

# Experimental investigation of upward and downward mixed convection in water flows using an optical fiber sensor

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## 1. Introduction

In natural-circulation nuclear safety systems and thermal energy storage systems, mixed convection often occurs in medium-to-high Prandtl number fluids such as molten salts and water, where heat transfer is governed by the interplay between inertial and buoyancy forces [1, 2]. In vertical internal flows, the relative direction between buoyancy force and bulk flow leads to buoyancy-aiding or buoyancy-opposing configurations, which can modify the wall-temperature distribution. Because mixed convection can induce localized heat-transfer enhancement or deterioration along the heated length, resolving its axial location is important for reliable design.

In this study, mixed convection experiments were conducted to investigate the influence of key parameters, including inertial forces, buoyancy forces, and flow direction. The outer-wall temperature was measured using a distributed optical fiber sensor (OFS), enabling axial wall-temperature profiling and identification of where heat-transfer enhancement or deterioration occurs. The experimental results of temperature distribution and local Nusselt (Nu) number can provide insights into heat transfer variations in the mixed convection regime.

## 2. Experimental setup

### 2.1 Experimental loop

To investigate mixed convection of medium-to-high Prandtl number fluids in a vertical heated channel, a closed-loop water facility (approximately 6 m tall) was constructed at POSTECH (Fig. 1). Joule heating was supplied by a DC power supply with a maximum electrical power of 20 kW. The flow direction in the test section was reversed using three-way valves to achieve buoyancy-aiding and buoyancy-opposing configurations. The inertia level was controlled by adjusting the pump speed to vary the mass flow rate, while the buoyancy level was controlled by changing the imposed heat flux. A reservoir tank and a cooler were incorporated to maintain a nearly constant inlet temperature and to remove the supplied heat from the loop. A bypass line and a flowmeter installed in the main line enabled fine adjustment and monitoring of the mass flow rate during each test.

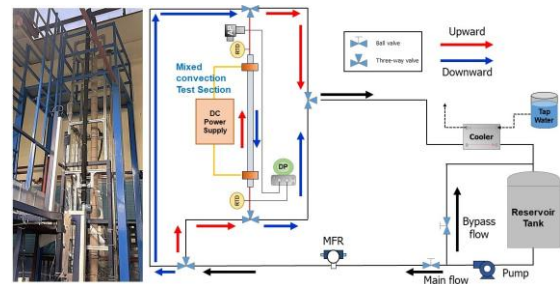


Fig. 1. Experimental loop installed at POSTECH

### 2.2 Test section

A 1-inch outer-diameter test section was employed, featuring a Joule-heated length of 4.3 m. The OFS was firmly installed within a 1 mm by 1 mm square groove machined along the outer wall, positioned exactly 15 cm away from the copper blocks at both ends. Furthermore, six thermocouples (TCs) were installed along the test section to provide reference data, allowing for the validation and calibration of the OFS temperature readings. The distributed OFS measured the outer-wall temperature over a 4.0 m span, yielding continuous axial wall-temperature profiles at a gage pitch of 1.03 cm and a sampling rate of 8 Hz. To mitigate entrance effects and end-region heat losses near the electrodes, only data from axial locations between 1.0 m and 3.5 m from the inlet (for each flow direction) were utilized for the analysis.

### 2.3 Experimental condition

To investigate mixed convection, the experimental conditions are summarized in Table I. These conditions were selected to represent mixed- and forced-convection regimes based on previously proposed convection regime maps [3, 4]. Reynolds (Re) and Rayleigh (Ra) numbers were evaluated using fluid properties based on the film temperature, and the Ra number was defined based on the tube inner diameter. Under these conditions, the difference between the supplied heat and the absorbed heat was within 10%.

Table I: Experimental conditions

	Mixed convection case	Forced convection case

Reynolds number	4000-9000	6600-7800
Rayleigh number	$2 \times 10^6 - 2 \times 10^7$	$2 \times 10^5 - 3 \times 10^5$
Flow direction	Upward / downward flows	

### 3. Experimental results

#### 3.1 Temperature distribution results

To analyze the temperature distributions, the measured wall temperatures and the calculated bulk fluid temperatures were utilized. Under the constant heat flux condition provided by the Joule heating method, the local bulk temperature,  $T_{bulk,x}$ , was calculated as expressed in Eq. (1). The local bulk temperature is derived using the measured inlet bulk temperature ( $T_{bulk,in}$ ), axial location ( $x_{location}$ ), mass flow rate ( $\dot{m}$ ), specific heat of the fluid ( $c_p$ ), and the heat flux ( $q''$ ).

$$T_{bulk,x} = T_{bulk,in} + \frac{q'' \pi D_i}{\dot{m} c_p} \cdot x_{location} \quad (1)$$

Axial temperature distributions were compared for different convection regimes and flow directions. In the mixed-convection case (Fig. 2), the upward-flow case exhibited higher wall temperatures than the downward-flow case, whereas the bulk-temperature distributions were nearly identical under the same imposed heat flux. In the upward-flow case, the wall-to-bulk temperature difference was relatively large in the upstream region, implying reduced heat-transfer performance; further downstream, this difference decreased gradually, suggesting a partial recovery trend that may be related to temperature-dependent property variations and the resulting change in the local buoyancy-inertia balance along the tube. The downward-flow case showed a relatively smooth, nearly linear axial temperature distribution with a more uniform wall-to-bulk temperature difference, implying comparatively uniform heat-transfer trends along the heated length.

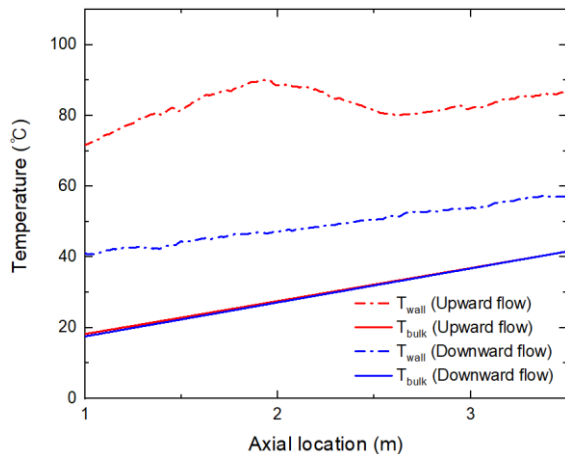


Fig. 2. Temperature distribution of mixed convection case.

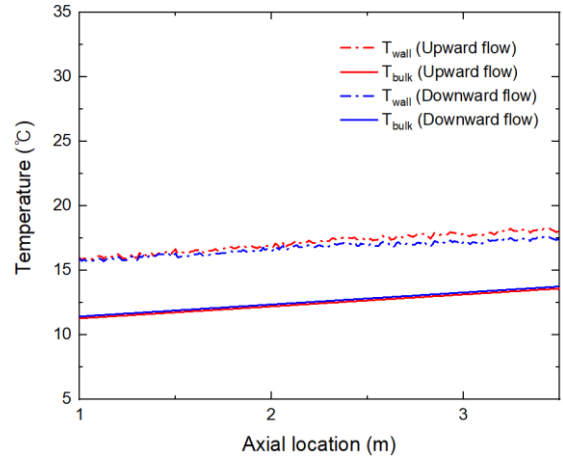


Fig. 3. Temperature distribution of forced convection case.

Under forced-convection conditions (Fig. 3), both wall and bulk temperature profiles were similar for the two flow directions, indicating comparable wall-to-bulk temperature differences and weak buoyancy influence in this regime.

#### 3.2 Heat transfer results

The local Nusselt number ( $Nu_{local}$ ) was calculated from the measured wall-to-bulk temperature difference using Eq. (2).

$$Nu_{local} = \frac{q''}{(T_{wall} - T_{bulk})} \cdot \frac{D_h}{k_f} \quad (2)$$

To quantify mixed-convection effects, the ratio  $Nu_{local}/Nu_{fc}$  was evaluated, where  $Nu_{fc}$  is the forced-convection baseline obtained from the Gnielinski correlation (Eq. (3)), which is commonly applied for turbulent internal flows [5] over wide Re number ranges ( $3 \times 10^3 < Re < 5 \times 10^6$ ).

$$Nu_{fc} = \frac{(f_d/8) \cdot (Re - 1000) Pr}{1 + 12.7 \left( Pr^{1/4} - 1 \right) \cdot (f_d/8)^{0.5}} \quad (3)$$

$$\text{where } f_d = (1.82 \log_{10}(Re) - 1.64)^{-2}$$

Under forced-convection-dominant conditions, local Nu showed limited sensitivity to flow direction (Fig. 4), remaining within approximately  $\pm 30\%$  of the forced-convection correlation.

However, at higher heat flux (mixed convection case), flow direction became a key parameter as shown in Fig. 5: upward flow tended to exhibit heat transfer deterioration ( $Nu_{local}/Nu_{fc} < 1$ ) whereas downward flow showed enhancement ( $Nu_{local}/Nu_{fc} > 1$ ). These results suggest that the direction and magnitude of buoyancy relative to the bulk flow govern the transition between heat-transfer enhancement and deterioration in vertical mixed convection.

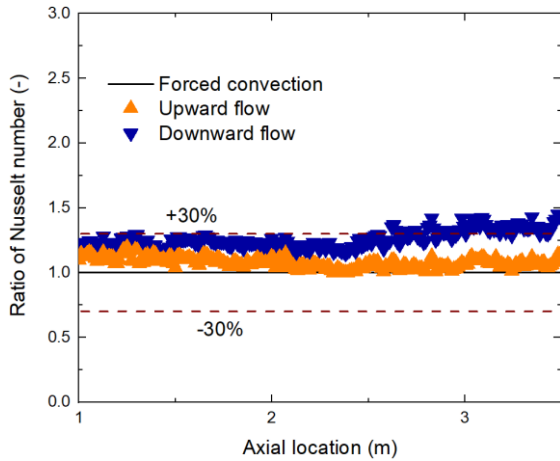


Fig. 4. Axial distributions of  $Nu_{local}/Nu_{fc}$  for forced convection cases.

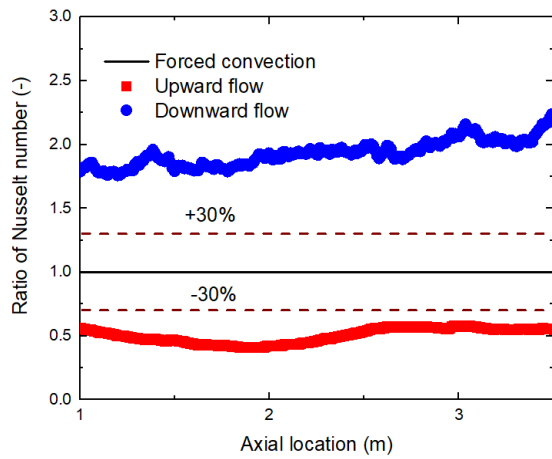


Fig. 5. Axial distributions of  $Nu_{local}/Nu_{fc}$  for mixed convection cases.

Therefore, for nuclear safety and thermal energy storage systems employing medium-to-high Prandtl number fluids, it is important to develop mixed-convection regime maps and predictive heat-transfer models that account for the relative strengths of inertia and buoyancy and the buoyancy-aiding/opposing nature associated with flow direction.

#### 4. Conclusions

Mixed and forced convection experiments were conducted in a vertical heated tube using distributed fiber-optic wall-temperature measurements. In the mixed-convection regime, flow direction significantly affected the wall-temperature distribution and the local heat transfer: the upward-flow case tended to show heat-transfer deterioration ( $Nu_{local}/Nu_{fc} < 1$ ) whereas downward flow showed enhancement ( $Nu_{local}/Nu_{fc} > 1$ ). Under forced-convection-dominant conditions, the effect of flow direction was negligible. These results provide experimental evidence for the development of mixed-convection regime maps and predictive heat-transfer models that account for inertia, buoyancy, and flow-direction (buoyancy aiding/opposing) effects.

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#### REFERENCES

- [1] Shin, Yukyung, Seok Bin Seo, and In Cheol Bang. "Study on flow characteristics of high-Pr heat transfer fluid near the wall in a rectangular natural circulation loop." *International Journal of Heat and Mass Transfer* 121 (2018): 1350-1363.
- [2] Park, S., Ko, Y., Nam, S., Jeong, J., and Yun, B., "Experimental Investigation on Convective Heat Transfer in a Vertical Annulus under Natural Circulation Water Flow Conditions," *Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 22-23, 2025*.
- [3] Metais, B., and E. R. G. Eckert. "Forced, mixed, and free convection regimes." (1964): 295-296.
- [4] Chae, Myeong-Seon, G. U. Kang, and B. J. Chung. "Review of Mixed Convection Flow Regime Map of a Vertical pipe." *Transactions of the Korean Nuclear Society Spring Meeting, 2015*.
- [5] Chae, Myeong-Seon, and Bum-Jin Chung. "Investigation of buoyancy influence on mixed convection in a vertical channel through PIV measurement." *International Journal of Thermal Sciences* 163 (2021): 106776.