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Experimental investigation of flow and heat transfer for natural circulation flow in an inclined narrow rectangular channel

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ABSTRACT

Narrow rectangular channels are widely used in heat transfer exchangers. We conducted an experimental study under natural circulation conditions to investigate the flow resistance and heat transfer characteristics of water in a one-sided heated narrow rectangular channel. The experiments were performed at pressures of 0.2 MPa and 0.3 MPa, with inlet subcooling temperatures ranging from 30 to 70 K and heat flux ranging from 20 to 90 $kW \cdot m^{-2}$. In a laminar flow regime for a channel with a heated lower plate, both the heat transfer coefficient and friction factor increased with increasing inclination angle. For a channel with a heated upper plate, the inclination angle had an insignificant influence on both the heat transfer coefficient and friction factor. In both transitional and turbulent flow regimes, increase in the Reynolds number suppressed the influence of inclination angle on the heat transfer coefficient and friction factor. The present study suggests that flow resistance and heat transfer in an inclined, narrow rectangular channel with a heated lower plate can be enhanced, as compared to the parameters of a vertical channel. Thermal instability (driven by buoyancy force) is the main factor influencing flow and heat transfer characteristics.

1. Introduction

In recent years, the extremely high heat removal efficiency of narrow rectangular channels has made them the focus of much research in areas such as aerospace, micro-electronics, and nuclear power. Meanwhile, because of their passive safety, researchers have had high expectations of the ability of natural circulation systems to eliminate reactor heat under accident conditions.

According to classifications by Kandlikar (2002), a gap size between 1 and 3 mm can be regarded as a narrow or mini-channel. Pioneering research on flow and heat transfer characteristics in narrow rectangular channels was reported in the early 1950s by Kays and London (1952). Their experiment was conducted in a narrow rectangular channel with a 2-mm gap. The flow resistance results agreed well with those for a conventional channel. Afterwards, many studies were conducted on flow and heat transfer characteristics in narrow rectangular channels. However, the suitability of conventional fluid flow theory for narrow rectangular channels is still debatable, as reviewed by Steinke and Kandlikar (2006) in 2006. Recently, Ma et al. (2011) performed experiments in a vertical narrow rectangular channel, and their flow resistance results showed satisfactory agreement with conventional theory; however the heat transfer coefficient cannot be predicted with either the Dittus-Boelter (D-B) correlation (Dittus and Boelter, 1985) or the Gnielinski correlation (Gnielinski, 1976).

In addition to the aforementioned studies on symmetrically heated narrow rectangular channels, some studies on single-phase flow and heat transfer have been conducted for asymmetrically heated narrow rectangular channels. Under a laminar flow regime, Kurosaki and Satoh (1987) used numerical methods to study the effects of non-uniform heating on heat transfer in a thermally undeveloped gas flow in a horizontal rectangular duct. In their work, a vertical side wall was uniformly heated while the other walls were insulated. The results indicate that heat transfer rate and flow resistance increase with increasing secondary flow, because of buoyancy in the asymmetrically heated narrow rectangular channel. Under a turbulent flow regime, Sparrow and Cur (1982) experimentally investigated the effect of asymmetrical heating on fully developed turbulent heat transfer. In their test section, the two

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Nomenclature			
General symbols			
Ah	Wetted perimeter	Y	Thickness of the heating plate(m)
C	Coefficient in Eq. (19)	y	Distance from the outside wall of the heating plate (m)
De	Equivalent diameter (m)	ΔP	Pressure drop (Pa)
g	Acceleration of gravity (m/s^2)	ΔP_g	Gravitational pressure drop (Pa)
Gr	Grashof number	ΔP_f	Frictional pressure drop (Pa)
h	Heat transfer coefficient (W/m^2/K)	ΔP_a	Acceleration pressure drop (Pa)
i	Enthalpy (J/kg)	ΔP_m	Measured pressure drop (Pa)
k	Thermal conductivity (W/m)	**Greek symbols**	
L0	Length of heating region (m)	α	Channel aspect ratio
L1	Distance between two pressure taps (m)	α_v	Volume coefficient of expansion (1/K)
m	Mass flow rate (kg/s)	δ	Height of the channel (m)
Nu	Nusselt number	λ	Friction factor
Pr	Prandtl number	Φ	Volumetric heat generation rate (W/m^3)
Po	Poiseuille number	$\bar{\rho}_{ch}$	Average density of the channel (kg/m^3)
Q	Heating power (W)	θ	Inclined angle (rad)
q	Heat flux (W/m^2)	**Subscripts**	
Re	Reynolds number	b	Bulk flow
Ri	Richardson number	f	Fluid
T	Temperature (K)	in	Inlet
u	Mean fluid velocity (m/s)	l	Laminar
V	Volume of the heating plate (m^3)	out	Outlet
ν	Dynamic viscosity (Pa•s)	sub	Subcooling
w	Width of the channel (m)	t	Turbulent
x	Distance from the inlet (m)	w	Heating plate
		W,i	Inner surface of the heating plate
		W,o	Outer surface of the heating plate

long sides of the narrow rectangular cross section were heated at different preselected heat fluxes, while the two short sides were not heated. Two cases of asymmetrical heating have been studied in their experiments: (a) One of the two long sides is heated, while the second is not heated, and (b) both of the long sides are heated, with the heating rate at one side being twice that of the other. The heat transfer coefficients for case (a) are lower than those for the symmetrically heated duct. For case (b), the coefficients for the more strongly heated wall are also below the values for symmetrical heating, while the coefficients for the less-heated wall are greater than those for symmetric heating.

In terms of studies associated with inclined conditions, Maughan and Incropera (1987) experimentally investigated mixed convection heat transfer for airflow in an inclined channel heated uniformly from below. They found that heat transfer is initially dominated by forced convection, and shows a sharp decrease in terms of *Nu* in the thermal entrance region. However, a sudden increase in *Nu* occurs along the flow direction. The thermal instability caused by secondary flow is the main reason for the sudden increase in *Nu*. A similar phenomenon was numerically predicted by Cheng and Ou (1982), and Incropera and Schutt (1985).

Most of the studies on single phase flow convection heat transfer were conducted under forced circulation conditions. However, Yang et al. (2006) investigated heat transfer for water flow in a heated vertical tube under natural circulation conditions. When comparing the experimental data with available literature predictions of forced flow correlations, they found that the Nusselt number in the fully developed region was approximately 30% lower than in the predictions for forced flow correlations. This was due to flow laminarization in the layer, induced by co-current bulk natural circulation and free convection. This remarkable discovery has been verified by Wang et al. (2014). Wang et al. conducted natural circulation flow convection heat transfer experiments in a circular channel, and their experimental results agree well with the Yang correlation predictions (Yang et al., 2006).

Although many researchers have investigated narrow rectangular channels, the flow resistance and heat transfer characteristics for natural circulation flow in an inclined narrow rectangular channel are still unknown. Before natural circulation systems can be widely used in heat exchangers, the thermal hydraulic performance for natural circulation flow in a narrow rectangular channel must be clearly understood. In this study, experiments were conducted under natural circulation conditions in an inclined, narrow rectangular channel with a gap of 2 mm. Flow resistance and heat transfer characteristics in laminar, transitional, and turbulent flow regimes were studied. Additionally, the effects of inclination angle on flow resistance and heat transfer characteristics were analyzed under different conditions.

2. Experimental apparatus

2.1. Natural circulation loop

The schematic diagram of the experimental apparatus is presented in Fig. 1. The primary loop is located on a 2.5 × 3.5 m^2 rectangular rolling platform, which can rotate around the shaft or be fixed at a given inclination angle. The primary loop consists of a pressurizer, a preheater, an electromagnetic flow meter, the test section, a cooler, an auxiliary coolant pump, and several valves and connecting pipes. The secondary loop consists of a water feed pump, a cooler, an air cooling tower, a water tank, etc.

De-ionized water was heated to the preset temperature in the preheater. Then, it flowed into the test section, where the flow resistance and heat transfer characteristics were investigated. After it was uniformly heated in the test section, hot water flowed into the cooler, to be cooled through the adiabatic riser. Acting as the heat sink, the cooler was placed at the top of the loop, as shown in Fig. 1. Finally, the cooled water flowed back through the downcomer into the preheater.

2.2. Test section

Fig. 2 shows a schematic diagram of the test section, which consists of a heating plate, a quartz glass, a silicon rubber O-ring, a mica plate, and a pair of holders. A narrow rectangular channel with a width of 40 mm and a gap of 2 mm was constructed with a covered concave quartz glass on the heating plate. The waterproofing of the narrow channel is guaranteed by the sealing silicon

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