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Heat transfer and pressure drop in corrugated channels

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ABSTRACT

The convective heat transfer and pressure drop characteristics of flow in corrugated channels have been experimentally investigated. Experiments were performed on channels of uniform wall temperature and of fixed corrugation ratio over a range of Reynolds number, $3220 \le Re \le 9420$. The effects of channel spacing and phase shift variations on heat transfer and pressure drop are discussed. Results of corrugated channels flow showed a significant heat transfer enhancement accompanied by increased pressure drop penalty. The average heat transfer coefficient and pressure drop enhanced by a factor of 2.6 up to 3.2 and 1.9 to 2.6 relative to those for parallel plate channel, respectively, depending upon the spacing and phase shift. The friction factor increased with increasing channel spacing and its phase shift. The effect of spacing variations on heat transfer and friction factor was more pronounced than that of phase shift variation, especially at high Reynolds number. Comparing results of the tested channels by considering the flow area goodness factor (j/f), it was better for corrugated channel with spacing ratio, $\varepsilon \le 3.0$ and of phase shift, $\O \le 90°$. Comparisons of the present data with those available in literature are presented and discussed.

1. Introduction

In recent years, due to the increasing demand by industries for heat exchangers that are more efficient, compact and less expensive, heat transfer enhancement has gained great momentum. For this purpose, two techniques have been identified: 'passive' and 'active' [1]. Passive technique uses special surface geometries, or fluid additives. Because of more costs involved, active technique has attracted relatively little attention in research and practice, and passive technique through the use of various surface geometries such as corrugated channels to be preferred [2].

The heat transfer characteristics of flow through such corrugated channels are quite different than parallel plate channels. In corrugated channel, the main flow direction is parallel to the channel waviness, but the local flow direction is always changed due to channel waviness. The thermal boundary layer formed on its walls is periodically interrupted by flow recirculation, separation and reattachment and thereby increase of convective heat transfer coefficient. However, such gains in heat transfer are invariably accompanied by increased pressure drop penalty.

Several studies on heat transfer enhancement using such passages have been reported [3]. Goldstein and Sparrow [4] were the first to report local and average convection heat transfer coefficients in a corrugated passage using the naphthalene technique. Their passage included two different corrugations with an angle of 30°. Comparison of their results with parallel plate passage data showed an enhancement in the average convection heat transfer by a factor of 3 in turbulent flow regimes. O'Brian and Sparrow [5] obtained an empirical correlation of the average Nusselt number for turbulent flow in corrugated channels with sharp edged corrugation peaks. They reported that friction factor was almost independent of Reynolds number. The promoted flow separation accompanied with sharp edged corrugations however, causes large pressure drops. Mendes and Sparrow [6] performed an experimental study on converging–diverging tubes turbulent flow in the entrance and fully developed regions. They investigated the effect of different aspect ratios and taper angles on the heat and mass transfer behaviors. The largest taper angle resulted in highest heat and mass transfer rates and accompanied by larger pressure drop. They related that to the promotion of strong circulation zones and flow separation. Comparing their results with the straight tubes revealed an overall enhancement in heat transfer rates for the converging–diverging channel.

The effect of corrugated channel height on flow and heat transfer characteristics for water was also investigated by Sparrow and Comb [7]. They reported that the increase of the channel height resulted in a valuable increase in Nusselt number but the friction factor substantially increased. Islamoglu and Parmaksizoglu [8] investigated the heat transfer coefficients and friction factor for air flowing in corrugated channel of two different spacing and single

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Nomenclature

A	amplitude/surface area, m^2
c_p	specific heat, j/kg K
D_h	hydraulic diameter, m
f	friction factor
h	heat transfer coefficient W/m^2 K
j	colburn factor, $(Nu/Re\ Pr^{1/3})$
k	thermal conductivity, W/m K
L	pitch of corrugated channel waviness, mm
L_t	axial length of the channel, mm
Nu	Nusselt number, $(h\ D_h/k)$
Pr	Prandtl number, $(c_p\ \mu/k)$
p	pressure, Pa
Q_{in}	heat input rate to channel's walls, W
Re	Reynolds number, $(u\ D_h/\upsilon)$
S	channel spacing, mm
T	temperature, K
V	volume flow rate, m^3/s
u	flowing air velocity, m/s
W	channel width, mm

Greek symbols

Δ	difference
ε	channel spacing ratio, $(S/2A)$
γ	channel corrugation ratio, $(2A/L)$
Ø	phase shift
θ	corrugation angle
ρ	density, kg/m^3
ν	kinematic viscosity, m^2/s

Subscripts

a	air
c	channel cross-section
i	at inlet conditions
m	mean value
o	at outlet conditions/orifice
w	at wall conditions

superscripts

–	average

corrugation angle of 20°. It is reported that over a flow range of $1200 < Re < 4000$, a substantial increase in both fully developed Nusselt number and friction factor was obtained due to changing of channel spacing from 5-mm to 10-mm, however the flow area goodness factor slightly decreased. Ali and Ramadhyani [9] demonstrated heat transfer and flow visualizations in riangular corrugated channel with water as working fluid for two different channel spacing. They concluded that the performance of corrugated channel with larger spacing is much better than that of smaller spacing. Comparing their results with that of parallel plate channel, they pointed out that the corrugated channel had much higher Nusselt number. Islamoglu et al. [10] measured heat transfer and pressure drop for turbulent air flow in a corrugated duct having an angle of 30°. They presented an empirical correlation of cycle-average fully developed Nusselt number.

Sang and Hyung [11] conducted experimental and numerical study on flow and local heat/mass transfer characteristics of wavy duct using a naphthalene sublimation technique. The flow visualization and CFD simulation were used to predict the overall flow structures inside the duct. The results showed that complex secondary flows and transfer processes exist inside the wavy duct resulting in non-uniform distributions of the heat/mass transfer coefficients on the duct side walls. They reported that the average heat/mass transfer coefficients are higher than those of the smooth circular duct, and. that enhancement was accompanied by increased pressure drop penalty. Naphon [12] investigated the heat transfer characteristics and pressure drop in a channel of different corrugation angle under constant heat flux. The experiments were performed for laminar and turbulent flow. It is concluded that heat transfer and pressure drop were tremendously enhanced compared to those of parallel plate channel. They related that to the promoted recirculation zones and flow separation in corrugated channel flow.

Wang and Vanka [13] conducted numerical studies of flow and heat transfer in periodic wavy passages having phase angle of 180°. The steady-flow pattern was observed for $Re \leq 180$, after which there was self-sustained oscillatory flow, leading to destabilization of laminar thermal boundary layers and thus provide a natural mechanism of heat and mass transfer enhancement. In the steady-flow regime, the average Nusselt number for the wavy channel was slightly larger than that for a parallel plate channel. Meanwhile, the heat transfer enhanced by a factor of 2.5 in the transitional-flow regime. Friction factors for the wavy channel were about twice those for the parallel plate channel in the steady-flow region, and remained almost constant in the transitional regime. Forced convection for flow through a periodic array of a wavy-wall channel has been investigated numerically by Wang and Chen [14]. It is reported that the major region of flow reversal occurs at higher Reynolds numbers. As the wavelength ratio and the Reynolds number increase, the local Nusselt number increases manifestly in the converging section of the wavy-wall channel and show a small change in the diverging section.

Zhang et al. [3] numerically investigated the effect of fin waviness configuration and its spacing on flow and heat transfer characteristics in uniform temperature channels with sinusoidal wall corrugations for laminar flow regime ($Re < 1000$). It is reported that the strength of developed recirculation cells depends on Reynolds number, spacing ratio (ε) and corrugation ratio (γ). As the spacing ratio decreases, viscous forces dominate and dampen the swirl; with large spacing, the impact of wall waviness diminishes and the core fluid flows largely undisturbed. The extent of swirl increases with flow rate, when multiple pairs of helical vortices are formed. This significantly enhances the overall heat transfer coefficient and pressure drop penalty, when compared to those in a straight channel of the same cross-section. It is also reported that the flow area goodness factor (j/f) increases with small spacing. The optimum j/f enhancement was obtained in the swirl flow regime ($Re > 100$) with corrugation ratio, $\gamma > 0$ and spacing ratio, ε range of $0 \leq \varepsilon \leq 1.2$.

From the preceded survey, it is obvious that the enhancement of heat transfer using corrugated passages is one of interested subjects to the researchers. Although several studies for steady- and unsteady-flows have been reported, little knowledge is available on the flow and heat transfer characteristics in such passages. This work will contribute the heat transfer and pressure drop characteristics in channels with corrugated walls.

2. Test rig

A schematic diagram of the experimental apparatus is shown in Fig. 1. Air, the working fluid was drawn from the laboratory by the induced blower (6) via a bell mouth inlet (1) into the upstream