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Evaluating thermoacoustic properties of heating appliances considering the burner and heat exchanger as acoustically active elements

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ABSTRACT

Heat exchangers are an essential constituent part of many combustion systems. The thermoacoustic instability in such systems is a common problem and it has been studied extensively. However, the heat exchanger has not gained much attention in the field of combustion thermoacoustics, leading to a lack of knowledge about the thermoacoustic interactions between the burner and the heat exchanger. In this paper, a modeling approach is introduced to study these interactions in an academic representation of a heating appliance, comprised of a perforated slit burner and a tube heat exchanger. Both elements are considered thermally and acoustically active. A CFD model is used in a two-dimensional domain to simulate the response of the system to small amplitude broadband velocity perturbations. The thermochemical and acoustic coupling between the burner and the heat exchanger is investigated and a method is introduced to decouple their effects and study them separately. The extents to which this method is valid are addressed by varying the distance between the elements. Results show that as long as the flames do not impinge on the heat exchanger surface, a linear network modeling approach can be applied to construct the acoustic response of the composed configuration from the responses of its constituting elements. This approach requires registering the average velocity on a properly chosen intermediate plane between the burner and heat exchanger. Choosing this plane may be to some point difficult, i.e. when the burner and heat exchanger are close and cannot be considered independent. Moreover, when flame impingement occurs, the interactions between the flame and heat exchanger affect their individual thermoacoustic behaviors and the burner plus heat exchanger assembly needs to be considered as one coupled acoustic element. Particularly, flame impingement changes the phase of the heat absorption response of the heat exchanger and it may significantly alter the acoustic properties of the coupled assembly. The physics lying behind the effects of such interactions on the thermoacoustics of the system is discussed. The obtained results signify that a correct stability prediction of an appliance with burner and heat exchangers requires considering active thermoacoustic behavior of both elements as well as their interactions.

1. Introduction

Thermoacoustic instabilities are frequently present in lean (partially) premixed combustion and have been studied for more than a century [1–3]. Such instabilities may occur in various systems, such as gas turbines, boilers and other heating systems. Many of combustion appliances include not only heat sources (burners) but also heat sinks (heat exchangers). In the combustion thermoacoustic research, the common practice is to treat the burner as the solely active thermoacoustic element and the other components as passive elements (such as ducts, vessels and terminations, including heat exchangers) [4]. One of the crucial prerequisites of this modular method is the possibility to distinguish and separate the "acoustic elements" from each other, and accordingly to encapsulate their acoustic behavior as a property of the given element only. This paradigm is the basis of the network model approach, where the subsystems are described as linear elements with two acoustic inputs and two outputs (two-ports), interrelated via a Transfer Matrix (*TM*) or a Scattering Matrix (*SM*). The heat

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release response to acoustic excitation of velocity in an active element, like burner, can be naturally described within the concept of the thermoacoustic Transfer Function (*TF*). For acoustically compact elements (where the size of the element is negligible compared to the acoustic wavelength), the *TM* is related to the *TF* through the heat release rate [5,6]. There are multiple examples in the literature, where this approach has proven to be productive in predicting system instabilities and evaluating different measures of passive and/or active control [7–10].

On the system level, the heat exchanger is designed to absorb most of the heat produced by the burner and create a reverse temperature jump of the same order of magnitude as the burner. On the other hand, it is well known that an acoustically forced flow may create a fluctuating heat flux on the bodies in the flow [11,12]. Therefore, the heat exchanger may potentially be an additional active acoustic element next to the burner in the acoustic network. The activity of a heat exchanger can be included in the acoustic network analysis. As an example, the authors have demonstrated in an earlier publication that in a simple one-dimensional Rijke burner with a flame and heat exchanger, the thermoacoustic properties of the heat exchanger can significantly alter the stability of the system [13]. However, the aforementioned study has been purely acoustic and considered approximated and frequency independent transfer functions for the burner and heat exchanger, neglecting any direct interactions.

On the other hand, the practical need to reduce the built volume of combustion appliances and minimize nitrogen oxides, leads to the desire to locate the heat exchanger very close to the burner. The smaller this distance, the more questionable it becomes to consider the burner and the heat exchanger as two acoustically independent elements. It is known that in the limit case of impinging flames, the intense interaction of a flame with a heat exchanger leads to significant changes of the acoustic properties of the flame. Particularly, it was observed that impingement may change the noise produced by the flame [14–16]. Similarly, the proximity of a flame to the heat exchanger surface can affect the periodic heat transfer between the surface and hot gases. In other words, the fluctuations induced by the flame dynamics may alter the acoustic properties of the heat exchanger. Consequently, the thermoacoustic properties (e.g. *TF* and *TM*) of the combination of the burner and heat exchanger may differ drastically from when considered independent. Therefore, one may a-priori expect that the mutual interactions between the burner and the heat exchanger may alter their individual thermoacoustic properties. Consequently, the direct interactions (hydrodynamic, heat transfer and chemical reactions) will impose a range of implications for the acoustic network modeling of a combustion system with interacting burner and heat exchanger.

The practical relevance, fundamental interest and shortage of knowledge about the burner-heat-exchanger thermoacoustic interactions has stimulated the present research. The ultimate goal of this investigation is to elucidate the physical nature of burner-heat-exchanger interactions in respect to their thermoacoustic behavior. Particularly, the aim is to answer the following questions:

- What are the conditions for considering the combined *TF/TM* of the burner and heat exchanger as the superposition of their individual *TF/TM's*, and how can this be done properly?
- When do the interactions between them affect the individual *TF/TM's*, and what is an applicable method to reconstruct a combined *TF/TM*?
- What are the physical phenomena and governing parameters responsible for these interactions?

To solve the formulated problem and questions, a particular configuration is studied that consists of a bed of idealized Bunsen-type wedge shaped (two-dimensional) premixed flames anchored on slot perforations in a burner deck, and interacting with a heat exchanger consisting of a series of idealized cylindrical tubes placed downstream the burner (see Fig. 1). This academic configuration is representative for the design of a majority of heating appliances and is composed of relatively simple elements which have been intensively studied in the past on theoretical, experimental and numerical levels [12,17–19].

CFD is chosen as the research tool because there are no convenient and easily measurable indicators for the oscillating rate of heat transfer from the hot gases to the heat exchanger (unlike the chemiluminescence of chemical radicals for flame heat release). Consequently, within a physical experiment, it is feasible to evaluate the effects of the heat exchanger on the acoustic properties of the flame, but it is difficult to detect the reciprocal effects of the flame on the heat exchanger. This fact motivates the use of the CFD-based analysis within the present research.

By changing the distance between the burner and heat exchanger, one can alter the intensity of the mutual interactions. For large distances, no hydrodynamic interaction is expected. However, as the distance decreases the hydrodynamic and thermal fields created by the flame and heat exchanger begin to interact. These interactions can be extremely intense and complicated when the flame impinges on the heat exchanger surface. Details of the situations that may occur are discussed in the following section.

Ultimately, by studying this simplified configuration, general conclusions are formulated regarding the physics of the processes responsible for the interactions, considering the thermoacoustic aspects of this problem. The drawn conclusions are generic by nature and can be applicable to other configurations as well.

2. Governing phenomena of the interactions between a burner and a downstream placed heat exchanger

A picture of the constructed burner-heat-exchanger system and a schematic of the simplified configuration used as the simulation geometry are illustrated in Fig. 1. Symmetry has been used in order to reduce the size of the computational domain and to model the effects of the neighboring flames and heat exchanger tubes. The mixture enters from the inlet at the bottom and the flames stabilize on the slit perforations. The combustion products flow toward the heat exchanger tubes and leave the domain at the outlet. In addition to the dimensions mentioned in Fig. 1, other important length scales are flame height ($L \approx 5$ mm), flame thickness ($\delta \approx 0.5$ mm) and the smallest acoustic wavelength ($\lambda \approx 1370$ mm), which is calculated for a maximum temperature of 2000 K and highest relevant frequency of 1000 Hz.

A-priori, for a heating appliance containing a burner and heat exchanger and in presence of acoustic perturbations, one can foresee several hypothetical interaction scenarios between the two elements. These interactions are mainly governed by the distance between them and are illustrated in Fig. 2. This figure shows the flow streamlines and the flame shape. In the limit case where the distance is sufficiently large to smoothen all non-uniformities (thermal, kinetic and fluid dynamic), the heat exchanger is exposed to a uniform flow of burned gases with the acoustic perturbations on top of the mean flow (see Fig. 2a). In this case, the subsystems can be treated separately from the point of view of either convective fluid dynamics or acoustics. Consequently, there are no difficulties to define spatial boundaries as inlets and outlets for the burner and the heat exchanger as the succeeding element. Usually these boundaries are defined where acoustic waves can be considered one-dimensional and planar. It can even be necessary and reasonable to include some extra acoustic elements, such as ducts, to model the propagation of acoustic waves between the burner and the heat exchanger [20].

At some level of proximity between the subsystems, either the convective or the acoustic perturbations do not smoothen to a negligible level (see Fig. 2b). In this case, the thermoacoustic behav-