International Journal of Heat and Mass Transfer 127 (2018) 834–842

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Influence of heat exchangers blockage ratio on the performance of thermoacoustic refrigerator

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ARTICLE INFO

Article history:
Received 25 November 2017
Received in revised form 26 May 2018
Accepted 29 May 2018

Keywords:
Thermoacoustic
Low Mach number approximation
Blockage ratio
Heat exchangers
Optimization

ABSTRACT

In this paper, a numerical study is carried out to assess the effect of heat exchangers plates inter-spacing on the performance of a thermoacoustic refrigerator (TAR). Considering that typically most of the heat loss occurs near the heat exchangers, a great emphasis will be placed on the space between the latter and the stack. Several geometric arrangements of heat exchangers plates inter-spacing were tested. The numerical method used is based on two-dimensional low Mach number model. This model assumes that the length of the assembled heat exchangers and stack is less than the wavelength. The results are in agreement with those provided by the DeltaEC software. It can also be observed that the larger the heat exchangers plates inter-spacing, the greater the cooling impact through the thermoacoustic effect.

1. Introduction

A great of research has recently been developed to find out new cooling technologies working without the use of harmful products for the environment. One of theses technologies is based on the thermoacoustic phenomena, that use the heat transfer between a compressible fluid in oscillation and a solid plate. Thermoacoustic technology received considerable attention due to the fact that it uses simple devices without mobile mechanical parts in comparison with conventional technologies. In addition, there are several potentials for development for this technology, particularly regarding miniaturization. However, the low efficiency of devices penalizes the industrial and domestic use of this technology.

It is obvious that the role of the heat exchangers in thermoacoustic devices is crucial in influencing the performance of the entire device. Understanding and solving the specific issues of heat exchangers, such as the abrupt changes that occur in cross sections and edge effects, represent a challenge for researchers. Indeed, several studies have been conducted in order to find ways of optimizing the heat transfer between heat exchangers and the fluid.

As a first step, Worlikar and Knio [1] developed a low Mach number model for a compressible flow so that to simulate acoustically driven flows around a thermoacoustic stack without any heat exchangers for a wide range of drive ratio. They found that a periodic vortex dominates the flow near the edges of the stack. Worlikar et al. [2] modified their model to be able to handle a two-dimensional, thermally stratified and unsteady flow in a stack. Thereafter, Worlikar and Knio [3] extended the model to simulate devices with isothermal heat exchangers and perfect thermal contact with stack plates. The results revealed that the optimum stack performance is achieved when the length of the heat exchanger is nearly equal to peak-to-peak fluid particle displacement.

Besnoin and Knio [4] used the previous model to perform a parametric study regarding the effect of stack length and the gap between the stack and the heat exchanger on the heat transfer process. They concluded that near the stack corners, the flow and the heat transfer processes are dominated by the edge effects and multi-dimensional phenomena. On the other hand, in addition to the geometric parameters. Marx and Blanc-Benon [5] investigated the effects of the acoustic Mach number on the heat pumping performance of the device. They showed that the maximum heat pumping occurs when the distance between the stack and the heat exchangers is on the same order of magnitude as particle displacement.

Nasfor et al. [6] made experimental measurements to show that the thermal property and geometrical parameters of the heat exchanger as well as the operating conditions influence the heat transfer near the heat exchangers. Akhavabazaz et al. [7], for their part carried out a theoretical and experimental study to quantify the impact of fluid blockage of the heat exchangers on the

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.144
0017-9310/

Nomenclature

c	sound speed
P_0	mean fluid pressure
P_a	acoustic pressure
T_{hot}	hot heat exchanger temperature
k	thermal conductivity
C_p	isobaric heat capacity
u	longitudinal velocity component
v	transverse velocity component
ΔT	temperature difference along the plate
L_{res}	resonator length
L_s	stack length
e	stack thickness, exponential
D_r	drive ratio $= \frac{P_a}{P_0}$
e_x	heat exchangers thickness
x_c	distance from the closed end of the resonator to the center of stack
H	height of the computational domain
L_D	computational domain length

Greek Symbols

λ	wavelength
κ	wave number
μ	fluid dynamic viscosity
δ_κ	thermal penetration depth in the fluid
ρ	density
γ	specific heat ratio $= \frac{C_p}{C_v}$
ε	distance between stack and heat exchanger
β_r	blockage ratio parameter
τ	period of the acoustic oscillation
ω	pulsation

Subscripts and Superscripts

$\sim$	dimensional terms
0	mean order
1	first order (terms of order M)
2	second order (terms of order M^2)

performance of a TAR using a small and a large thermal contact area of the heat exchangers. They also studied the case without heat exchangers and concluded that the fluid blockage influences the performance optimization parameters of the TAR, which are the cooling power and the heat that is exchanged with the heat exchangers. Later, Lotton et al. [8] proposed an analytical model of the transient temperature profile to investigate the thermal effect carried along the stack. This model provides a good qualitative agreement with experimental results.

Piccolo [9] studied the effect of both the operating conditions and the geometrical parameters on the performance of the associated stack and the heat exchangers. He used a two-dimensional computational method based on the energy balance equation and energy fluxes in both, solid and fluid. The main results of this work showed that the heat transfer coefficient of the heat exchangers plates affects the temperature difference, the high transfer coefficient values lead to improve the performance of the device, and to reduce the heat exchangers length compared to the particle displacement. This study confirms that the heat exchanger interspacing must be between the range of $2\delta_k$ and $4\delta_k$.

In the same way, Tasnim et al. [10] evaluated the impact of working fluids, of the operating conditions and of mean pressure on the performance of a TAR. They showed that using working fluids with high thermal diffusivity does not imply an increase of the device performance.

Putra and Agustina [11] tested both the effect of the stack plate thickness and the input voltage of the loudspeaker on the temperature difference beween the ends of stack's plates. The experimental results showed that a high amplitude of the input acoustic wave produces a large temperature difference and a high cooling rate. They also observed that the thermal performance and the cooling rate increase when the plate thickness decreases.

This study's innovative feature, compared with those mentioned above, is the use of a two-dimensional low Mach number model to investigate the influence of heat exchangers blockage ratio on the heat pumping performance of a TAR and investigate the interaction between the blockage ratio of the stack and that of the heat exchangers. This interest in the blockage ratio is motivated by the fact that this parameter has a substantial influence on the thermoviscous behaviour of the flow around the edges of the stack and of the heat exchangers and the area located between these two components. The blockage ratio controls the abrupt changes of the sections and the resulting multi-dimensional nonlinear mechanisms, such as the generation of harmonics, nonlinear thermal effects and swirling jets. This is why particular attention is given to the area located between the stack and the heat exchangers.

The computational code used in this study has already proved its effectiveness during many numerical investigations that aimed to study thermoacoustic devices. These were carried out considering the two functioning modes: the refrigerator and the engine. The initial study using this code in refrigeration mode was carried out by Duthil et al. [12] and was validated through an experimental bench test at the LIMSI (Laboratoire d'Informatique pour la Mécanique et les Sciences de l'Ingénieur, CNRS-France). Other studies using this code to simulate thermoacoustic engines were carried out by Hireche et al. [13,14] and Ma et al. [15]. The latter compared the results of the computational code with those of experiments conducted by Atcheley et al. [16].

2. Device description

The studied device is the one used in the experimental investigation described in [12]. It consists of a resonator with a length of $\tilde{L}_{res} = 3.728$ m, filled with helium at a pressure of $\tilde{P}_0 = 10$ bars, closed on the left side and coupled with loudspeaker on the other side. The stationary wave imposed by the loudspeaker is characterized by the drive ratio parameter $Dr = 0.63\%$ and a pulsation $\tilde{\omega} = 858.476\ \mathrm{s}^{-1}$. A polyethylene stack with a length of $\tilde{L}_s = 5 \cdot 10^{-2}$ m and a thickness of $\tilde{e} = 2 \cdot 10^{-4}$ m is located in the resonator with two heat exchangers placed at a distance of $\tilde{\varepsilon} = 6 \cdot 10^{-4}$ m on each side. These heat exchangers are also considered as a pile of plates made of polyethylene and measuring a length of $\tilde{L}_s/4$ and a thickness of $\tilde{e}_x$. The difference in cross-section of the stack and the heat exchangers is represented by the blockage ratio parameter β_r as follows:

$$\beta_r = \frac{\tilde{e}_x}{\tilde{e}} \tag{1}$$

This parameter is inversely proportionate to the heat exchangers plates inter-spacing. The hot heat exchanger is located in front of the closed side of the resonator and is maintained at a fixed uniform temperature of $\tilde{T}_{hot} = 300$ K, while the cold heat exchanger is