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Experimental and numerical study on heat transfer and pressure drop performance of Cross-Wavy primary surface channel

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ABSTRACT

The Cross-Wavy primary surface heat exchanger is one of the most promising candidates for microturbine recuperators. In this paper, naphthalene sublimation experiments are performed for Cross-Wavy channels in a wind tunnel. The experimental results indicate that the entrance region has a small effect on the unit-averaged heat transfer coefficient of whole Cross-Wavy channels. Correlations of Nusselt number and friction factor in the Cross-Wavy channel are obtained. However, only the Cross-Wavy channel with a large equivalent diameter is tested because the actual Cross-Wavy channels are very complicated and small. Therefore, based on the similarity rules, five Cross-Wavy channels with similar structures but different equivalent diameters are further investigated by numerical simulations. The numerical results indicate that the Cross-Wavy channels with similar structures but different equivalent diameters have similar thermal-hydraulic performance in the studied Reynolds number range.

1. Introduction

Microturbines are widely used in the distributed power generation field due to high efficiency, small size, light weight, low emissions, low noise, high reliability, low maintenance and fuel flexibility. A compact and highly efficient recuperator is very important for the efficiency and cost of a microturbine system. The recuperator is a heat exchanger that transfers heat from the hot exhaust gas to the compressed air, which can increase the thermal efficiency of the cycle from 17–20% to 30% or higher [1]. Based on the existing technology, the thermal efficiency of a 100 kW microturbine with an efficient and compact primary surface recuperator can reach 35% [2]. Exploring highly efficient primary surface recuperators is still one of the most important issues for the wide application of microturbines.

The typical primary surface structures are Cross-Wavy (CW), Cross-Corrugated (CC) and Cross-Undulated (CU) channels [3]. In order to design a highly efficient primary surface recuperator, it is necessary to study the flow and heat transfer characteristics of primary surface channels. Utriainen and Sunden [4] compared the thermal hydraulic performances of CC, CW, CU primary surface channels and a plate-fin channel for a 50 kW microturbine. The results indicated that the CW and CC primary surfaces had superior performances over the others giving a small volume and weight of the heat transfer matrix. Doo et al. [5] proposed novel CC primary surface structures for an intercooler in an aero-engine. It was found that the pressure drop could be reduced by 15% by the novel anti-phase and full wave rectified secondary corrugation primary surfaces, but the heat transfer capacity changed a little compared to the conventional sinusoidal primary surfaces. Ma et al. [6] numerically investigated the flow and heat transfer characteristics of an improved offset-bubble primary surface channel, which was based on the CC primary surface and offset-strip plate-fin channels. The average area goodness factor for the offset-bubble primary surface channel was 41% higher than that of the CC primary surface with the pitch-over-height being 3.1 and the inclination angle being 60°. The average area goodness factor was 71% higher than that of the offset-strip plate fin channel. Zhang and Chen [7] performed experiment and numerical simulations to disclose the transitional behavior and heat transfer performance in a CC triangular channel under the uniform heat flux boundary condition. It was shown that the low-Reynolds number k-ω turbulence model agreed well with

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Nomenclature

A	amplitude of waviness, mm; total area, m^2
A_c	cross-sectional area, m^2
C	constant
C_n	naphthalene vapor concentration, kg/m^3
C_{air}	naphthalene vapor concentration of air flow, kg/m^3
c_p	specific heat, J/(kg K)
D	mass diffusion coefficient, m^2/s
d_e	equivalent diameter, mm
dm	weight change of naphthalene layer, mg
dt	experimental time, s
f	Darcy friction factor
H	height, mm
h	convective heat transfer coefficient, W/(m^2 K)
h_m	mass transfer coefficient, kg/(m^2 s)
L	wavelength, mm; channel length, mm
m	index
Nu	Nusselt number
Re	Reynolds number
R_n	gas constant of naphthalene vapor, 64.87 N m/(kg K)
p	pressure, Pa
$p_{v,w}$	saturated vapor partial pressure of naphthalene, Pa
P	pitch, mm; perimeter, mm
Pr	Prandtl number
q_m	mass flow rate, kg/s
q_w	heat flux, W/m^2
r	radius of curvature in cross section, mm
R	radius of curvature in streamwise direction, mm
S	area of wetted surface, m^2
T	temperature, K
u, v, w	velocity components in x, y, z directions, m/s
U	area-averaged velocity in the cross section, m/s
V	volume of channel, m^3
w_m	average velocity in z direction, m/s
x, y, z	coordinates, m

Vectors

$\mathbf{F}$	body force vector, N/m^3
$\mathbf{u}$	velocity vector, m/s

Greek symbols

α	thermal diffusivity, m^2/s
β	wall temperature gradient in z direction, K/m
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
Δp	pressure drop, Pa
ΔT_m	logarithmic mean temperature difference, K

the experimental data for Reynolds numbers ranging from 500 to 5000. The results of Ciofalo et al. [8] showed that in the CC channel, the laminar model was suitable when the Reynolds number was less than 3000, but the low-Reynolds number k-ε model and large eddy simulation had the best agreement with the experimental results when the Reynolds number was greater than 3000. Zhang and Che [9] compared different turbulence models for numerical simulations of CC channels, and the results indicated that the low Reynolds number k-ε and shear-stress transport k-w models were suitable for the numerical investigation. Ashok and Talekala [10] conducted a CFD simulation to evaluate the effect of geometrical parameters, and it was found that the heat transfer coefficient increased as the aspect ratio increased, but it decreased as the corrugation angle increased. Liu and Cheng [11] proposed a new multi-objective optimization method to design a primary surface recuperator. It was found that the mass of the first optimized core was reduced by 13.6% compared to the routine design, while the volume of the second optimized core was further reduced by 8.3% compared to the first optimized core. Wang et al. [12] experimentally investigated the heat transfer and pressure drop of a CC primary surface heat exchanger and the Genetic Algorithm method was used to obtain the single-side heat transfer coefficient. The Genetic Algorithm method provided better prediction of the Nusselt number than the regression analysis. The averaged relative deviation of the Nusselt number with the experimental data predicted by the Genetic Algorithm method was 1.95%, while that by the regression analysis was 2.84%. In a previous study, a numerical model with multiple periodic boundary conditions was proposed for the CW channels, and a linearly decreasing wall temperature boundary condition was used to replace the constant wall temperature boundary condition [13]. It was found that with the increase of the ratio of the amplitude to channel pitch, both the heat transfer and pressure drop increased. Tavakoli and Hosseini [14] used the Chorin's artificial compressibility method to study the pressure drop in a cross corrugated channel, and showed that the friction factor decreased with the increase of the gap between the adjacent plates. The effects of wave number and Reynolds number on the velocity and thermal fields were also studied [15]. The saturation efficiency increased as the wave number along the media depth increased, but decreased as the Reynolds number or the amplitude to wavelength ratio increased. Xia et al. [16] compared a complex corrugation microchannel with a rectangular microchannel in a chip cooling system. The pumping power of the complex corrugation microchannel was reduced by 18.99% when the total thermal resistance equaled to 0.446 K/W. Khoshvaght-Aliabadi [17] performed a numerical simulation to study the thermal-hydraulic performance of a sinusoidal-corrugated channel with Al_2O_3-water nanofluid. Khoshvaght-Aliabadi and Sahamiyan [18] further conducted an experiment and demonstrated that the corrugated channel and Al_2O_3-water nanofluid could enhance the comprehensive performance of the minichannel heat sink. Wang et al. [19] reviewed the related work on the primary surface heat exchangers, including the CC, CU, CW, double-wave CC, offset-bubble and 3D anti-phase secondary corrugation primary surface channels.

Many experimental works have also been performed to study the flow structure or heat transfer performance in general channels. Masiukiewicz and Anweiler [20] applied stereological methods to quantitatively estimate the two-phase flow structure in minichannels. Naphon [21] measured the average Nusselt number and friction factor of the corrugated channels with V corrugated upper and lower plates. Giordano et al. [22] examined the flow and temperature fields by using the Particle Image Velocimetry (PIV), Stereo PIV, and the infrared thermography along with a heated thin foil heat flux sensor in a channel with a finite circular cylinder. Chung et al. [23] applied the naphthalene sublimation method to measure the mass and heat transfer performance in ribbed channels. In fact, the naphthalene sublimation technique has been used for heat and mass transfer measurements in gas turbine blades [24], circulating fluidized beds [25], and outside surfaces of tube-fin heat exchangers with vortex generators [26] or triple-finned tubes [27]. Although there are many experimental studies on general channels, such as ribbed channels, cross corrugated channels and spiral-like channels, only few experimental studies have been performed on the CW primary surface channels in the open literature. Moreover, there are few experimental heat