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 heat 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 aids forced convection. This is seen when the buoyant motion is in the same direction as the forced flow. Elenbaas (1956) pioneered experimental investigation into natural convection heat transfer in pelloth 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
same direction as the forced motion (heating in upward flow or cooling in downward flow), thus enhancing heat transfer (Incropera [12,13], Sudo, Morshedy et al. [18]). The second case is when natural convection opposes forced convection (heating in downward flow), thus enhancing heat transfer (Incropera [19], Joye et al. [5]). The criterion for 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...
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