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Experimental Investigation on Convective Heat Transfer in a Vertical Annulus under Natural Circulation Water Flow Conditions

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1. Introduction

Natural circulation (NC) flow is a key thermal-hydraulic phenomenon that removes decay heat from the reactor core after shutdown under abnormal or accident conditions in nuclear power plants. The amount of NC flow is determined by the buoyancy of coolant and pressure drop. However, the magnitude of both forces is small. Therefore, accurate prediction of heat transfer and pressure drop coefficients is essential for evaluating the cooling performance of nuclear fuel.

For this, 1-D safety analysis codes such as the MARS [1] and SPACE [2] typically use the maximum values from the Dittus-Boelter[3] and Churchill-Chu[4] models for heat transfer coefficients. These models are used for forced convection and natural convection, respectively. Existing heat transfer models including the Dittus Boelter and Churchill-Chu models show significant differences within each convection regime [5, 6]. Also, Current studies on NC flow using water are mostly conducted under low-temperature and low-pressure conditions. In the present study, we conducted experimental investigation on the heat transfer coefficient under natural circulation flow to evaluate the existing model and correlation for the safety analysis codes.

2. Experimental set up

2.1 Experimental facility

The experimental facility consists of a vertical annular test section, heat exchanger, circulation pump, preheater, accumulator and piping systems as shown in Fig. 1.

The vertical annular test section consists of a circular channel with an inner diameter of 15.3 mm and an indirect heater rod with an outer diameter of 9.5 mm at the channel center. The test section is designed to allow replacement of three circular channels of which inner diameters of 15.3, 19.5, and 23.5 mm while the heater rod remains fixed, as in Fig. 2. The corresponding gaps between the heater rod surface and the channel inner wall are 2.9, 5, and 7 mm, respectively. The heater rod is positioned at the center of the test section by the heater grid. The heated length of the heater rod is 804 mm. Along the axial direction of the heater rod, a total of 8 K-type thermocouples with a diameter of 0.5 mm are installed at 100 mm intervals on the outer surface of the heater rod. The cooling water temperatures inside of the test section are also measured at the same elevation with the wall temperature thermocouples for the analysis of flow characteristics.

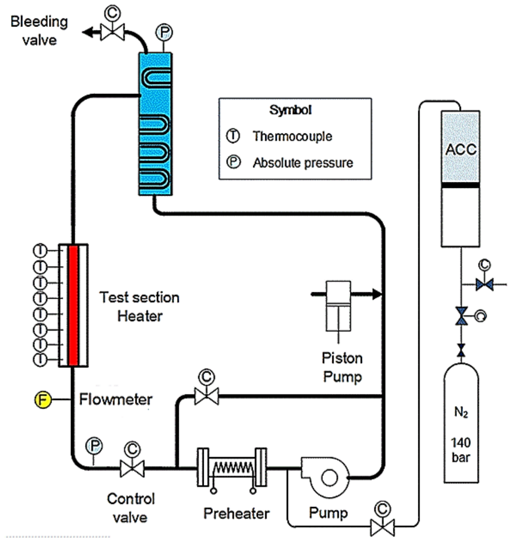


Fig. 1. Schematic of experimental facility

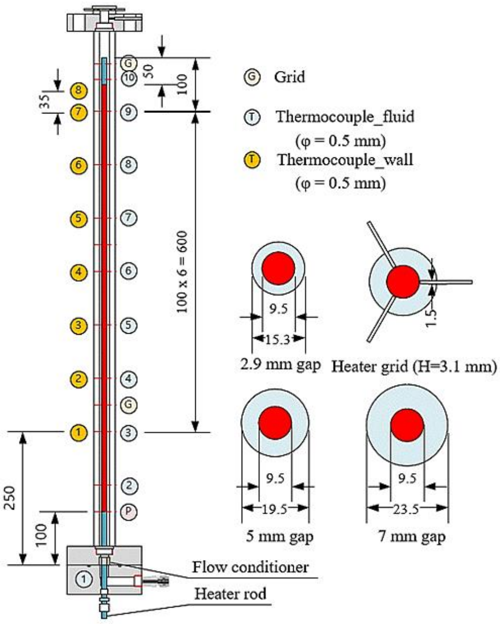


Fig. 2. Schematic of the test section

The elevation difference between the centers of the test section and heat exchanger is 2.4 m. A canned motor centrifugal pump was employed to perform forced circulation experiments for verifying the experimental set up and measurement system. A preheater with a maximum power of 50 kW is equipped to establish the preset inlet coolant temperature. An accumulator using nitrogen gas was used for the regulation of the loop pressure with a control accuracy of 0.1 bar.

2.2 Data reduction method

The local heat transfer coefficient is calculated from Newton's law of cooling as follows:

$$h = \frac{q''}{T_w - T_f} \qquad (1)$$

The wall temperature is measured using embedded thermocouples along the heater rod. The average fluid temperature is determined from the energy conservation equation even though TCs for the fluid temperature are installed at the center of the annular gap. Local heat transfer coefficients are expressed in terms of the Nusselt number(Nu) that represents the ratio of convective heat transfer to conduction as a dimensionless temperature gradient as follows.

$$Nu = \frac{hD_h}{k_f} \qquad (2)$$

3. Experimental results

3.1 Adiabatic Forced Circulation Experiment

Forced circulation experiments were conducted to verify the experimental set up and measurement system. Figure 3 shows the local Nu measured under the condition of Reynolds number(Re) = 15,000 and comparison of existing convective heat transfer models. The experimental results showed a similar trend predicted by Dittus-Boelter[3] model which is commonly used for fully turbulent conditions. This confirmed the reliability of the measurement system.

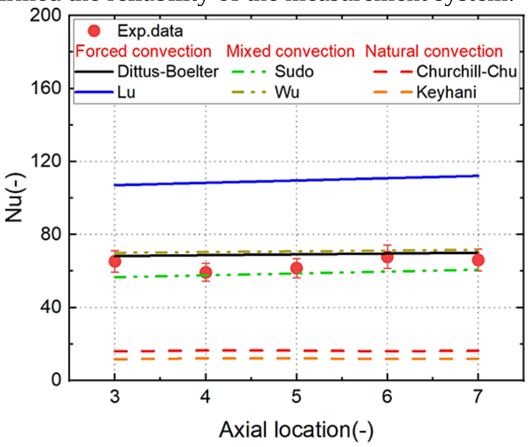
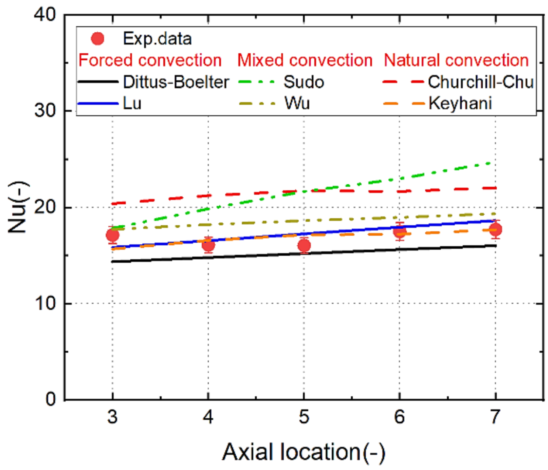


Fig. 3. Local Nu of forced circulation experiment(2.9 mm gap test section)

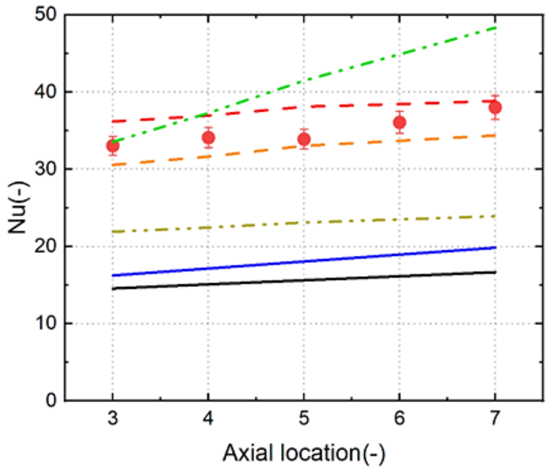
3.2 Natural Circulation Experiment

Natural circulation experiments were conducted at the condition of inlet temperature ranging from 40 to 80℃, pressure of 30 bar and heat flux ranging from 33 to 208 kW/m^2.

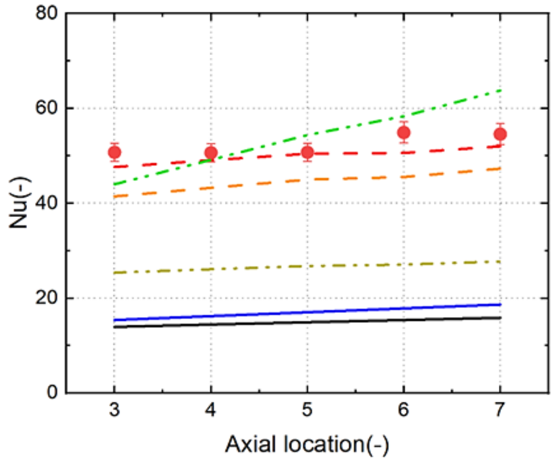
Figure 4 shows the convective heat transfer coefficients obtained according to gap size of test section, and prediction with existing convective heat transfer models. The experimental results showed that heat transfer characteristics varied with gap size. As the gap size increased, the forced convection models tended to underestimate and the natural convection models (Churchill-Chu[4], Keyhani[7]) showed better agreement with the experimental results. Also, the average Rayleigh number(Ra) and local Nu increased with gap size. A large gap size resulted in lower flow velocity and required a higher heat flux to maintain the equivalent Re. As the heat flux increases, the temperature gradient along radial direction becomes steeper and fluid temperature near the heated wall increases. Consequently, the buoyancy effect near the wall is enhanced and the heat transfer coefficients are increased.



(a) 2.9 mm gap (Re_{avg} : 2,560, Ra_{avg} : 2.3×10^6)



(b) 5 mm gap (Re_{avg} : 2,750, Ra_{avg} : 1.4×10^7)



(c) 7 mm gap (Re_{avg} : 2,580, Ra_{avg} : 3.7×10^7)

Fig. 4. Local Nu of all gap test section under T_{in}=60℃

According to Fig 5, lower inlet temperatures led to increased Ra and local Nu. Lower inlet temperature conditions required a higher heat flux to maintain the equivalent Re. As a result, the enhanced buoyancy effect resulted in the increase of heat transfer coefficients. Therefore, the observed effects of gap size and inlet temperature indicate that the Nu increases as buoyancy effects become more significant.≈

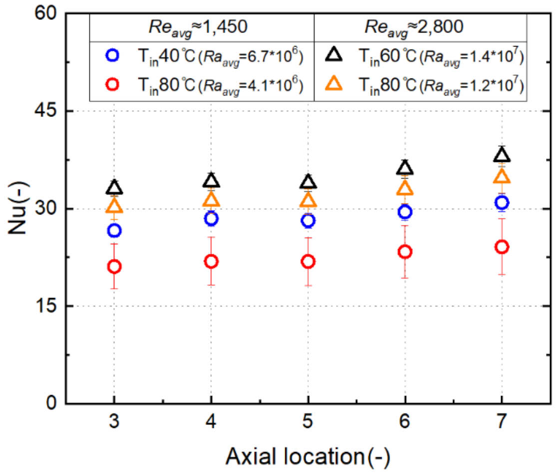


Fig. 5. Local Nu of 5 mm gap test section

5. Conclusions

Present study investigated the local Nu under natural circulation flow in the annular test sections with 2.9, 5, and 7 mm gaps. The measurement system was validated through forced circulation experiments under fully turbulent flow condition. It is found that the average Ra and local Nu are increased as the gap size increased at a given Re number condition. Also, lower inlet temperatures led to increases in both the average Ra and local Nu at a given Re number conditions. These effects of gap size and inlet temperature indicate that the Nu increases due to increase of buoyancy effects.

NOMENCLATURE

$\boldsymbol{\rho}$	Density $[\boldsymbol{kg/m^3}]$
$\boldsymbol{T_f}$	Fluid temperature [K]
$\boldsymbol{Gr}$	Grashof number $[\boldsymbol{g\beta(T_w - T_f)D_h^3/v^2}]$
$\boldsymbol{q''}$	Heat flux [W/m²]
$\boldsymbol{h}$	Heat transfer coefficient [W/m²·K]
$\boldsymbol{D_h}$	Hydraulic diameter [m]
$\boldsymbol{v}$	Kinematic viscosity $[\boldsymbol{\mu/\rho}]$
$\boldsymbol{Pr}$	Prandtl number $[\boldsymbol{C_p\mu/k}]$
$\boldsymbol{Ra}$	Rayleigh number $[\boldsymbol{Gr \cdot Pr}]$
$\boldsymbol{Re}$	Reynolds number $[\boldsymbol{\rho V D_h/\mu}]$
$\boldsymbol{k}$	Thermal conductivity [W/m·K]
$\boldsymbol{V}$	Velocity $[\boldsymbol{m/s}]$
$\boldsymbol{\mu}$	Viscosity [Pa·s]
$\boldsymbol{T_w}$	Wall temperature [K]

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