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Experimental study of heat transfer characteristics in a 180-deg round turned channel with discrete aluminum-foam blocks

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ABSTRACT

This work experimentally investigated the local and average heat transfer characteristics in a 180-deg round turned channel with discrete aluminum-foam blocks. The air was used as coolant. Several aluminum-foam blocks (0.90 porosity and 10 PPI pore density) were installed discretely in the 180-deg round turned channel with the square cross section. Total four kinds of test section, with various arrangements of aluminum-foam blocks, were employed. The results indicate that the local peak values of the Nusselt numbers would appear at the positions of the aluminum-foam blocks. The local Nusselt numbers of the upper and bottom walls were higher than those of the side walls in the straight ducts; while the local Nusselt numbers of the outer side wall were higher than those of others walls in the turn. The local Nusselt numbers of the inner side wall generally were the lowest values. Besides, the average Nusselt numbers of the present porous channels were 74–140% higher than that of the empty channel, suggesting the significant heat transfer enhancement of the aluminum-foam blocks. Furthermore, in the straight duct, the staggered aluminum-foam blocks could promote heat transfer more efficiently than the symmetric aluminum-foam blocks did. The average Nusselt numbers of Model 3 and Model 4 (the whole channel filled with aluminum-foam blocks) were 20–30% higher than those of Model 1 and Model 2 (only straight ducts filled with aluminum-foam blocks). It is noteworthy that the pressure drops of Model 1 and Model 3 test sections (vertically symmetric configuration) are much higher than those of Model 2 and Model 4 test sections (vertically staggered configuration) by 180–280%.

1. Introduction

The heat transfer enhancement of 180-deg turned channel has been a topical subject for a number of years. This type of design is used on internal cooling of gas-turbine blades, internal cooling of high-speed rotary machine tools and electronic equipment cooling systems. The mounting ribs on the wall surface of channel can enhance the heat transfer capacity [1–6]. Besides the design of fixing additional ribs, some special configurations have been proposed and discussed. For example, Hirota et al. [7,8] researched the heat and mass transfer of 180-deg sharply turned channel, and proposed the configuration of oblique intermediate divider. The 180-deg turned channel is divided by the intermediate divider into connected Duct One and Duct Two. The oblique intermediate divider results in flaring Duct One with flaring Duct Two or tapered Duct One with tapered Duct Two, so that the heat transfer distribution of overall 180-deg sharply turned channel is changed significantly. Pamula et al. [9] experimentally discussed the heat transfer characteristics of the 180-deg rectangular turned channel with the two-row-hole intermediate divider. They found that, in comparison to non-perforation configuration, the two-row-hole configuration could form the impingement cooling and transverse flow vortex effect in the second duct, and further enhance the heat transfer capacity by 2–3 times. Bunker [10] produced pin-fin array on the outer wall of the bend section top of 180-deg rectangular turned channel to enhance the heat transfer of that zone. The experimental results indicated that in comparison to smooth wall surface, the pin-fin array could increase the heat transfer coefficient of the top outer wall by 2.5 times. Chen et al. [11] proposed the configuration of mounting turning air guide vane in the bend region of 180-deg round turned channel with 45-deg rib. They found that the air guide vane could reduce the flow resistance, and the rib in the bend region increased the heat transfer capacity by 15%. Schuler et al. [12] proposed the configuration of mounting single or double-air guide vane in the second turn of the bend section of 180-deg rectangular turned channel with 45-deg rib. They found that the single inner air guide vane or double-air guide vane could reduce the pressure drop by 25%, and the heat transfer performance of bend region was almost consistent with that without

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Nomenclature

A	overall area of heated surfaces (m^2)
C_f	friction factor, Eq. (4)
D_h	hydraulic diameter of the test channel (m)
j	Colburn factor, $j = \overline{Nu}/Re/Pr^{1/3}$
k	thermal conductivity (W/m/°C)
Nu	Nusselt number, Eq. (2)
q_{in}	total input heat flux (W/m^2)
q_{loss}	loss heat flux (W/m^2)
Re	Reynolds number, Eq. (1)
S	axis along the main flow direction (m)
T	temperature (°C)
U	average air velocity at the channel inlet (m/s)

Greek symbols

μ	viscosity (kg/m/s)
ρ	density (kg/m^3)

ΔA	weighted area for each T_w (m^2)
Δp	pressure drop through the channel (pa)

Subscripts

B	bottom wall
f	fluid
I	inner side wall
i	at channel inlet
O	outer side wall
U	upper wall
w	heating wall

Superscript

–	average

air guide vane. However, if a single outer air guide vane was mounted, the pressure drop was increased by 12%, and the influence on heat transfer was negative. Xie et al. [13] numerically simulated the heat transfer characteristics of the 180-deg rectangular turned channel with semicircular protrusion array or semicircular dimple array on its top outer wall. They indicated that in comparison to smooth wall configuration, their configuration could obtain two times of heat transfer enhancement, and the pressure drop was increased only by 6%. Jeng et al. [14–16] proposed the configuration of intermediate divider with multiple perforations in the 180-deg turned channel. The coolant in the first duct entered the second duct ahead of time through perforations due to the bypass effect, so that the temperatures of upstream and downstream hot wall surfaces were relatively consistent, to avoid local high temperature at the wall surface of downstream channel. Thus, the interior of machine member was cooled uniformly. In addition, the perforations in the intermediate divider had additional perturbation effect on the air flow, the bypass air flew through the perforations and the main flow affect each other, that may gain the overall heat transfer capacity. Jeng et al. [14] used transient liquid crystal method to measure the detailed heat transfer coefficient distribution on the bottom wall and outer wall of 180-deg rectangular turned channel. Moreover, flow visualization technique and steady-state heat transfer experimentation were used to investigate the fluid flow and heat transfer characteristics of 180-deg round turned channel [15]. The experimental results indicated that large size and positive angle of perforations influenced local Nusselt number distribution significantly, and the overall heat transfer declined as the perforation size increased, especially when the perforation was at positive angle. However, when the perforation size was small, the overall heat transfer was higher than that without perforations by about 10%, and the influence of perforation angle was insignificant. Jeng et al. [16] also found in rotational state that, the local Nusselt number of outer wall of bend section was significantly higher than the trailing surface and leading surface. At high rotation rates, the local Nusselt number difference between trailing surface and leading surface of the first duct in the perforation configuration was apparently greater than that of the configuration without perforations. In the second duct, the local Nusselt number difference between trailing surface and leading surface of the perforation configuration was less apparent than that of the non-perforation configuration.

There are a number of studies concerning porous medium to heat transfer. Angirasa [17,18] conducted steady-state experiment to discuss the heat transfer enhancement of aluminum foams. The aluminum foams did not fill up the overall channel, there was still space above and by the aluminum foams, and he used one equation model to simulate the heat transfer characteristics of the channel full of aluminum foams at high Reynolds number. Calmidi and Mahajan [19] studied the forced convection of aluminum-foam channel. The porosities and pore densities of aluminum foams for the experiment separately were 0.91–0.97 and 5–40 PPI (pores per inch), extensive and valuable experimental data were obtained. The numerical simulation of two equation model was used to estimate the important empirical equations of porous thermal properties, such as the heat transfer coefficient between fluid and porous medium solid, and the transverse thermal dispersion conductivity. Ko and Anand [20] studied the periodically arranged aluminum-foam blocks in the channel with wall surface heated uniformly, completed a series of experimental measurement, and found that the aluminum-foam blocks increased the heat transfer by 300% effectively. Fu et al. [21] and Leong and Jin [22,23] experimentally observed the heat transfer characteristics of aluminum-foam or copper-foam channel with oscillating flow at different frequencies and amplitudes. They found that the metal-foam heat sink with oscillating flow could implement effective thermal control for modern electronic modules generating high heat. Tzeng and Jeng [24,25] investigated the heat transfer characteristics of aluminum foams with 90-deg turned flow or impinging jet flow. They found that the aluminum foams enhanced the heat transfer by 2–3 times, and indicated that the nozzle width, impinging distance, foam height and nozzle straightener influenced the overall and local heat transfer. Tzeng and Jeng [26] experimentally explored the heat transfer of aluminum foams at porosity of 0.93/10 PPI and compressed aluminum foams at porosity of 0.8 and 0.7 in rectangular channel without bypass clearance. The experimental results indicated that the uncompressed aluminum foams had higher Nusselt number than the compressed aluminum foams. Sopian et al. [27] used the second straight duct with porous medium of a 180-deg rectangular turned channel as solar thermal energy collecting system. They found that in comparison to the configuration without porous medium, the configuration with porous medium increased the thermal efficiency by 60–70%. Tzeng et al. [28] filled the four-duct S-turned channel with compressed aluminum foams at porosity of 0.8, and experimentally discussed the heat transfer characteristics in radial high-speed rotation. They indicated that on the trailing surface of the third straight duct, the Nusselt number of the