Heat transfers in heat exchangers in steady and oscillating flows

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ABSTRACT

Heat exchangers (HX) are a key constitutive element in thermoacoustic machines. Although they are required to operate with oscillating gas, their design is mostly guided by direct extrapolation of the knowledge applicable to steady flow HX, due to the lack of objective criteria for the design of oscillating flow HX. Most of the works in the literature present theoretical or numerical results, but very few experimental data are available to rule on the strong hypothesis leading to the extrapolation. This study presents the comparative measurements of the heat transfers capabilities of triangular louvered fin HX in steady and oscillating flows under otherwise similar conditions.

1. INTRODUCTION

Thermoacoustic machines are thermodynamic machines that make use of a temperature gradient along a porous material to generate mechanical energy in the form of high level acoustical waves (then called thermoacoustic engines), or conversely make use of an acoustic wave to transport heat from a cold source to a hot source (thermoacoustic heat pump or refrigerator). Due to an innate ability to exploit low-grade heat at low temperatures, the former generate a growing interest for waste heat recovery, and their operation with inert gas provides a certain eco-friendliness to the latter. However both types of machines rely heavily on the ability of their HX on either sides of the porous element to provide and extract sufficient quantities of heat, with adequate efficiency. Design of thermoacoustic machines usually relies on the established knowledge of HX in steady flow to extrapolate their performance with oscillating fluids [1], but only scarce studies

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actually took a closer look at the question, either from an experimental [2, 3] or a numerical point of view [4], and each time for a particular geometry of HX. Here, an experimental approach is proposed to comparatively qualify the performance of an HX in both steady and oscillating to provide keys in future designs.

2. EXPERIMENTAL SETUPS

Two experimental setups are presented, allowing for the measurement of the performance of the studied heat exchanger that is the heat exchanged between the two fluids circulating in the exchanger for controlled conditions of mass flow and temperature. The object of interest is a 30 rows triangular louvered fin aluminum, designed as a car oil radiator and shown in Figure 1.

Figure 1: Studied HX - a 30 rows triangular louvered fin aluminum car oil radiator with dimensions L 285mm * l 235mm * h 50mm.

2.1. Steady flow characterization

Figure 2 presents a schematic view of the test bench for steady flow of the secondary fluid: hot water is the primary fluid circulating at a known flow rate $\dot{m}_w$ in closed loop comprising a thermo-regulated tank where two 2kW thermostats maintain a constant temperature. The secondary fluid is air pushed through the fins of the exchanger by an HVAC tube axial fan, at the steady flow rate $\dot{m}_{air}$ measured with an anemometer. Temperatures of both fluids at the entrance and the exit of the exchanger are monitored. The downstream secondary fluid temperature is measured after the fluid has been thoroughly mixed and homogenized.

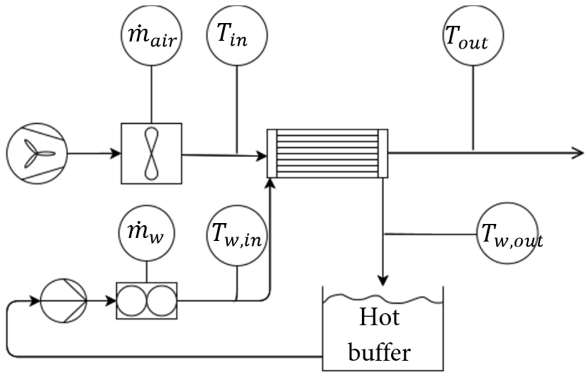

Figure 2: Schematic of the setup for steady flow secondary fluid exchanger qualification.

The heat Q exchanged from each fluid to the exchanger is evaluated independently for both fluid from the temperature difference and the flow rate of each fluid as

$$Q_{air\ or\ w} = \Delta T \rho c_P \dot{m}, \tag{1}$$

with $\Delta T = T_{out} - T_{in}$ the temperature difference of the fluid along the HX, ρ the fluid density and c_P its massic heat capacity.

2.2. Oscillating flow measurements

The characterization of the exchanger under oscillating secondary fluid requires significant modifications, as shown on Figure 3. The flow source is changed for a large surface, large displacement electrodynamic loudspeaker backed by a closed duct to maximize the acoustic velocity it is able to provide. The acoustic flow rate $\dot{m}_{air,ac}$ of the secondary fluid is inferred from the measurement of the acceleration a of the loudspeaker membrane with a laser vibrometer:

$$\dot{m}_{air,ac} = \frac{a}{2\pi f} S, \tag{2}$$

with S the surface area of the membrane and f the excitation frequency.

In order to evacuate the heat transferred to the secondary fluid (its mean position is stationary in his case), a second similar HX is affixed parallel to the first one with a 10 mm gap. Faced with the difficulty to measure the actual temperature of the oscillating fluid, only the temperature of the water circulating in and out of both exchangers is monitored.

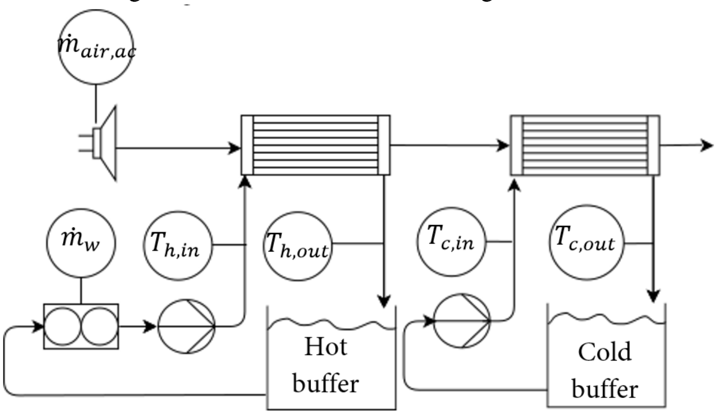

Figure 3: Schematic of the setup for oscillating secondary fluid HX qualification.

3. RESULTS

From temperatures and flow rates measurements, heat fluxes are inferred and plotted on Figure 4.

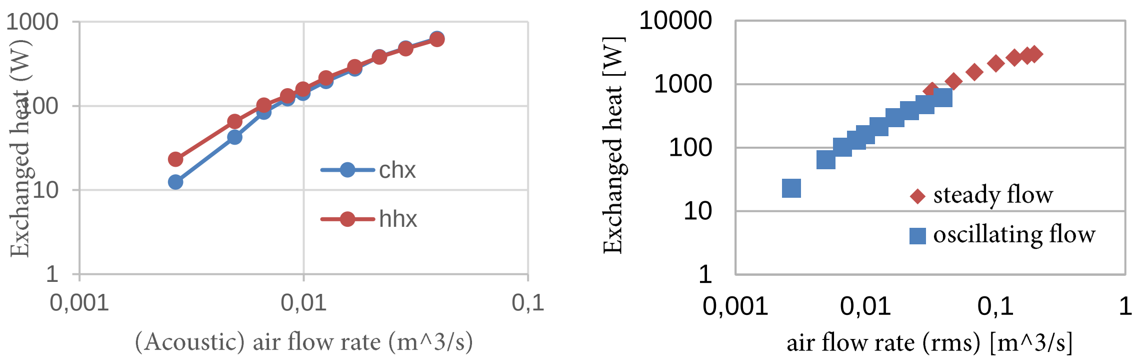

Figure 4: Heat exchanged in both HX vs the acoustic flow rate the hot buffer at 50°C, $\dot{m}_w$=5l/min, and the cold buffer at 18°C. Left: both HX for the oscillating flow, right: summary for both cases.

For low acoustic flow rates, i.e. small acoustic displacements, the secondary fluid remains confined within the thickness of the HX and therefore heat cannot be removed from (or moved to) the HX, as is witnessed by the 2-to-1difference between the heat removed from the hot HX and the heat captured by the cold HX at the lowest air flow. At higher flow rates however, the amplitude of the oscillations bring a higher proportion of the fluid to travel from one HX to the other, and the heat removed from one becomes equal to the one provided by the other.

From these results, the efficiency of the heat exchanger is deduced according to:

$$\eta_{steady} = \frac{Q_{air}}{Q_{water}}, \tag{3}$$

$$\eta_{osc} = \sqrt{\frac{Q_{chx}}{Q_{hhx}}}, \tag{4}$$

where the square root is due to the presence of two HX in series; both are plotted in Figure 5.

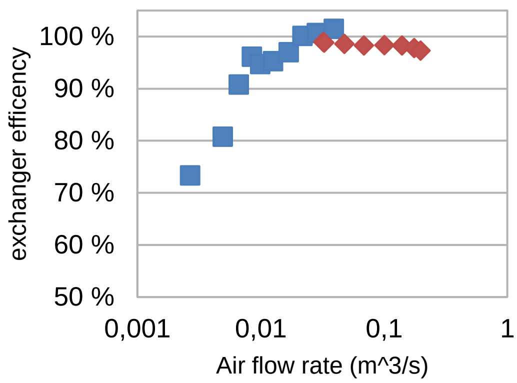

Figure 5: Comparison of HX efficiency between acoustic or steady flow rates of the secondary fluid for otherwise similar operating conditions.

4. CONCLUSIONS

Preliminary studies have been conducted to compare the behavior and performance of a louvered fins HX with its secondary fluid subjected to a steady or oscillating (i.e. acoustic) flow. It appears that, at high oscillating amplitudes (as is the case in thermoacoustic applications, forgetting about around-threshold low amplitudes) where the secondary fluid is allowed to circulate in and out of the exchanger, performances of both configurations are comparable. The assumption of equivalence of behavior between steady and oscillating flow seems in this case to be applicable.

REFERENCES

1. I. A. Ramadan, H. Bailliet, G. Poignand, and D Gardner. Design, manufacturing and testing of a compact thermoacoustic refrigerator. Appl Therm Eng, 189:116705, May 2021.
2. A. Piccolo and A. J. Jaworski. Experimental study of heat transfer characteristics of finned-tube and circular-pore heat exchangers in oscillatory flow. Appl Therm Eng, 181:116022, November 2020.
3. Z. Yu, X. Mao, and A. J. Jaworski. Experimental study of heat transfer in oscillatory gas flow inside a parallel-plate channel with imposed axial temperature gradient. Int J Heat Mass Tran, 77:1023–1032, 2014.
4. A. Piccolo and G. Pistone. Estimation of heat transfer coefficients in oscillating flows: the thermoacoustic case. Int J Heat Mass Tran, 49(9-10):1631–1642, May 2006.