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Aeroacoustic response of an array of tubes with and without bias-flow

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ABSTRACT

Heat exchangers, consisting of tube arrays in a cross-flow are a vital component of power generation systems. They are of interest from an acoustic point of view, because they can reflect, transmit and absorb an incident sound wave; in other words, they have the potential to act as a sound absorber and even as a passive control device to prevent a thermoacoustic instability in the power generation system. This paper presents a fundamental study of the aeroacoustic response of a tube array with and without bias-flow (also called cross-flow). The study has a theoretical and experimental side. On the theoretical side, a new model, based on the assumption of quasi-steady flow, was developed to predict the acoustic reflection and transmission coefficient of a tube array with bias-flow. Also, the model by Huang and Heckl (Huang and Heckl, 1993, Acustica 78, 191–200) for the case without bias-flow was evaluated. On the experimental side, flow-duct experiments using a multi-microphone technique were performed to validate the predictions from both models. The agreement was found to be very good for low frequencies. The measurements revealed the limit of validity of the quasi-steady model in terms of the Strouhal number. Although this limit is quite low, our quasi-steady model can serve as a valuable tool for designers of heat exchangers.

1. Introduction

This paper investigates the acoustic response of an array of tubes (also referred to as a tube row). Tube rows are components in many engineering systems, where they may act as heat exchangers. A well-known example is the heat exchanger tubes in a domestic boiler (see Fig. 1). The main elements, from an acoustic point of view, are the combustion chamber, the flame, the tube row, and the cross-flow (or bias-flow) through the gaps between the tubes. The combustion chamber acts as an acoustic resonator, and the flame acts as a potential sound source, generating a high-amplitude acoustic field; the tube row scatters the acoustic waves, and the cross-flow introduces aerodynamic effects.

Altogether, this is a scenario where several physical effects occur simultaneously:

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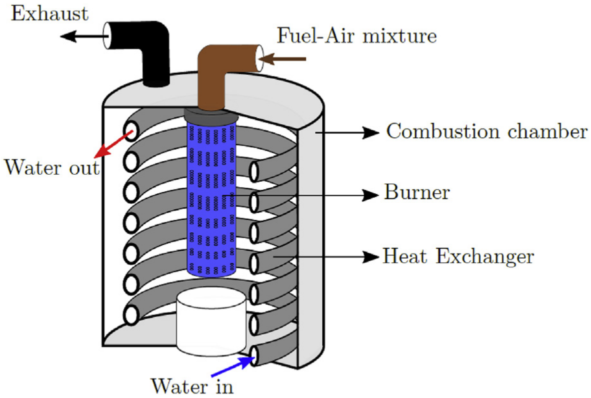

Fig. 1. Schematic of a domestic boiler system.

- thermoacoustic instabilities excited by the flame in the combustion chamber;
- reflection and transmission of acoustic waves impinging on the tube row;
- flow separation due to the cross-flow, leading to jet formation and vortex shedding downstream of the tube row, as well as to viscous and thermal boundary layers;
- feedback between the acoustic field and the aerodynamic effects, leading to synchronised vortex shedding;
- vibrations of the individual tubes, leading to structural resonances and losses.

Our work is motivated by the possibility that the tube row, together with the cross-flow, could provide a form of passive instability control. However, in order to investigate this possibility, it is necessary to have a model for the acoustic behaviour of the combined system, tube row plus cross-flow. The aim of our paper is to present such a model. We consider the simplest configuration: a tube row with or without bias-flow and an incident acoustic wave. We do *not* include thermoacoustic effects in our model, nor structural vibrations; in other words: we treat the fluid surrounding the tube row as homogeneous, and the “tubes” as solid rods. Our study is two-dimensional in the sense that the cross-flow and acoustic waves are perpendicular to the tubes. The tubes are all parallel and equally spaced. It should also be noted that in the present work, we consider only a single row of tubes (hence termed tube row) and not tube bank (or bundle).

Wave scattering by a periodic array of scatterers is a phenomenon that occurs widely in physics and engineering. Examples are: water waves scattered by off-shore structures, electromagnetic waves diffracted by a wire grating, and acoustic waves used for non-destructive testing (NDT) purposes to examine periodic arrays of tubes immersed in a fluid. Studies involving *acoustic* waves have been performed by Mungur and Fahy [1] and Kristiansen and Fahy [2] who reduced the problem by treating the tube row as layer of a homogeneous medium with an effective density and speed of sound. Linton and Evans [3] used a multipole expansion method to describe the acoustic scattering of water waves by an array of rigid cylinders. Heckl et al. [4,5] built on Twersky's grating theory [6–8] and developed expressions for the reflection and transmission coefficients of plane pressure waves impinging from arbitrary directions on a grating formed by fluid-filled flexible cylindrical tubes. In Huang and Heckl [9], they extended the model to include several loss mechanisms (structural losses in the flexible tube walls, viscous and thermal losses at the tube surfaces).

While the papers quoted in the previous paragraph are about tube rows without cross-flow, there are also relevant studies for the case *with* cross-flow. Quinn and Howe [10] studied a row of infinitesimally thin rigid strips in cross-flow and calculated the attenuation of an incident sound wave; they found that the attenuation increases with decreasing Strouhal number; in other words, for a given tube diameter and frequency, the sound attenuation increases with increasing cross-flow velocity. However, in their approach they considered a highly idealised configuration (rigid strips instead of rigid tubes), so their results can be seen only as a qualitative indication. Dowling and Hughes [11] derived expressions for the reflection and transmission coefficient of a slit plate (equivalent to a row of rigid rectangular rods) in cross-flow. Their expressions show that the absorption coefficient increases with cross-flow velocity, and is largely independent of the frequency. However, all these studies mentioned in this paragraph rely on the Kutta condition, i.e. they assume that the scatterer has a sharp edge.

A configuration closely related to an array of cylinders in cross-flow is a single cylinder in a hard-walled flow-duct, because this can be modelled by the method of image sources. This configuration has been considered by the group of Hirschberg [12–14] in their work on modelling human voice production. They represented the wind-pipe by a rectangular duct, the vocal chords by two diaphragms (half-cylinders) stretched across the duct with a gap between them, and the air expelled from the lungs by a mean-flow. They used the quasi-steady theory, first proposed by Ronneberger [15] in their model. In quasi-steady theory, the combined flow field (cross-flow superimposed by acoustic wave) is treated as a succession of steady flows. This assumption is obviously valid for steady flows, but it also works well if the superimposed acoustic field has a low frequency [16–18]. Using this approximation, Hofmans [19,20] calculated the reflection and transmission coefficient of a sharp edged diaphragm in a flow-duct.