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EXPERIMENTAL INVESTIGATION OF CONVECTIVE HEAT TRANSFER IN A NARROW RECTANGULAR CHANNEL FOR UPWARD AND DOWNWARD FLOWS

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Heat transfer characteristics in a narrow rectangular channel are experimentally investigated for upward and downward flows. The experimental data obtained are compared with existing data and predictions by many correlations. Based on the observations, there are differences from others: (1) there are no different heat transfer characteristics between upward and downward flows, (2) most of the existing correlations under-estimate heat transfer characteristics, and (3) existing correlations do not predict the high heat transfer in the entrance region for a wide range of Re. In addition, there are a few heat transfer correlations applicable to narrow rectangular channels. Therefore, a new set of correlations is proposed with and without consideration of the entrance region. Without consideration of the entrance region, heat transfer characteristics are expressed as a function of Re and Pr for turbulent flows, and as a function of Gz for laminar flows. The correlation proposed for turbulent and laminar flows has errors of ±18.25 and ±13.62%, respectively. With consideration of the entrance region, the heat transfer characteristics are expressed as a function of Re, Pr, and z^* for both laminar and turbulent flows. The correlation for turbulent and laminar flows has errors of ±19.5 and ±22.0%, respectively.

KEYWORDS : Convective Heat Transfer, Rectangular Channel, Entrance Region, Heat Transfer Correlation

1. INTRODUCTION

Forced convective cooling through micro and narrow channels is very effective and is widely used in many engineering applications, from small computer devices to large systems, such as heat exchangers and research reactors, since it provides more cooling surface for efficient heat removal [1,2,3]. Because of their important role, the heat transfer characteristics through micro and narrow channels have been extensively studied for the past several decades [4,5]. In 1930, Dittus and Boelter proposed a convective heat transfer correlation for turbulent flows (10,000 < Re < 12,000 and 0.7 < Pr <120). This correlation is recommended only for rather small differences between wall and coolant temperatures. A few years later, in 1936, Sieder and Tate [6] developed another correlation that accommodates larger temperature differences by taking into account the variations in viscosity with fluid bulk and wall surface temperatures. The Sieder-Tate correlation is valid for Re > 10,000 and 0.7 < Pr < 16,700. In 1945, Colburn et al. [4] proposed another correlation similar to the Dittus-Boelter correlation, but considered the properties at film temperature. The film temperature is the arithmetic mean of the bulk and wall surface temperatures. The existing correlations for turbulent forced convection heat transfer proposed by Colburn, Dittus-Boelter, and Sieder-Tate are listed below:

Dittus-Boelter : $$Nu = 0.023\, Re_b^{0.8}\, Pr_b^{0.4} \quad (1)$$

Sieder-Tate : $$Nu = 0.027\, Re_b^{0.8}\, Pr_b^{1/3} (\mu_b/\mu_w)^{0.14} \quad (2)$$

Colburn : $$Nu = 0.023\, Re_f^{0.8}\, Pr_f^{0.3} \quad (3)$$

Levy et al. [7] experimentally investigated the heat transfer to water in thin rectangular channels (2.54×63.5 mm). The range of Re covered from 6,000 to 200,000. The authors concluded that the experimental data were considerably lower than those obtained in a circular pipe. In 1969, Battista and Perkins [8] performed a local heat transfer experiment for turbulent flows of air in a vertical square duct. They developed a local heat transfer correlation as

$$Nu = 0.021 Re^{0.8} Pr^{0.4} \left(\frac{T_w}{T_b}\right)^{-0.7} \left[1 + \left(\frac{z}{D_h}\right)^{-0.7} \left(\frac{T_w}{T_b}\right)^{0.7}\right] \quad (4)$$

This correlation is the same as that found by Campbell and Perkins [9] for local heat transfer coefficients in a nominally equilateral duct. The experimental conditions were inlet Re varied from 21,000 to 49,000, and the maximum temperature ratio of wall to bulk was approx. 2.13. The axial distance considered was between x/D = 22 and x/D = 155. After x/D equals to 50, the entry correction shown in the bracket in Equation 4 can be neglected as given with

$$Nu = 0.021Re^{0.8}Pr^{0.4}\left(\frac{T_w}{T_b}\right)^{-0.7} \quad (5)$$

Perkins et al. [10] proved that the correlation's applicable range can be extended to Re of at least 4,000 and x/D of at least 12. The working fluids were helium and nitrogen gas.

Recently, Sudo et al. [11,12] studied single-phase convective heat transfer characteristics between upward and downward flows through a narrow rectangular channel (2.25×40 mm). The range of Re was from 100 to 40,000 and the range of Pr was from 3.5 to 10. Unlike Levy et al.'s experimental observations [7], Sudo et al. [12] observed different heat transfer characteristics between upward and downward flows. The downward flows resulted in a lower heat transfer coefficient than that for the upward flows. In addition, different transitions from turbulent to laminar regions were observed for the upward and downward flows: for the downward flows, the transition exists when Re is less than 3,000, while for the upward flows the transition exists when Re is less than 4,000. The authors found that the Colburn, Dittus-Boelter, and Sieder-Tate correlations were still applicable to both upward and downward turbulent flows, but the Dittus-Boelter correlation fits best with ± 20% uncertainty against their experimental data. For laminar flows, the correlations developed by Sudo et al. [12] are as follows:

$$\text{Upward} \quad \begin{aligned} &: Nu = 2.0\,\mathrm{Gz}^{0.3} \text{ for } \mathrm{Gz} \geq 40 \\ &: Nu = 6.0 \text{ for } 16 < \mathrm{Gz} \leq 40 \end{aligned} \quad (6)$$

$$\text{Downward} \quad \begin{aligned} &: Nu = 0.915\,\mathrm{Gz}^{0.4} \text{ for } \mathrm{Gz} \geq 40 \\ &: Nu = 4.0 \text{ for } 16 < \mathrm{Gz} \leq 40 \end{aligned} \quad (7)$$

Churchill and Usagi [13] expressed a general formula to predict the Nusselt number. The general formula was validated using empirical formulas. The developed correlation is valid for all ranges of Gz and Pr, and is given as

$$\frac{Nu}{3.657[1+(Gz/30.8)^{8/3}]^{1/8}} = \left[1+\left(\frac{(Gz/33)^{1/2}}{[1+(Pr/0.0468)^{2/3}]^{1/4}[1+(Gz/30.8)^{8/3}]^{1/8}}\right)^4\right]^{1/4} \quad (8)$$

Bejan and Sciubba [14] fitted the local Nusselt number data of Hwang and Fan [15] using empirical formulas of the Churchill-Usagi correlation type, which resulted in

$$Nu = \left[(0.359(z^*)^{-1/2})^{1.583} + 8.235^{1.583}\right]^{1/1.583} \quad (9)$$

Gamrat et al. [2] numerically analyzed the convective heat transfer in rectangular micro-channels to investigate the entrance effect on laminar flows. They showed a good agreement between their analyses and predictions made by the Bejan-Sciubba correlation for Pr = 0.7 and Pr = 10. On the other hand, Hwang et al. [5] conducted an experiment to investigate the convective heat transfer characteristics in fully developed laminar flows of water flowing through a circular pipe with a constant heat flux. Their experimental results were compared with the local heat transfer correlation developed by Shah [16]. The Shah correlation is given as

$$Nu_x = \begin{cases} 1.302\, z^{*-\frac{1}{3}} - 1\,, & z^* < 0.00005 \\ 1.302\, z^{*-\frac{1}{3}} - 0.5\,, & 0.00005 < z^* < 0.0015 \\ 4.364 + 8.68(10^3 z^*)^{-0.506}\, exp\,(-41z^*)\,, & z^* > 0.001, \end{cases} \quad (10)$$

Based on these previous studies, considerable efforts have been put into investigating the heat transfer characteristics in narrow channels for laminar and turbulent flow regimes. However, there is conflicting data, and there is still a lack of experimental data to fully understand the heat transfer characteristics in narrow rectangular channels. Therefore, in the present study, an experiment is conducted to investigate the convective heat transfer in a narrow rectangular channel for upward and downward flows. The experimental conditions are Re varying from 496 to 54,305, Pr varying from 2.64 to 6.46, and heat flux varying from 7.8 to 801.8 kW/m^2. The working fluid is demineralized water. The experimental data are compared against the experimental data taken by Sudo et al. [11] and predictions made by many existing correlations. Since the experimental data obtained in the present study do not agree well with others, a new set of heat transfer correlations with and without consideration of an entrance effect is developed for laminar and turbulent flows.

2. EXPERIMENTAL FACILITY

Convective heat transfer experiments in a thin rectangular channel are performed at the RCS Thermal Hydraulic Loop located at the KAERI (Korea Atomic Energy Research Institute). The RCS Thermal Hydraulic Loop is available for various thermal hydraulic experiments from single phase heat transfer up to CHF (Critical Heat Flux) experiments [17]. The loop consists of a circulation pump, a mass flowmeter, preheater, steam-water separator, pressurizer, and heat exchanger as shown in Fig. 1. Since the loop was originally designed for high pressure, a level tank is installed on the top of the pressurizer in order to control the system pressure below 2.0 bar instead of using the pressurizer. The top of the level tank is open to the atmosphere. A test section designed for the present experimental study is connected to the RCS loop. Because the flow directions of the present study are upward and downward,