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ACOUSTIC SCATTERING BEHAVIOR OF A 2D FLAME WITH HEAT EXCHANGER IN CROSS-FLOW

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In practical heat production systems, premixed flames with cold heat exchanger in cross-flow is a widely used configuration. Self-excited thermoacoustic instabilities often occur in such systems. A practical way to predict the presence of the instabilities is the network model approach. In the present study, the configuration flame – heat exchanger is analyzed numerically. We first analyze the system as a network of segregated elements. Based on the resulting acoustic scattering matrix, the role of the heat exchanger as an amplifier of the flame resonant frequencies will be discussed. Then, results from the 1D network modeling are compared to results of compressible numerical simulations, performed for several distances between flame and heat exchanger. Finally, the limits to the validity of the segregated network model approach are discussed.

1. Introduction

Premixed flames with cold heat exchanger in cross-flow can be found in practical heat production systems, ranging from residential to industrial scale. A widely used configuration consists of pin or tube heat exchangers downstream a perforated premixed burner plate. In thermoacoustic systems, *heat sources* are known as the main source of acoustic disturbance energy. However, little research has focused on the role of *heat sinks* on the system acoustics. Indeed, the presence of cold heat exchangers introduces additional complexity to the study of such systems, since the heat transfer rate of heat exchangers is also sensitive to velocity perturbations, and the presence of the heat exchanger could either damp or enhance the system instability.

In the stability analysis of complex thermoacoustic systems, a widely adopted approach is the network modelling. In this framework, a combustion system is conceived as a network of segregated elements, each characterized by a set of analytical equations, which relate the downstream acoustics to upstream perturbations [1].

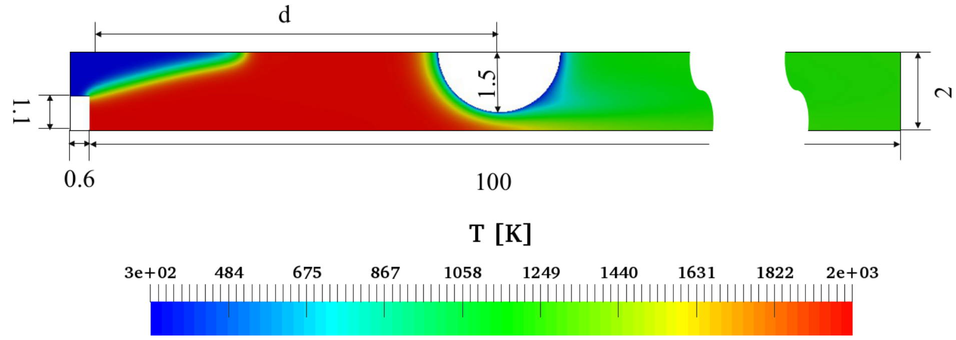

Figure 1: Temperature field of the system featuring flame and cold heat exchanger downstream. All dimensions are expressed in mm. Cases with varying distance d between burner deck and heat exchanger are analyzed. Here, $d = 10\,\mathrm{mm}$.

The network approach can be as well adopted for the case investigated in the present paper, which features a heat source (flame) and a heat sink (heat exchanger). However, depending on the distance between flame and heat exchanger, non-acoustic interactions due to changes in mean flow might occur, which could alter the acoustic scattering properties of the single elements. In particular, when the flame and the heat exchanger are very close to each other, the flame front might impinge on the heat exchanger tubes, altering both the combustion and the heat transfer processes. In this case, the system flame - heat exchanger cannot be modeled as a network of segregated elements anymore, but should be considered as a joint system, because of the mean flow interactions existing between the elements.

The goal of this study is to characterise the system with flame and heat exchanger from an acoustical point of view, and understand the conditions at which the network model approach can be considered valid, i.e. when the mutual influence between sink and source can be neglected. To do so, we first identify the scattering matrices of flame and heat exchanger separately by means of unsteady compressible simulations combined with system identification (Section 2). The scattering behaviour of the total system obtained from semi-analytical network models is discussed (Section 3). In order to prove the validity of the results given by network models, we compare them to scattering matrices obtained from direct identification of the joint system, for several distances between flame and heat exchanger (Section 4).

2. Numerical details

The system considered in the present study consists of a lean premixed 2D slit flame and a cold cylindrical heat exchanger downstream of the flame (see Fig. 1). A similar configuration is found in the previous work of Hosseini et al. [2, 3]. The burner deck consists of a row of slits of $0.6\,\mathrm{mm}$ width and $1.1\,\mathrm{mm}$ height. The heat exchanger consists of a row of cylindrical tubes, with a diameter of $3\,\mathrm{mm}$. The extension of the numerical domain in the direction normal to the flow is $2\,\mathrm{mm}$.

The code used for the compressible simulations is AVBP, developed by CERFACS and IFP-EN [1]. The temporal and spatial discretization is a second order Lax-Wendroff scheme. The unstructured mesh adopted for the direct numerical simulation has a maximum refinement of $2.0 \times 10^{-5}\,\mathrm{m}$ in the combustion zone and $4.0 \times 10^{-5}\,\mathrm{m}$ in the vicinity of the heat exchanger. Imposing an acoustic Courant number of 0.7, the time step used for the computation corresponds to $\sim 1.2 \times 10^{-8}\,\mathrm{s}$. At the inlet and outlet boundaries, acoustically non-reflecting boundary conditions are imposed, by means of the Characteristics Based State-space Boundary Conditions (CBSBC) [4].

A constant velocity and temperature boundary condition ($u_{in} = 1\,\mathrm{m\,s^{-1}}$, $T_{in} = 293\,\mathrm{K}$) is imposed

[1] www.cerfacs.fr/4-26334-The-AVBP-code.php

at the inlet and constant atmospheric pressure ($p_{out} = 101\,325\,\mathrm{Pa}$) at the outlet. The flow regime in the domain is laminar. No-slip wall boundary conditions are assumed for the burner deck and the heat exchanger surfaces. The upper and lower sides of the domain are symmetric in order to account for the presence of neighbouring flames. The premixture of air and methane is assumed as homogeneous at the inlet and has an equivalence ratio of 0.8. The combustion is modelled with a two-step reaction mechanism (see [5]). After combustion, the flow velocity and temperature reach $u_{hot} = 3.71\,\mathrm{m\,s^{-1}}$and $T_{hot} = 2005.5K$, respectively.

An adiabatic boundary condition is imposed on the burner deck, in order to rule out any preheating of the premixture at the inlet. This assumption does not correspond to the actual experimental conditions, in which the burner deck contributes to the heat loss of the flame.

The heat exchanger surface is set to a constant temperature of $323\,\mathrm{K}$. The choice of constant temperature simplifies the analysis, since it rules out the mechanism of conjugate heat transfer. However, the assumption of constant temperature at the heat exchanger surface leads to lower downstream temperature than in experiment. For this reason, in the present simulations the heat exchange between the flow and the cylinder is handled with a modified boundary condition, featuring a thermal resistance term (R_w) in the heat flux equation [2]:

$$\dot{q} = -(T_{wall} - T_{ref})/R_w, \tag{1}$$

where T_{ref} is the temperature at the heat exchanger surface and T_{wall} is the temperature of the hot fluid at the wall. For high values of thermal resistance R_w, the boundary behaves adiabatically, while for values of R_w approaching zero, the boundary behaves as a quasi-isothermal wall (for $R_w = 0$ the boundary condition diverges). In the present analysis, the value chosen for R_w is 0.001, which gives a good compromise between the desired physical effect and the numerical stability. Due to the heat transferred to the heat exchanger tubes, the flow temperature decreases to $T_{out} = 1318\,\mathrm{K}$. It should be noted that the outlet temperature in this study is much higher than the temperature of exhaust gases in real boilers, since in this analysis only a single row of cylindrical tubes has been taken into account.

2.1 External excitation and system identification

The scattering behaviour of an element in the acoustic network is charaterized by its transmission and reflection coefficients upstream and downstream. Equation (2) relates the output signals, f_d and g_u, to the incoming excitation signals f_u and g_d via the acoustic scattering matrix SM:

$$\begin{pmatrix} f_d \\ g_u \end{pmatrix} = \underbrace{\begin{bmatrix} T_{u\to d} & R_d \\ R_u & T_{d\to u} \end{bmatrix}}_{SM} \begin{pmatrix} f_u \\ g_d \end{pmatrix}, \tag{2}$$

in which $T_{u\to d}$, $T_{d\to u}$, R_d and R_u are the complex-valued upstream and downstream transmission and reflection coefficients of the system. f and g are the acoustic waves, related to the perturbations in velocity and pressure as:

$$f = \frac{1}{2}\left(\frac{p'}{\bar{\rho}\bar{c}} + u'\right) \qquad g = \frac{1}{2}\left(\frac{p'}{\bar{\rho}\bar{c}} - u'\right), \tag{3}$$

where $\bar{\rho}$ and $\bar{c}$ are the mean density and mean speed of sound. In this paper, we adopt a wavelet-based broadband signal as external excitation. This type of signals ensures a constant power spectrum in the frequency range of interest ($f = [0, 800]Hz$ for the present case), with low auto-correlation and zero cross-correlation. The amplitude of the excitation signals f_u and g_d is set to 5% with respect to the mean velocity at the inlet and outlet. Output signals f_d and g_u are registered at the same planes. In

[2] a detailed description of the boundary condition can be found at: www.cerfacs.fr/avbp/AVBP_V6.X/AVBPHELP/avbphelp.php

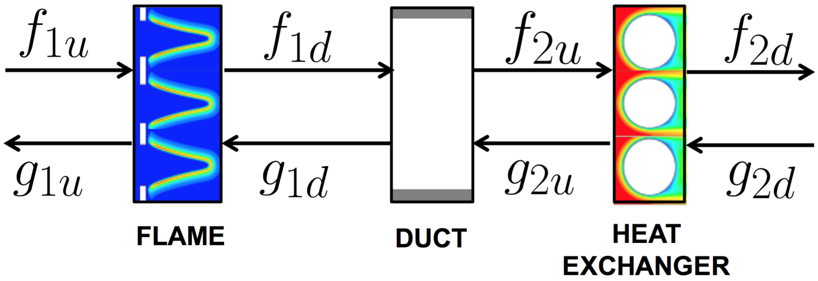

Figure 2: Network model of segregated elements

the post-processing, the unsteady time series are shifted, in order to compensate for the acoustic time delay between the reference planes and the position of the activ elements. The output error parametric model structure has been used for the identification of the Multi-Input Multi-Output system from the unsteady simulations [6, 7].

3. Network model of segregated elements

In this section, we first simulate the flame and heat exchanger separately, and then the joint system with varying distance d. In the acoustic network model approach, complex thermoacoustic systems are conceived as a network of segregated elements. This implies that the acoustic scattering behaviour of a single element does not depend on the presence of other elements in the acoustic network. In this study, the system under investigation is divided into 3 subsystems: a heat source (flame), a duct of length d and a heat sink (heat exchanger), as in Fig 2. The scattering matrices of flame and heat exchanger are identified separately, by means of compressible simulations. We use the single element sub-models as building-blocks for the complete acoustic network. The propagation of acoustic waves between the two elements is modelled by means of a lossless duct of length d. The varying acoustic propagation speed in the domain is accounted for in the present network model. In this section, we make use of the network model to understand how the presence of the heat exchanger - and its distance from the flame - impacts on the behaviour of the whole system. For our analysis, the in-house developed state-space based toolbox *taX* is used [8]. The results of this analysis are shown in Fig. 3. The gain of the scattering matrix is represented in the logarithmic scale, in order to visualize properly the heat exchanger behaviour. The scattering matrix of the flame in Fig. 3 shows a maximum at $f = 255Hz$. According to Bomberg et al. [9], the pronounced peaks in the acoustic response of the flame are due to intrinsic thermo-acoustic feedback (ITA). Such feedback mechanism is due to the unsteady thermal response of the flame to velocity perturbations, which generates acoustic waves travelling upstream and downstream. The upstream propagating component of these acoustic waves modulates the upstream velocity perturbations. As suggested in [9], the frequency at which such feedback loop exhibit resonance corresponds to the frequency at which the phase of the flame transfer function $\angle F(\omega)$ reaches $-\pi$. This can be easily verified in Fig. 4.

In the numerical simulation of the heat exchanger, the velocity profile at the inlet is assumed as uniform, in order to exclude any mean field effect deriving from the flame. This assumption should be accounted for, in the comparison between network model and the results of the joint system, since the flow field downstream the flame has a 2D distribution, which recovers to 1D at longer distances. Other inlet conditions such as temperature, density and mass fractions are taken from the downstream conditions of the flame.

Fig. 3 shows that the heat exchanger is almost acoustically transparent: the magnitude of the reflection coefficients upstream R_u and downstream R_d are close to zero, with a maximum of 0.2 at 800 Hz. The transmission coefficient upstream T_d is almost constant in the frequency range con-

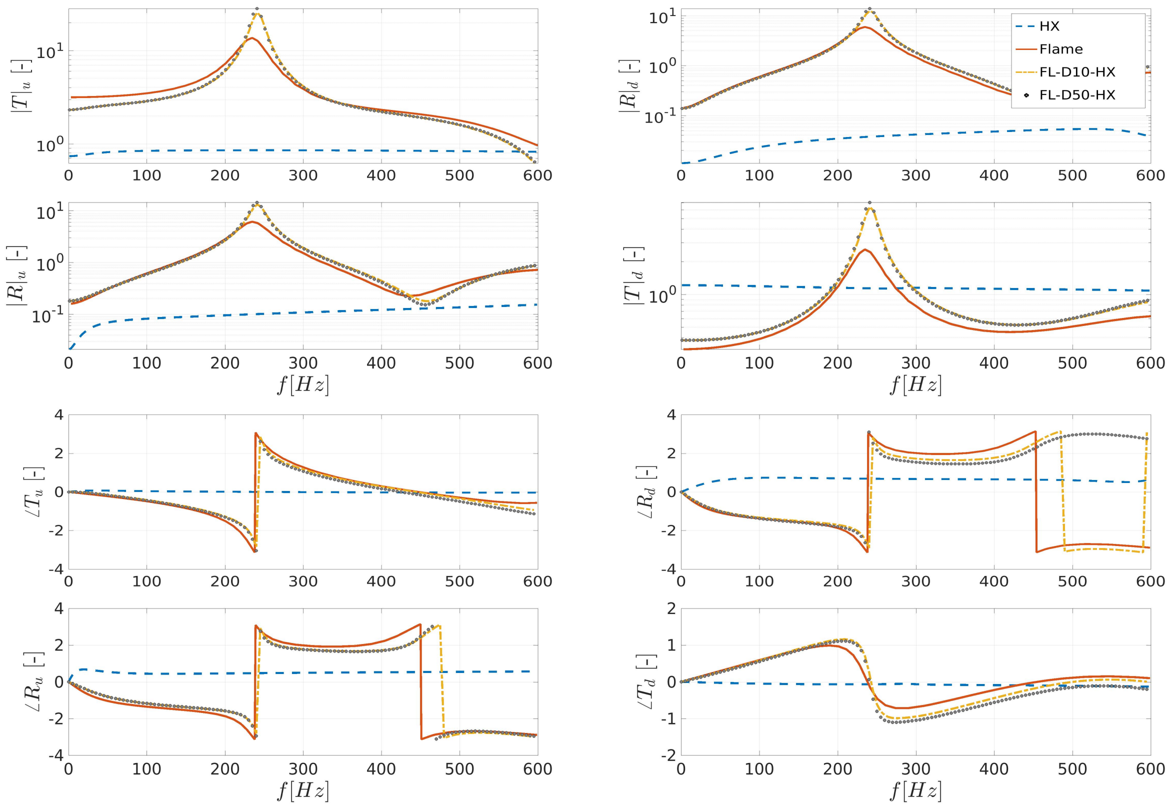

Figure 3: *Gain* and *Phase* of the scattering matrix for the heat exchanger (**HX**), flame (**FL**), the network model with flame–$10\,\mathrm{mm}$ duct–heat exchanger (**FL-D10-HX**) and the network model consisting of flame–$50\,\mathrm{mm}$ duct–heat exchanger (**FL-D50-HX**)

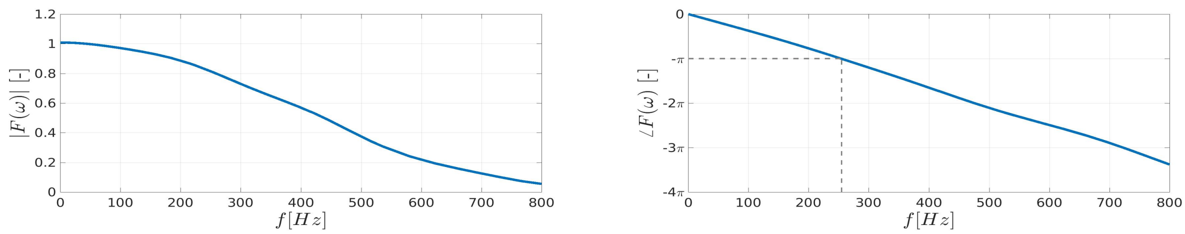

Figure 4: Gain and phase of the flame transfer function $F(\omega) = (\dot{Q}'/\bar{\dot{Q}})/(u'_{in}/\bar{u}_{in})$ without heat exchanger

sidered, and has a magnitude slightly below unity (~ 0.9). Similarly, the magnitude of downstream transmission coefficient T_d is also frequency invariant and is slightly above unity (~ 1.2).

As Fig. 3 shows, the scattering matrix of the total system shows higher peaks than the flame itself. These peaks are found at about 257 Hz, close to the resonant frequency of the flame. In the total system the heat exchanger acts as an amplifier of the intrinsic thermo-acoustic resonance. Analytically, such amplification can be explained as follows: referring to the scattering matrix in Eq. (2), the relation between the global acoustic scattering matrix and the single subsystems is described in Eqs. (4) . Terms with subscripts 1 refer to the flame, and terms with subscript 2 refer to the heat exchanger. The peaks in the scattering matrix depend mainly on $1 - (R_{1d}R_{2u}e^{-2ikL})$, which is the denominator of all four terms. Resonance sets in when the product between the flame downstream reflection coefficient, R_{1d} and the heat exchanger upstream reflection coefficient approach unity. In presence of a duct of length L, resonance also depends on the time lag e^{-ikL}, where $k = \omega/c$ and c is the speed of sound downstream the flame front.

$$T_{u\to d} = \frac{T_{1u}T_{2u}e^{-ikL}}{1 - R_{1d}R_{2u}e^{-2ikL}}, \qquad R_d = \frac{R_{1d}T_{2u}T_{2d}e^{-2ikL}}{1 - R_{1d}R_{2u}e^{-2ikL}} + R_{2d} \tag{4}$$

$$R_u = \frac{T_{1u}T_{1d}R_{2u}e^{-2ikL}}{1 - R_{1d}R_{2u}e^{-2ikL}} + R_{1u}, \qquad T_{d\to u} = \frac{T_{1d}T_{2d}e^{-ikL}}{1 - R_{1d}R_{2u}e^{-2ikL}}.$$

Away from the resonant frequency, the behaviour of the system mainly follows the flame scattering properties. Moreover, the results in Fig. 3 show that the variation of the distance between flame and heat exchanger does not impact significantly on the system acoustic response. In fact, the cases $d = 50\,\mathrm{mm}$ and $d = 10\,\mathrm{mm}$ do not differ noticeably in the scattering matrix magnitude. The difference in phase becomes non-negligible only at higher frequencies, when the compactness is not satified anymore.

In the present study, the minimum length considered for d is $8\,\mathrm{mm}$. For distances lower than $8\,\mathrm{mm}$, it is reasonable to question the validity of the results from the network model. As noted above, the distance is intended as between the burner deck and the center of the heat exchanger tube. In the actual system, the flame is about $4\,\mathrm{mm}$ high and the heat exchanger has a radius of $1.5\,\mathrm{mm}$. It follows that for a distance of $8\,\mathrm{mm}$, the flame tip is in fact only $2.5\,\mathrm{mm}$ away from the tube row. At shorter distances, as already shown by Hosseini et al. [2] [3], the presence of the heat exchanger in the nearfield of the flame can deeply impact on the nature of the system, which might show non-linear behaviour.

4. Identification of the joint thermoacoustic system

In order to explore the validity of the network model approach, direct numerical simulation of the joint system featuring flame and heat exchanger are carried out for the case of d=$50\,\mathrm{mm}$, $20\,\mathrm{mm}$, $10\,\mathrm{mm}$ and for the "limit case" of $d = 8\,\mathrm{mm}$. The results have been compared to the scattering matrix in Fig. 3. Discrepancies arising between CFD and network model are then discussed and explained.

4.1 Case d>20 mm

At a distance of 20 mm between the two elements, it is reasonable to presume that no mean field effects exist between flame and heat exchanger. The flow profile approaching the heat exchanger can in fact be approximated as block profile, since only 0.1% deviation in the incoming velocity profile is found and non-uniformities in temperature profile are negligible. As shown in Fig. 5, the scattering matrix resulting from CFD gives very good agreement with respect to the network model. The gain is well resolved for all the frequencies and, in particular, the resonant peak is correctly captured for all the terms in the scattering matrix. Minor discrepancies can be found in the phase at higher frequencies, see Fig. 5. Such discrepancies mainly occur in the terms involving downstream signals and are caused by the error made in the time delay estimation of the acoustic waves propagating from the heat exchanger to the outlet reference plane, at which the signals are registered. In fact, the temperature field downstream the heat exchanger is mainly 2D, due to the wake after the cylindrical tubes. Indeed, the non-uniform temperature field represents a source of error for the estimation of the speed of sound, and thus, for the phase of the total scattering matrix.

4.2 Case d<10 mm

As the distance between flame and heat exchanger descreases, CFD simulations show that the value of the resonant peak also decreases. In fact, results in Fig. 5 show that the scattering matrix for the cases of $10\,\mathrm{mm}$ duct has a resonance peak which is significantly lower than the case of $50\,\mathrm{mm}$ duct. This means that the network model obtained from segregated elements is not valid anymore when the distance between burner deck and heat exchanger is approximately $10\,\mathrm{mm}$. The reason behind such discrepancy is the different response of the heat exchanger in presence of a 2D distribution in the incoming velocity profile. For d=$10\,\mathrm{mm}$, the velocity downstream the flame front presents a maximum deviation of 5% along the Y direction. Such deviation slightly changes the acoustic scattering behaviour of the heat exchanger, as shown in Fig. 6. The scattering matrices in Fig. 6 are identified directly from the compressible simulations of the joint system, and the input and output

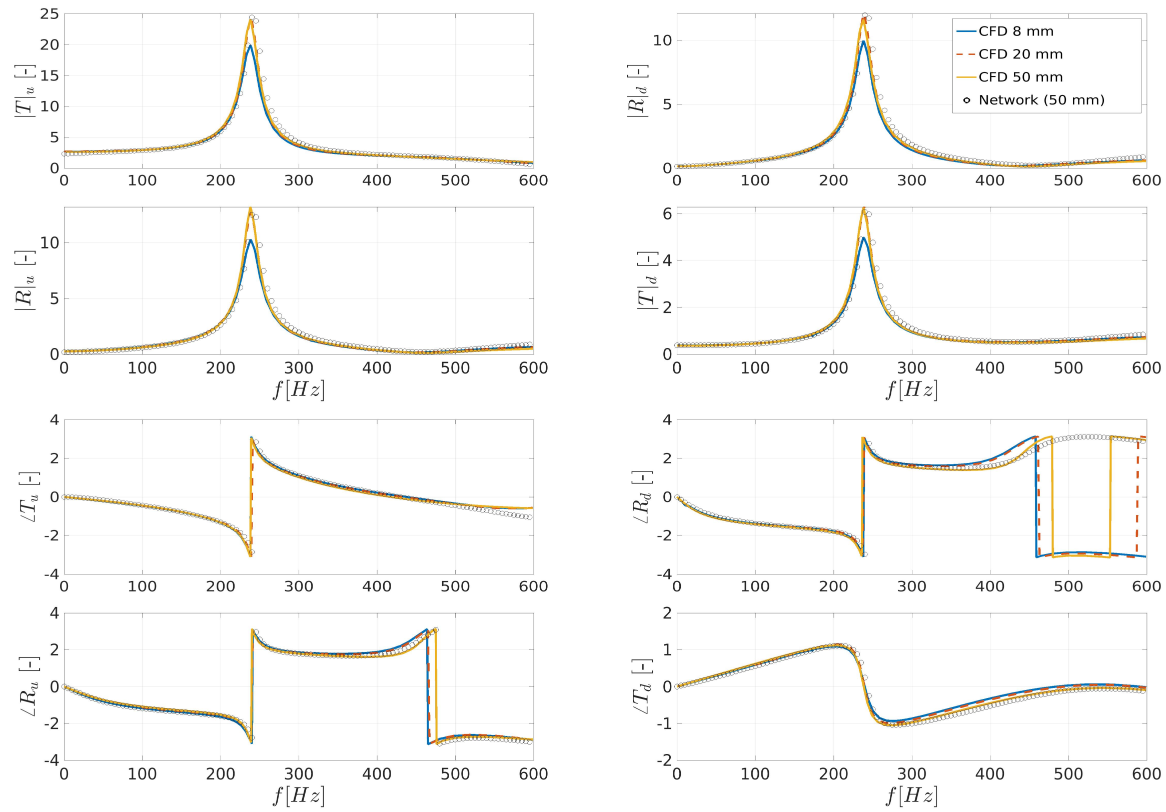

Figure 5: Gain and phase of the scattering matrix resulting from CFD of the joint system with ducts of $8\,\mathrm{mm}$ (**CFD08**), $20\,\mathrm{mm}$ (**CFD20**) and $50\,\mathrm{mm}$ (**CFD50**) between flame and HX , compared to the network model consisting of flame – $50\,\mathrm{mm}$ duct – heat exchanger (**FL-D50-HX**). The case with duct length of $10\,\mathrm{mm}$ (**CFD10**) is omitted, but shows similar values as the case (**CFD08**) . The frequency range is restricted to [0,600] Hz to better visualize the resonance peak.

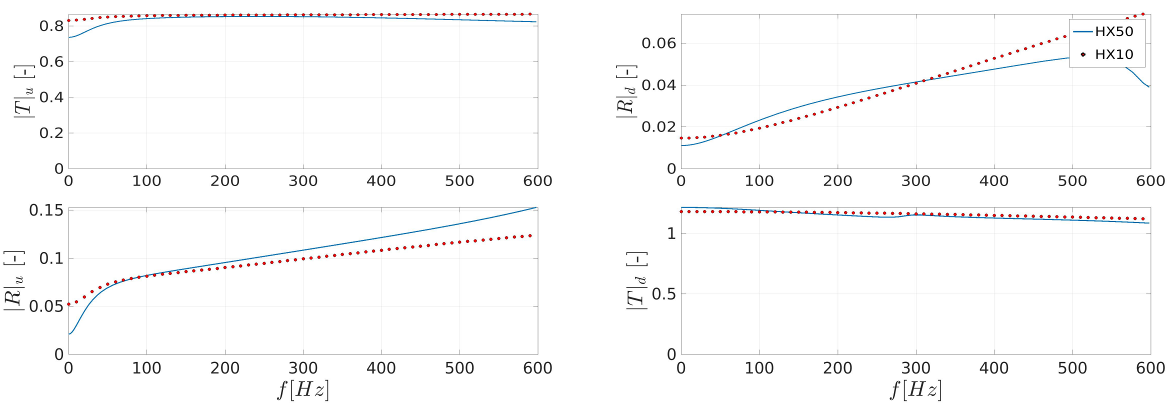

Figure 6: HX scattering matrix gain identified from the simulations of joint systems featuring $10\,\mathrm{mm}$ duct (HX10) and $50\,\mathrm{mm}$ duct (HX50)

signals f and g are registered at reference planes placed just up and downstream of the heat exchanger, for both cases considered in the paper. Due to the high sensitivity of the system at resonant frequencies (see Eqs. (4)), the small change in heat exchanger scattering properties results in a conspicuous decrease of the peak response.

5. Conclusions

In the present study, we analyzed and discussed the acoustic scattering behaviour of a thermoacoustic system consisting of a 2D slit premixed flame and a cylindrical heat exchanger. A resonance peak is found in the scattering matrix of the flame, due to the intrinsic feedback mechanism. Both results from CFD-system identification and network model show that the presence of the heat exchanger downstream the flame amplifies the resonance around the same frequency. Comparison between CFD and network modeling shows that the peak in acoustic response of the system can be correcty captured by the network model for the case of d=$50\,\mathrm{mm}$, and in general, when the mean flow effects due to the short distance between the elements are negligible. When the distance between heat source and heat sink decreases, 2D mean flow effects on the heat exchanger scattering behaviour cannot be neglected anymore. CFD results for the case of d=$10\,\mathrm{mm}$ and d= $8\,\mathrm{mm}$ show that the resonance peak in the scattering matrix decreases considerably and that the predictions given by the network model are no longer accurate. The next step is to analyze the role of the heat exchanger on the system stability, and understand how the heat exchanger scattering behaviour changes in presence of non-uniform velocity profiles. Moreover, a study of the acoustic behaviour of the system in presence of realistic experimental boundary conditions (heat loss at combustor walls, conjugate heat transfer) is also needed.

6. Acknowledgements

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