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Experimental study on mixed convection in an asymmetrically heated, inclined, narrow, rectangular channel

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ABSTRACT

Experimental study on mixed convection in the entrance region of a one-side-heated narrow rectangular channel has been carried out. We have performed a series of experiments under natural circulation conditions with *Re* ranging from 1000 to 3000 and inclination angle ranging from 0° to 30°. Meanwhile, we conducted flow visualization experiments to identify secondary flow driven by temperature difference between the lower, heated and upper, unheated plate of the channel. It is found that thermal instability can be enhanced by increasing the inclination angle of the channel. The secondary flow induces the onset of thermal instability (OTI) while increasing in *Re* delays the OTI. A sudden increase of hear transfer coefficient and friction factor has been observed after the OTI. The traditional identification criteria for mixed convection are not suitable for the inclined, narrow rectangular channel with a heated lower side. However, transverse Richardson number can identify mixed convection in the channel. The experiment results, together with image data for the flow condition in the inclined narrow rectangular channel, offer valuable data to improve the engineering design of plate-type fuel assembly and similar heat exchangers.

1. Introduction

With a higher power produced per unit volume, the plate-type fuel element is used in some reactor core to meet the requirements of reactor miniaturization. Since there is more heat generated in unit fuel volume, the heat flux on the fuel cladding goes higher, leading to a rise of fuel and cladding temperature, which results in a threaten to the integration of the fuel element. A method which enables the total thermal output of the fuel element to increase without increasing the maximum fuel or cladding temperature is to enhance the heat transfer between the cladding and coolant. The coolant flow channel in the core with plate-type fuel elements is a narrow rectangular gap, which is of higher heat transfer coefficient. So there are certain advantages with the introduction of plate-type fuel element and narrow gap channel. Firstly, the heat generated in unit fuel volume is increased as a result of the thinner plate making the heat conduction easy, and secondly narrow gap channel result in more heat transfer. Different from other heaters, the reactor core is sensitive to bubbles, since bubbles will affect the reactivity, which will lead to power oscillations and finally threaten the safety of reactor core. So single phase flow and heat transfer play an important role in heat removing from reactor core.

Natural circulation is gradually employed in the thermal-hydraulic design of nuclear reactor to reduce noise and enhance passive safety. However, natural circulation flow, without the support of pumps, can only provide a lower mass flow rate than required. The low mass flow rate induces a heat transfer deterioration. As a result, the method for heat transfer enhancement is of great importance for natural circulation flow.

Mixed convection heat transfer exists when natural convection currents are of the same order of magnitude as forced flow velocities [1]. Elenbaas [2] pioneered experimental investigation into natural convection heat transfer in pallet channel in 1942. Afterwards, many investigations were conducted on mixed convection, as a combination of natural convection and forced convection. Many studies (Joye et al. [3–5], Behzadmehr et al. [6,7], Incropera et al. [8–13] and Dogan et al. [14]) have found mixed convection as an efficient way to enhance heat transfer. Because of this advantage, mixed convection is incorporated into many engineering applications such as solar collectors, ventilation of electronic devices, compact heat exchangers and nuclear reactors.

A review conducted by Dawood et al. [15] divided mixed convection into three cases. First case is when natural convection aids forced convection. This is seen when the buoyant motion is in the

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Nomenclature

General symbols

A	area of the heating plate
De	equivalent diameter
g	acceleration of gravity
Gr	Grashof number based on De $\left[= \frac{g \cdot \beta (T_w - T_f) De^3}{\nu^2}\right]$
Grx	Grashof number based on x $\left[= \frac{g \cdot \beta (T_w - T_f) x^3}{\nu^2}\right]$
h	heat transfer coefficient
i	enthalpy
k	thermal conductivity
$L0$	length of heating region
$L1$	distance between two pressure taps
m	mass flow rate
Nu	Nusselt number
Po	Poiseuille number
Pr	Prandtl number
q	heat flux
R	thermal resistance $\left[= \frac{1}{hA}\right]$
Re	Reynolds number
Re_x	Reynolds number based on x $\left[= \frac{u \cdot x}{\nu}\right]$
Ri	Richardson number $\left[= \frac{Gr}{Re^2}\right]$
Ri^*	transverse Richardson number $\left[= \frac{Gr \cdot \sin\theta}{Re^2}\right]$
w	width of the channel
x	distance from the inlet
Y	thickness of the heating plate
y	distance from the outside wall of the heating plate
ΔH	height difference between the heat source and heat sink
ΔP	pressure drop
T	temperature
u	mean fluid velocity
V	volume of the heating plate
ΔP_a	acceleration pressure drop
ΔP_d	driven head of the natural circulation loop
ΔP_f	frictional pressure drop
ΔP_g	gravitational pressure drop
ΔP_m	measured pressure drop
ΔT_{sub}	subcooling temperature

Greek symbols

$\overline{\rho}_{ch}$	average density of the channel
$\Delta\rho$	density difference
θ	inclination angle
λ	friction factor
δ	height of the channel
Φ	Volumetric heat generation rate
α	channel aspect ratio

Subscripts

b	bulk flow
in	inlet
out	outlet
w	wall of heating plate
w,i	inner surface of the heating plate
w,o	outer surface of the heating plate

same direction as the forced motion (heating in upward flow or cooling in downward flow), thus enhancing t heat transfer (Incropera [12,13], Sudo, Morshedy et al. [18]). The second case is when natural convection opposes forced convection (heating in downward flow or cooling in upward flow). This, in turn, either diminishes (Jackson et al. [19]) or enhances heat transfer (Laouche et al. [20], Joye et al. [3,4]). Laouche et al. [20] numerically studied the heated downward flow, their result indicates that high buoyance will induce flow reversal for the fluid near the heating wall, and the interaction between the imposed downward flow and the upward buoyancy flow will result in secondary flow near the heating wall. This result gives a succinct explanation for the heat transfer enhancement in the second case. The last case is referred to as transverse flow.

Transverse flow occurs when the buoyant motion acts perpendicular to the forced motion (flow in horizontal and inclined, heated pipe and channel). This enhances fluid mixing, and creates a very high heat transfer coefficient. Since 1960s, lots of investigations have been conducted on mixed convection in horizontal and inclined, uniformly heated pipes. Ede [21], Mori et al. [22], Bergles et al. [23], and Barozzi et al. [24], performed experiments to describe the velocity and temperature distribution of flow in uniformly heated horizontal pipes, then studied the flow and heat transfer characteristics of mixed convection in its fully developed region. Their results show that the Nusselt number increases with Ra, and the secondary flow occurs at a high Grashof number in such pipe. Chong et al. [25,26] throughly investigated effect of inclination angle on mixed convection heat transfer of thermal entrance region in a uniformly heated, inclined rectangular duct for laminar and transition flow. They concluded that the friction factors decreased with the increase of inclination angle, while the heat transfer coefficient first increased with inclination angle up to a maximum value and then decreased. the optimum inclination angle that yield the maximum heat transfer coefficient decreased from 30° to −30° with the increase of Reynolds number. Mori et al. [27], Iqbal [28], and Faris et al. [29] conducted a detailed theoretical investigations on mixed convection for the fully developed flow in a horizontal pipe that is uniformly heated. Mori et al. used air as working fluid, their theoretical results agreed reasonably with their experimental results. They concluded that Nusselt numbers and heat transfer coefficients are function of *Re*, *Ra* and *Pr*. Choudhury et al. [30], Piva et al. [31], and Orfi et al. [32–34] conducted numerical studies on horizontal and inclined pipes to simulate mixed convection. The results reveal that the buoyance effects have a considerable influence on the fluid flow and heat transfer characteristic. Ou et al. [35] and Yan [36] numerically investigated mixed convection in an inclined, rectangular channel at the fully developed and entrance regions. They reported that the heat transfer and flow resistance in mixed convection were higher than in forced convection. Nevertheless, all these studies mentioned above were performed under uniform heating condition, contrary to the asymmetrically heated channel that is obtained in practice.

Osborne et al. [11], Maughan et al. [9], Chiu et al. [37], Koizumi et al. [38], and Ozsunar et al. [39] performed experiments to investigate the heat and mass transfer in inclined and horizontal, asymmetrically heated rectangular channel. Their experimental results indicates that thermal instability and secondary flow happen more easily in asymmetrically heated channel than symmetrically heated channel.

This variety of mixed convection makes a comprehensive correlation difficult to obtain, and when it is, the applicability of the correlation is limited (Jackson et al. [19]. Joye et al. [5]). The criterion to judge when mixed convection occurs is still debatable (Huang