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Heat transfer of laminar oscillating flow in finned heat exchanger of pulse tube refrigerator

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ABSTRACT

In order to characterize the heat transfer of heat exchangers employed by pulse tube refrigerators, an experimental apparatus was built to investigate the heat transfer performance of a water-cooled finned heat exchanger operating in laminar oscillating flow. The test results summarized into the Nusselt number with respect to the maximum Reynolds number and the Valensi number were presented. The increases in the maximum Reynolds number and the Valensi number both lead to a rise in the Nusselt number. The comparisons of the experimental results and the available typical correlations were conducted and discussed. A new correlation of the Nusselt number to the maximum Reynolds number and the Valensi number was proposed, with which the results have a maximum deviation of 6.3% compared with the experimental values.

1. Introduction

The heat transfer in an oscillating flow is attractive for many heat engines and refrigerators, such as Stirling engines, thermoacoustic engines and pulse tube refrigerators. Much effort has been made for better understanding the heat transfer characteristics in the oscillating flow, and then for better designing the heat exchangers employed in the abovementioned heat engines and refrigerators. In contrast with a unidirectional flow, the cyclic reversion of fluid velocity direction of the oscillating flow, together with the influence of oscillating pressure on the fluid temperature, brings a big challenge for characterizing the oscillating-flow heat transfer.

A review of the related literatures shows that two typical strategies have been used for characterizing the heat transfer of the oscillating flow, of which one emphasized the cyclically varying temperature profiles in the fluid and the oscillating heat flux at the wall surface [1–8]. Complex Nusselt numbers were used to correlate the oscillating fluid-to-wall temperature differences and the oscillating heat flux. Nika et al. [1], Liu and Garrett [2], and Chen et al. [3,4] formulated the complex Nusselt number based on the linear thermoacoustic theory [9,10]. Kornhauser and Smith [6,7] carried out the measurement of the complex Nusselt number. A dimensionless heat flux, similar to the complex Nusselt number, was proposed in the experimental investigation by Bouvier et al. [8]. The complex Nusselt number can reflect the variation of the Nusselt number within one oscillation cycle, and can also indicate the phase relation of the oscillating fluid-to-wall temperature differences and the oscillating heat flux, which are important characteristics of the oscillating flow.

The other strategy focused on the space-cycle averaged heat transfer characteristics in a channel or a whole heat exchanger, leading to a space-cycle averaged Nusselt number. Piccolo and Pistone [11], and Meng et al. [12] studied the space-cycle averaged heat transfer characteristics by means of numerical simulations. Cooper et al. [13] performed an experimental investigation of the convective heat transfer from the heated floor of a rectangular duct subjected to a low frequency, large tidal displacement oscillating flow (0.1–0.6 Hz, peak-to-peak displacement amplitudes of 3.5–22.86 m). Zhao and Cheng [14] studied the heat transfer of the oscillating air in a long copper circular tube, heated by the uniform heat flux at outer surface. They correlated the Nusselt number to a dimensionless oscillation amplitude of fluid and a dimensionless frequency. Brewster et al. [15] measured the heat transfer coefficient of a heat exchanger with copper parallel plates mounted onto a copper block, in a thermoacoustic engine system with an external driving piston. Leong and Jin [16] investigated the heat transfer in the oscillating flow through a parallel-plate channel filled with aluminum foam. Nsofor et al. [17] observed the heat transfer at the finned-tube type heat exchanger of a thermoacoustic refrigeration system, and summarized their experimental data with a Nusselt

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Nomenclature

A_1	area of the base surface
A_2	surface area of the fin
A_{flow}	flow area of the heat exchanger
A_{o}	dimensionless oscillation amplitude
c	specific heat
C	acoustic compliance
d	Diameter
d_{h}	hydraulic diameter
f	frequency
h	convective heat transfer coefficient
H	height
k	thermal conductivity
l	length
n	number of the fins
Nu	Nusselt number
p	pressure
p_{A}	pressure amplitude
Pr	Prandtl number
Q	heat flow
q_V	volume flow rate of cooling water
Re_{max}	maximum Reynolds number
Re_{rms}	root mean square Reynolds number
Re_{ω}	kinetic Reynolds number
t	temperature/time
u_{max}	velocity amplitude
U_{max}	volume velocity amplitude
V	volume
Va	Valensi number

Greek symbols

δ	thickness
δ_{ν}	viscous penetration depth
δ_{κ}	thermal penetration depth
γ	specific heat ratio
η	efficiency
ν	kinematic viscosity
ρ	density
ω	angular frequency
ξ	correction factor for heat balance

Subscripts

c	cool fluid side
cor	correction
Cu	copper
f	working fluid
fin	fin
h	warm fluid side
i	the ith fin
res	reservoir
w	wall
water	cooling water
wi	inner surface (base surface)
wo	outer surface

number correlation to Reynolds number. Wakeland and Keolian [18] introduced a concept of "effectiveness" to analyze the heat exchanger's performance in an oscillating flow. The space-cycle averaged Nusselt number is consistent with the conventional understanding of the Nusselt number, and can be directly used for designing the heat exchangers working in an oscillating flow.

Additionally, the visualization techniques of temperature field [19–22] have been developed and applied in the study of the heat transfer in an oscillating flow. The variation in the temperature field during one cycle could be measured to summarize the space-cycle heat transfer characteristics.

Following the second strategy mentioned above, this study focused on the heat transfer of a finned heat exchanger usually applied as the ambient-temperature heat exchanger in a pulse tube refrigerator. An experimental apparatus was built according to the operating conditions of the pulse tube refrigerators, which will be presented in next section in details. Based on the measured data, the space-cycle averaged Nusselt numbers (shortened as "Nusselt number" for simplicity in the following context) were calculated and plotted with respect to the maximum Reynolds number and the Valensi number, which are the important and widely used similarity criterions for the oscillating flow [3,4,8,11,14,16–18]. Upon comparing our results with some typical reported works, a new expression was proposed to correlate the Nusselt number to the maximum Reynolds number and the Valensi number.

2. Experimental apparatus and measurement

2.1. Experimental apparatus

The ambient-temperature heat exchangers in a pulse tube refrigerator cool the working gas at its hot ends. Thus, our experimental apparatus is designed for the test of a water-cooled heat exchanger. As schematically shown in Fig. 1, the experimental apparatus consists of a linear compressor, a tested heat exchanger, a needle valve and a reservoir.

The pressure-wave generator is a linear compressor of type 2S132W, fabricated by QDrive for driving a Stirling-type pulse tube refrigerator. The mean electricity input power of the compressor is 500 W, powered by an AC power supply of type PCR2000M fabricated by Kikusui Electronics Corp., with the operating parameters of AC 1–270 V, 20 A, 2000 VA, and 40–500 Hz. The jacket of the compressor is cooled by water to prevent the overheating, especially for the case with large working current. The maximum

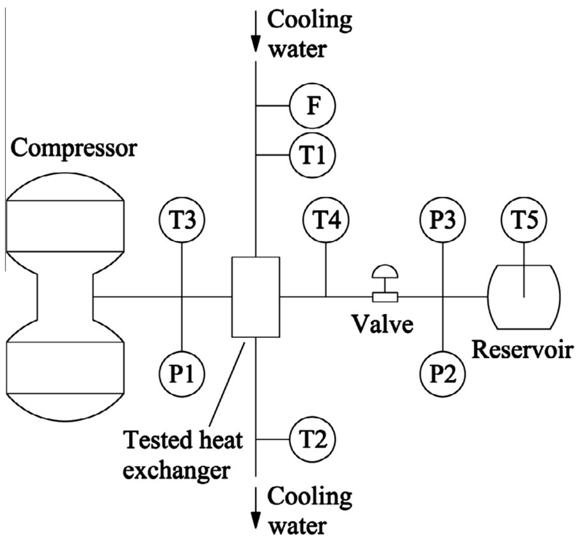

Fig. 1. Schematic of the experimental apparatus.