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Thermal performance of finned-tube thermoacoustic heat exchangers in oscillatory flow conditions

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A B S T R A C T

Heat exchangers play a key role in the overall performance of thermoacoustic devices. Due to the complex nature of oscillatory flows, the underlying mechanism of heat transfer in oscillatory flows is still not fully understood. This work investigates the effect of fin length and fin spacing on the thermal performance of finned-tube heat exchangers. The heat transfer rate between two finned-tube heat exchangers arranged side-by-side in an oscillatory flow was measured over a range of testing conditions. The results are presented in terms of heat transfer coefficient and heat transfer effectiveness. Comparisons are made between experimental results of this work and a number of models, such as the Time-Average Steady-Flow Equivalent (TASFE) model, the Root Mean Square Reynolds Number (RMS-Re) model and the boundary layer conduction model, as well as several empirical correlations in literature. A new empirical correlation is proposed to be used for the prediction of thermal performance for finned-tube heat exchangers in oscillatory flows. The uncertainties associated with the measurement of heat flux are estimated.

1. Introduction

Thermoacoustic technology is based on thermoacoustic effects, whereby fluid adjacent to solid boundaries undergoes a thermodynamic cycle to either generate acoustic power from heat input or transport heat using the acoustic power supplied. In thermoacoustic heat engines, heat input is provided through hot heat exchangers in order for the engines to produce acoustic power in stacks or regenerators, while waste heat leaves the systems through ambient heat exchangers. In thermoacoustic refrigerators, heat is drawn from low temperature sources via cold heat exchangers, transported along stacks or regenerators, and rejected to high temperature sinks via ambient heat exchangers. The thermal interaction of heat exchangers with working fluids is crucial for the performance of the thermoacoustic devices.

The optimization of different parts of thermoacoustic refrigerators, including heat exchangers, in order to obtain the maximum cooling load, was presented by Minner et al. [1] and Tijani et al. [2]. The distance between neighbouring fins, or the fin spacing, was suggested to be about 2–4 times the thermal penetration depth, in order to have an effective heat transfer between heat exchangers and working fluids. The fin length was recommended to be no longer than the displacement amplitude.

Worlikar and Knio [3], Besnoin and Knio [4], and Marx and Blanc-Benon [5] made numerical investigations of the effect of a number of relevant parameters on the heat transfer from heat exchangers made of plate fins in oscillatory flows. These parameters in non-dimensional form include the heat exchanger length, the fin spacing and the gap between heat exchangers and plate stacks. In their numerical study of similar heat exchangers made of plate fins, Piccolo and his co-worker [6–8] introduced a model to predict the non-dimensional heat transfer coefficients, i.e. the Nusselt number and the Colburn-j factor. The validation of the model was undertaken by making a comparison to the experimental results obtained by Brewster et al. [9]. The comparison showed a discrepancy of about 20%.

Wakeland and Keolian [10] studied the heat transfer between two identical heat exchangers over a range of frequencies and displacement amplitudes. The plate fins of the heat exchangers were made out of extruded aluminum micro channels, which were essentially flat tubings with internal fins or ligaments for extra support and rounded edges. The experiment setup involved

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the two heat exchangers only, with no stacks in between. The heat transfer performance was expressed in terms of heat transfer effectiveness (the ratio of the actual heat transfer rate to the maximum possible heat transfer rate). The correlations of the heat transfer effectiveness were established in accordance to the operating conditions: low and high displacement amplitudes. Peak et al. [11] investigated the thermal performance of a heat exchanger within a thermoacoustic refrigerator. The construction of the heat exchanger used is similar to an automotive radiator. Flat fins are brazed onto flat tubes with square edges. Correlations of the dimensionless heat transfer coefficient in terms of Colburn-j factor were developed. Subsequent investigations were conducted by Nsofor et al. [12] and Tang et al. [13]. In both experimental studies, circular heat exchangers with secondary fluids flowing along the circumference were studied. The heat exchangers had fins cut out in the central part using electrical discharge machining. Heat transfer correlations were proposed based on their experimental data. In addition, the experimental results were compared with several existing models, such as the Time-Average Steady-Flow Equivalent (TASFE) model, the Root Mean Square Reynolds Number (RMS-Re) model and the boundary layer conduction model.

As can be seen, the effect of the geometrical parameters of heat exchangers and operating conditions on the heat transfer to the oscillatory gas has been studied to some extent, but largely using the numerical approach. This is caused by the fact that it is rather impractical to have a large number of heat exchangers with different geometrical parameters for test. Furthermore, the plate fins examined in the numerical studies were often assumed to have constant wall temperature, and the effect of the oscillatory flow obstructed by the fins of finite thickness on heat transfer was neglected. These conditions are not always satisfied for heat exchangers in practical applications, which makes experimental studies critically important. The information from experimental studies on the effect of geometrical parameters of heat exchangers and operating conditions on the heat transfer to the flow is scarce. In this study, the effect of the fin length and the fin spacing on the heat transfer performance of finned-tube heat exchangers in oscillatory flow conditions is investigated. The fin length and the fin spacing, in their non-dimensional forms, are varied by changing the mean pressure and the acoustic displacement amplitude. The experimental results are compared with some models and empirical correlations that are available in literature. In addition, a new correlation of the heat transfer effectiveness is proposed based on the experimental results in this work, which can be useful in the design of thermoacoustic heat exchangers for practical applications.

One of the important parameters for heat transfer taking place in oscillatory flow is the thermal penetration depth (δ_κ). It is defined as follows

$$\delta_\kappa = \sqrt{\frac{2k}{\omega\rho_m c_p}}. \tag{1}$$

Here k, ρ_m and c_p are the thermal conductivity, the mean density and the isobaric specific heat of the working gas, respectively. ω is the angular frequency. The thermal penetration depth (δ_κ) denotes a distance from the wall, within which heat can diffuse into the gas during a time of the order of an oscillation period. Another key parameter that influences the heat transfer is the gas displacement amplitude (ξ_a):

$$\xi_a = \frac{u_1}{\omega}, \tag{2}$$

Here u_1 is the velocity amplitude at the chosen location in the acoustic field. Acoustic oscillation is assumed to have a simple harmonic form. In standing waves, the gas displacement amplitude (ξ_a) can be easily obtained from the acoustic pressure amplitude using the following formula:

$$\xi_a = \frac{P_a \sin(k_w x)}{\omega\rho_m a}, \tag{3}$$

where P_a is the pressure amplitude measured at the acoustic pressure anti-node, $k_w(=2\pi/\lambda)$ is the wave number with λ being the wave length, x is the distance from the pressure anti-node, and a is the sound speed.

2. Experimental apparatus

To study the heat transfer from heat exchangers in oscillatory flows, two heat exchangers, one heated and another cooled, are placed side by side in a standing wave acoustic resonator. The resonator, of a total length of 8.9 m, was made of stainless steel pipes with internal diameter of 52.5 mm. Helium was used as the working gas for its popularity in thermoacoustic systems owing to its relatively low Prandtl number. The acoustic oscillation is excited by an electromagnetic linear motor (driver) mounted at one end of the resonator. The other end of the resonator is closed with a flange to make a half wavelength resonator. A schematic diagram of the experimental apparatus is shown in Fig. 1. The experimental apparatus also includes a hot and a cold water circulating loops, a gas charging system and a data acquisition system. In the hot and cold water circulating loops, the water temperatures in the water bathes were kept constant using PID control.

The two heat exchangers were placed in a 100 mm long pipe, with the internal diameter of 122 mm, which formed the test section. This pipe and the resonator maintain the internal pressure, while the heat exchanger casings and the spacers will only bear the acoustic pressure load during the tests.

In the test section, insulation was applied where applicable as shown in Fig. 2. A Duratec 750® ceramic plate with a low bulk thermal conductivity (1.46 $W\,m^{-1}\,K^{-1}$) was used to separate the hot and cold heat exchangers. Each heat exchanger was also separated from the test section end-flanges using machined polytetrafluoroethylene (PTFE) spacers (a bulk thermal conductivity of 0.25 $W\,m^{-1}\,K^{-1}$), to avoid a direct contact between the heat exchangers and the stainless steel flanges. Silicate wool with a thermal conductivity of 0.1 $W\,m^{-1}\,K^{-1}$ was placed in the empty space between the heat exchangers and the stainless steel housing. The internal surface of the stainless steel pipes on both sides of the test section was lined with a polyethylene (PE) sheet of a bulk thermal conductivity of 0.5 $W\,m^{-1}\,K^{-1}$. The thickness of the PE sheet is 1.0 mm, small enough not to cause a significant obstruction to the flow. The PE sheets are about 100 mm into the pipe measured from the flange surfaces, a length much longer than the maximum gas displacement amplitude in the current study.

2.1. Heat exchangers

The heat exchangers resemble the fin and tube (or finned-tube) type heat exchanger. The fins are made from 0.3 mm thick (t) copper sheets. Holes were drilled in each of the fins to allow three copper tubes to pass through. The tubes have 6.0 mm outer diameter and 0.5 mm wall thickness. Fins were cut to the required length and assembled with the tubes and outer copper casing, shown in Fig. 2. The spacing between fins (D), that is, the size of the gap between any two adjacent fins, was maintained by inserts when the fins were joined to the tubes and the casing by