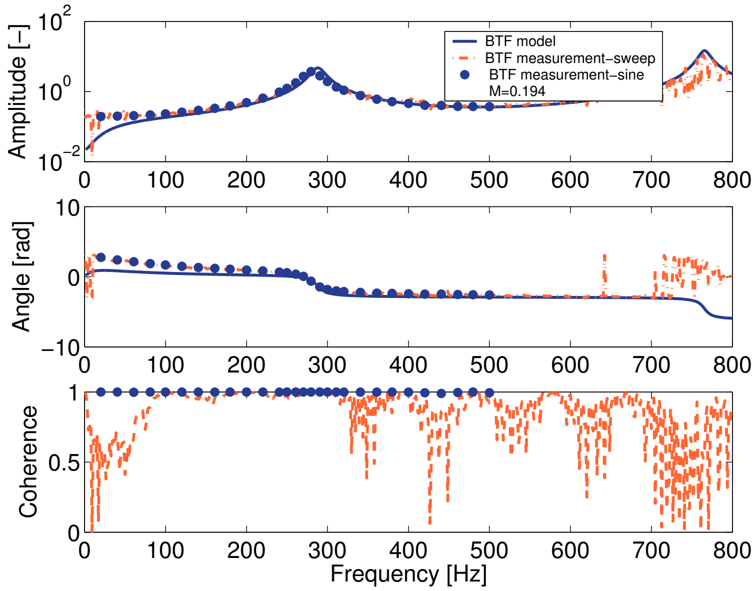

Figure 4: Predicted and measured burner transfer function

flame, the measured sound field is the result of the combination of the source (the flame) together with its acoustic domain, the combustion chamber. The transfer function $\frac{M'_{model}}{p'_{model}}$ expresses the relation between the acoustic source and the acoustic pressure at measuring point 2 (mp 2 in figure 3). This expression can be determined by a 1D acoustic model. However, it has shown that in the low frequency region, the model needs to be corrected. For that reason: $\frac{M'_{model}}{p'_{model}} = \frac{M'_{model}}{p'_{ss}}$. Here, p'_{ss} will be determined with results from steady state (no excitation used) measurements. For the approximation of the sound source of the flame M'_{model}, a so-called Von-Kárman spectrum is assumed. This spectrum is based on steady state RaNS CFD. This method is described in [9]. The authors take the Lighthill wave equation for acoustic pressure fluctuations and the flame acts as a monopole source term. The solution of this equation can be written as a Green's function.

$$G(x_0, t|x, t') = \frac{c_0}{A} H\left(t - t' - \frac{|x_0| - \underline{x}}{c_0}\right) \tag{3}$$

With A is the area of the combustion chamber.
The solution for the acoustic pressure is defined as a volume integral of the scaled chemical source term:

$$p'(x_0, t) = \frac{c_0}{A} \int\int\int BS_c d\underline{x} \tag{4}$$

With B as a sound generation constant and S_c is the chemical source term. Figure 5 shows the result for case 1. The predicted sound pressure level is compared with the measured power spectrum in the combustion chamber at location 2 (figure 2). The trend of the source agrees well with the measurements.

Finally, the flame reconstructed flame transfer functions are presented in figure 6. The figure shows the normalised flame transfer functions $H^*_f(\omega) = \frac{Q'}{m'_f} / \frac{\overline{Q'}}{\overline{m'_f}}$ and their phase angles.

The reason that the phase angles are not decaying continuously is probably caused by the

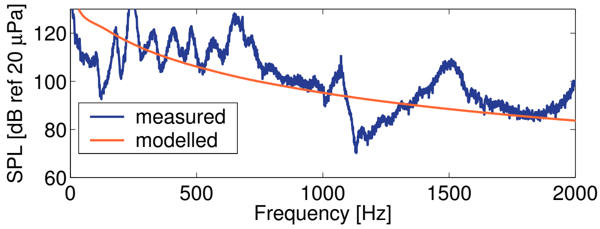

Figure 5: Predicted sound pressure level

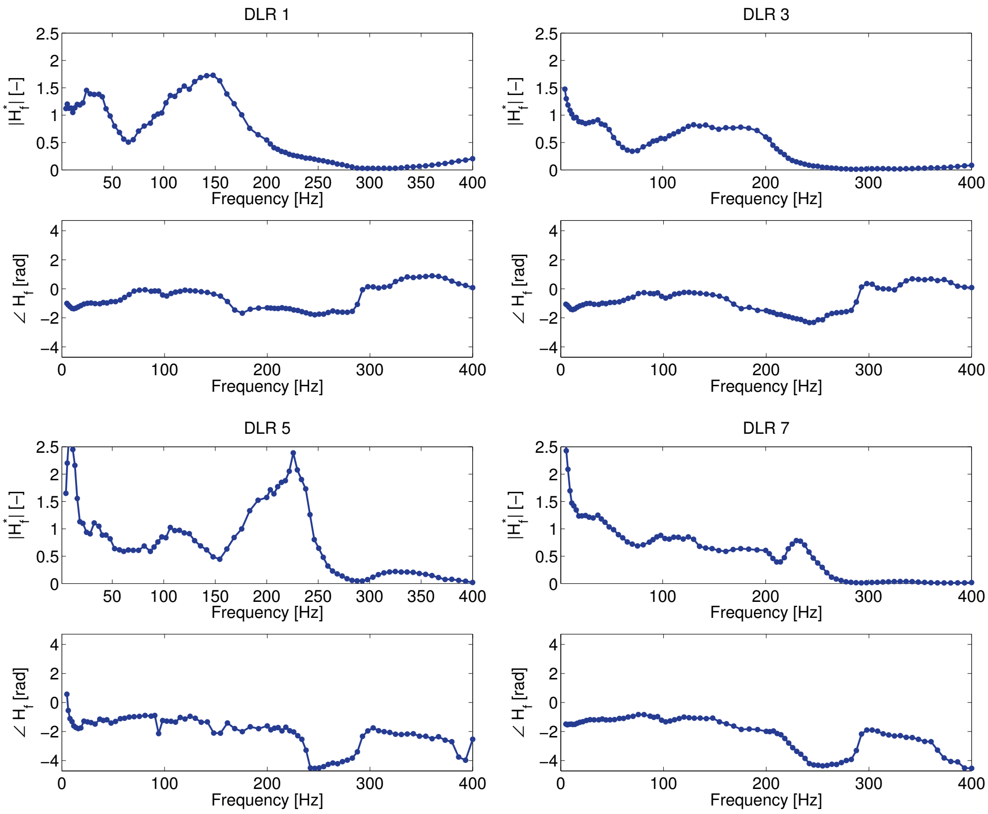

Figure 6: Measured amplitude and phase of the four cases

burner transfer function (see figure 4) which is used. Although the measured and the modelled burner transfer functions agree very well, it is probable that the combustion situation is not well enough approached during the burner transfer function experiments. For this reason, the resonance frequency in both the amplitude and phase angle have a deviation of approximately 50 Hz with reality.

Comparing the amplitude of the DLR 1 case and the DLR 3 case, the high peak around 150 Hz in the DLR 1 case has disappeared. The same is observed between the DLR 5 and DLR 7 case. It seems that the methane addition has taken away the peaks.

Comparing the DLR 1 and the DLR 5 case, the peak is moved to a higher frequency. Also, the fall off is moved to the right. This effect can also be seen in DLR 3 and DLR 7 case. The higher inlet temperature of air has broadened the low pass filter behaviour. This is observed by more authors [7].

CONCLUSIONS

The flame transfer function for two different compositions of syngas was determined. The inlet temperature of the combustion air was also varied.
It shows that the inlet temperature of the combustion temperature has an influence on the fall off frequency and the bandwidth of the spectrum in the amplitude of the transfer function.
Addition of methane damps the flame transfer function.
The measurements and the modelling of the burner transfer function should be reconsidered. Although the fuel is not preheated, it seems that the combustion changes the burner transfer function. The boundary conditions during combustion, concerning the burner transfer function need to be simulated more accurate.

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