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Technical Note

Measurement of local wall temperature and heat flux using the two-thermocouple method for a heat transfer tube

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ABSTRACT

The two-thermocouple method was investigated experimentally to evaluate its accuracy for the measurement of local wall temperature and heat flux on a heat transfer tube with an electric heater rod installed in an annulus channel. This work revealed that a thermocouple flush-mounted in a surface groove serves as a good reference method for the accurate measurement of the wall temperature, whereas two thermocouples installed at different depths in the tube wall yield large bias errors in the calculation of local heat flux and wall temperature. These errors result from conductive and convective changes due to the fin effect of the thermocouple sheath. To eliminate the bias errors, we proposed a calibration method based on both the local heat flux and Reynolds number of the cooling water. The calibration method was validated with the measurement of local heat flux and wall temperature against experimental data obtained for single-phase convection and two-phase condensation flows inside the tube. In the manuscript, Section 1 introduces the importance of local heat flux and wall temperature measurement, Section 2 explains the experimental setup, and Section 3 provides the measured data, causes of measurement errors, and the developed calibration method.

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1. Introduction

Passive safety systems of nuclear power plants (NPPs) contain in-tube condensation heat exchangers, which achieve high heat transfer efficiencies by using latent heat during phase changes. Examples include vertical condensers for the Isolation Condensers (IC) of Simplified Boiling Water Reactors (SBWR) [1], the Emergency Heat Removal System (EHRS) of International Reactor Innovative and Secure (IRIS) [2], and the Passive Residual Heat Removal System (PRHRS) of the System-integrated Modular Advanced ReacTor (SMART) [3]. Other examples are horizontally arranged U-shaped heat exchangers for the Passive Containment Cooling System (PCCS) of the Economic SBWR (ESBWR) [4], the Emergency Condenser System (ECS) of the KERENA (which was called SWR-1000 in the past) [5], and the Passive Auxiliary Feed-water System (PAFS) of the Advanced Power Reactor Plus (APR+) [6]. Most of these condensation heat exchangers are submerged in water-filled pools to transfer heat energy from the NPP side to the atmosphere in accident conditions.

Several experiments on in-tube condensation have been conducted in vertical [7–12] and horizontal [13–17] tubes to develop condensation models and verify the cooling performance of passive condensing heat exchangers. In experiments using an annulus-type condensation test section [7–10,12,14,16], the average heat flux of the entire tube can be measured from the enthalpy change of the cooling water between the inlet and outlet of the annulus channel. However, the average heat flux does not consider the multidimensional distribution of heat-transfer parameters that occurs because of variations in the flow condition during condensation or asymmetric two-phase flow regimes along horizontally arranged tubes. In addition to these factors, experiments [11,13,15,17] for condensing tubes in water pools cannot calculate the heat flux from the pool side. Therefore, it is important to develop measuring techniques for multidimensional local heat fluxes and wall temperatures in the condensation tube.

For a heat transfer tube with relatively large thermal conductivity, the local heat flux and wall temperature can be measured from the temperature gradient along the radial direction of the tube wall. To measure the temperature gradient, previous investigators [7–9,14–17] have applied two thermocouples (TCs) installed at different locations in the radial direction of the tube wall (the two-TC method), as shown in Fig. 1(a). However, this method has some

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Nomenclature

$c_{1,2}$	coefficients for the wall temperature correction factors
G	mass flux (kg/m^{2}s)
h	heat transfer coefficient (W/m^{2}K)
i_1	enthalpy of the cooling water at the inlet of the test section (J/kg)
i_2	enthalpy of the cooling water at the outlet of the test section (J/kg)
k_t	thermal conductivity of the tube material (W/mK)
L	heated length (m)
m_c	mass flow rate of the cooling water (kg/s)
P	heater power (W)
Q_c	heat transfer rate by enthalpy change of the cooling water (W)
q"	heat flux on the outer wall of the tube (W/m^2)
r_a	radius of the annulus channel (m)
r_i	radius of the inner wall of the heat transfer tube (m)
r_o	radius of the outer wall of the heat transfer tube (m)
Re_c	Reynolds number of the cooling water (–)
T_c	average bulk temperature of the cooling water (°C)
$T_{w\,a}$	temperature measured at location δ_a (°C)
$T_{w\,b}$	temperature measured at location δ_b (°C)
$T_{w\,o}$	temperature of the outer wall surface of the tube (°C)

Greek symbols

$\Delta T_{w\,a}$	correction factor for the wall temperature at location δ_a (°C)
$\Delta T_{w\,b}$	correction factor for the wall temperature at location δ_b (°C)
δ_a	depth of deep hole for the wall thermocouple installation (m)
δ_b	depth of swallow hole for the wall thermocouple installation (m)
ε	average deviation
$\lvert\varepsilon\rvert$	absolute average deviation
μ_c	dynamic viscosity of the cooling water (Ns/m^2)

Subscripts

avg	average value
cal	calibrated value
est	estimated value

uncertainties in high-heat flux conditions because of the limited accuracy associated with the exact positioning of the sensing element of the TCs, and thus requires calibration [14,18,19].

In the present study, we evaluated the accuracy of the two-TC method through the single-phase flow heat-transfer experiment in an annulus channel. The heat flux measured by the two-TC method was compared to that of an electrical heater with uniform heat generation. The outer wall temperature was also compared to that measured by a TC installed in a groove along the outside wall of the heater (the flush-mounted TC method [9,10]), as shown in Fig. 1(b). By analyzing the experimental data, we could identify the cause of uncertainty in the two-TC method and proposed a calibration method for its correction.

2. Experiments

This section describes the experimental setup and data reduction method for the local wall temperature and heat flux.

2.1. Experimental apparatus

Fig. 2 shows a schematic diagram of an experimental loop and a vertical annulus test section working with single-phase water flow. The annulus test section comprises a polycarbonate channel with

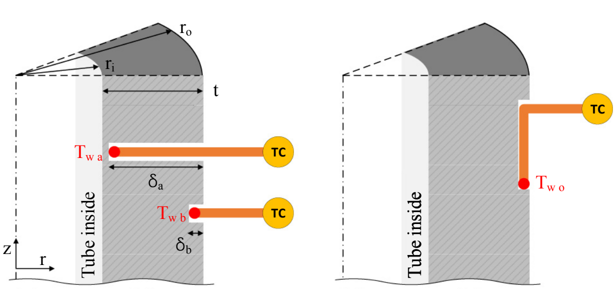


Fig. 1. Measurement methods for the local heat flux and the local wall temperature.

an inner diameter of 27.4 mm and a heat exchanger tube (SUS 304L) with an outer diameter of 21.4 mm. An electric heater rod with a power and heating length of 2 kW and 200 mm, respectively, was concentrically installed inside the tube to provide constant uniform heat flux. A heat transfer tube with a thickness of 4.5 mm (±0.1 mm) was selected — as opposed to a thin-walled tube of the prototypical design for the conventional passive safety systems — in order to reduce the measurement error of the temperature difference. Air gaps were provided at both ends of the heating section to prevent heat loss. Additionally, to minimize the uncertainty caused by the thermal contact resistance between the heater rod and inner surface of the tube, we applied a thermal enhancement compound (thermal conductivity of 8.4 W/mK) between them. The non-uniformity of the heat flux was confirmed to be within 4% of the average value in the present test.

The local TC measurement methods were applied on the outer wall surfaces at the middle elevation of the heat transfer tube (Fig. 2(b)). The two TCs were attached by brazing (BAg-7) at each location with depths of 1.0 mm and 4.0 mm from the outer tube surface. For comparison, a flush-mounted TC was installed in a groove along the outer tube wall on the surface opposite from the two TCs.

Experiments were conducted with a test-matrix comprising 125 conditions: 500–3000 kg/m^{2}s for the mass flux of the cooling water, 30–60 °C for the inlet temperature of the cooling water, and 7.9–142.6 kW/m^2 for the wall heat flux. The flow rate of the cooling water was measured using a Coriolis mass flow meter (Micro Motion CMF100), which has a relative measurement error of up to 0.25% of the measured value. The heater power was measured using a power meter (Yokogawa WT330), which has a measurement error of less than 6.1 W for the measured value. The temperature was measured using sheathed K-type TCs with diameters of 0.5 mm, which were calibrated against a wet-well calibrator (Fluke 6330) with a maximum accuracy of ±0.022 °C.

2.2. Data reduction

The local heat flux on the outer wall of the tube can be determined from the temperature profiles measured by the two-TC

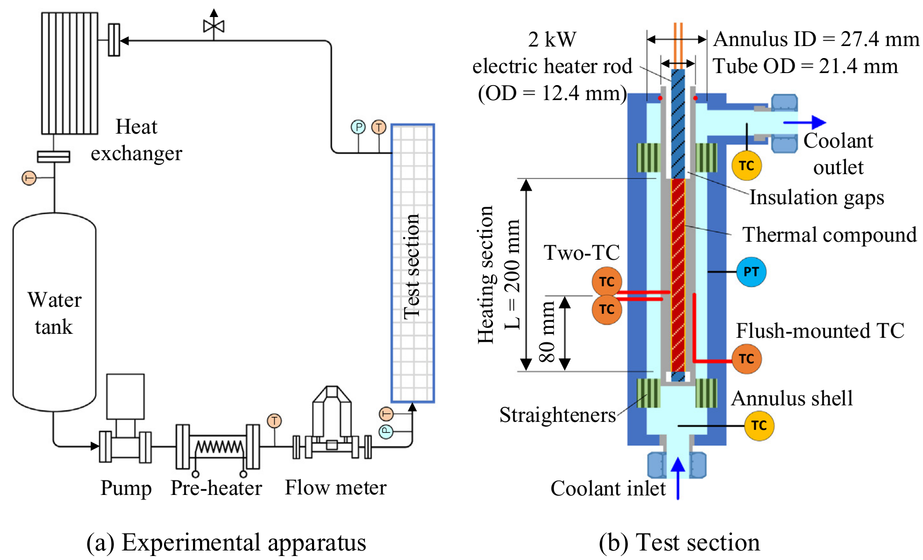


Fig. 2. Schematic diagrams of experimental apparatus and test section.

method as follows:

$$q'' = \frac{T_{w\ a} - T_{w\ b}}{r_o \ln\left(\frac{r_o-\delta_b}{r_o-\delta_a}\right)} k_t, \tag{1}$$

where r_o is the outer radius of the tube, $T_{w\ a}$ and $T_{w\ b}$ are the temperatures measured at local locations δ_a and δ_b, respectively, and k_t is the thermal conductivity of the tube material.

Using the local heat flux obtained from Eq. (1), the outer tube wall temperature can be determined as follows:

$$T_{w\ o} = T_{w\ b} + q'' r_o \ln\left(\frac{r_o - \delta_b}{r_o}\right) \frac{1}{k_t}. \tag{2}$$

3. Results and discussion

In this section, the heat flux and wall temperature measured by the two-TC method are evaluated and causes of their errors are investigated. Additionally, a calibration method for the wall heat flux and wall temperature is proposed and verified based on the experimental data.

3.1. Heat flux and wall temperature

The accuracy of the parameters measured by the two-TC method was quantified by the average deviation (ε), indicating the bias level of the error, and the absolute average deviation (|ε|), indicating the magnitude of the error, as follows:

$$\varepsilon = \frac{1}{n}\sum_{1}^{n}\frac{x - x_{ref}}{x_{ref}}, \tag{3}$$

$$|\varepsilon| = \frac{1}{n}\sum_{1}^{n}\left|\frac{x - x_{ref}}{x_{ref}}\right|, \tag{4}$$

where x and x_{ref} are the measured data and reference value, respectively, and n is the number of data points for the measurement.

For all test conditions, Fig. 3 shows the power applied to the heater rod (P) and the heat transfer rate from the heater rod to the cooling water (Q_c). Here, the heat transfer rate was calculated from the enthalpy change of the cooling water between the inlet and outlet of the test section as follows:

$$Q_c = m_c(i_2 - i_1), \tag{5}$$

where m_c is the mass flow rate of the cooling water, and i_1 and i_2 are the enthalpy of the cooling water at the inlet and outlet of the test section, respectively. The comparison shows that the |ε| between P and Q_c is within 6.4%.

The average heat flux at the outer surface of tube wall was also calculated from the applied heater power as follows:

$$q''_{avg} = \frac{P}{2\pi r_o L}, \tag{6}$$

where L is the heated length of the tube.

Fig. 4 compares the results of the local heat flux measured by the

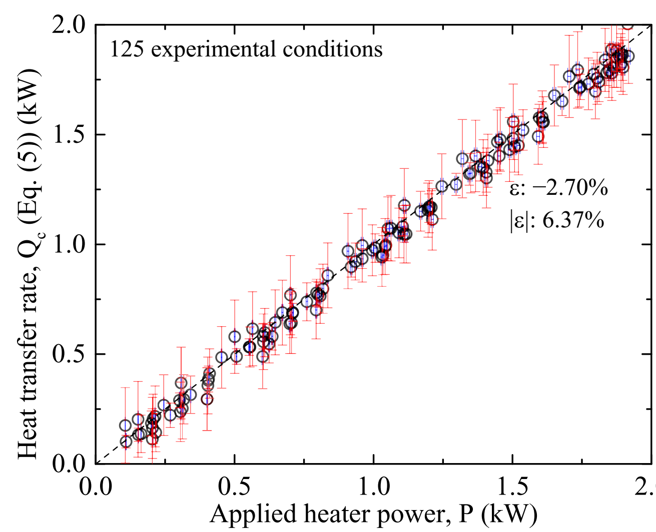


Fig. 3. Comparison of the applied heater power and the measured heat transfer rate.

two-TC method and the average heat flux of the electric heater. It reveals that the local heat flux measured by the two-TC method is higher than the average heat flux, and the degree of difference tends to increase as the mass flow rate of the cooling water decreases.

From the average heat flux of the tube, the temperature on the outer surface of the tube wall can be estimated as follows:

$$T_{w\ o\ est} = T_c + \frac{q''_{avg}}{h_{est}}, \tag{7}$$

where T_c is the average bulk temperature of the cooling water calculated by linear interpolation between the inlet and outlet temperatures of the cooling water, and h_{est} is the convective heat transfer coefficient estimated by Gnielinski's correlation [20], which is applicable to annulus channel flow.

Fig. 5 compares the local wall temperatures measured by the two different TC methods against the values calculated with Eq. (7). It shows that the flush-mounted TC is in good agreement with Eq. (7), i.e., |ε| is approximately 1.1%, whereas the temperature measured with the two-TC method is significantly lower than that of Eq. (7). This confirms that the flush-mounted TC can be treated as a reference instrument for wall temperature measurement in the present investigation. The error of the wall temperature measured by the two-TC method increases significantly as the heat flux increases, and its tendency also depends highly on the mass flux of the cooling water. This indicates that the two-TC method is unsuitable for measuring the local heat flux and the wall temperature.

Fig. 6 schematically illustrates the fin effect in the measurement of wall temperature causing the discrepancy from a true temperature profile:

- The thermal conductivity of the brazing material (BAg-7) differs from the tube material (SUS304L).
- The conductive heat transfer occurs through the TC sheath.
- The convective heat transfer to the cooling water is enhanced by the flow disturbance caused by the TC sheath.

For these reasons, the local wall temperature measured by the two-TC method tends to be lower than the actual value. Especially, the temperature measured at δ_b is more influenced in the installed

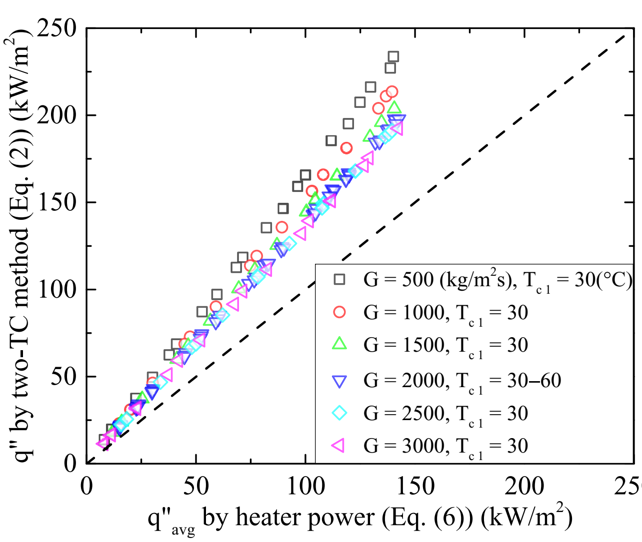


Fig. 4. Comparison of the local heat flux from the two-TC method and that from the power meter.

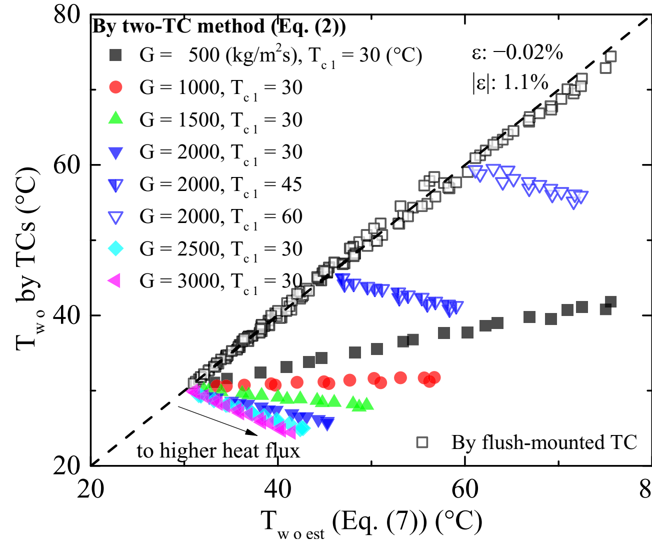


Fig. 5. Evaluation of the two local measurement methods for the wall temperature.

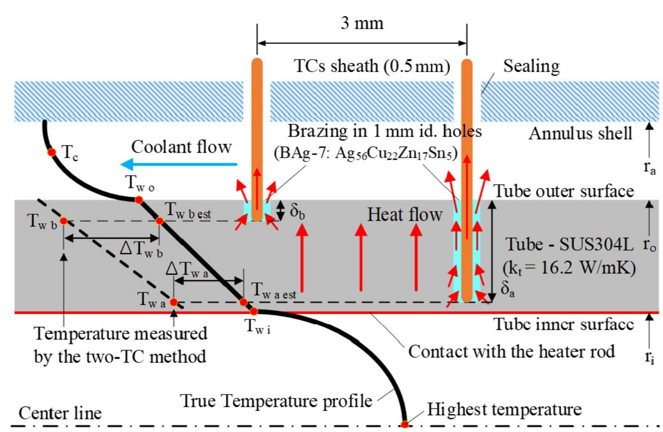


Fig. 6. Estimated true temperature profile and causes of measurement uncertainty in the two-TC method.

condition as shown in Fig. 1(a), so the heat flux is measured to be higher than the actual value, as shown in Fig. 4.

3.2. Development of calibration method

A calibration method was developed to eliminate the bias errors for both the local heat flux and the wall temperature measured by the two-TC method. The true temperatures ($T_{w\ a\ est}$ and $T_{w\ b\ est}$) at locations δ_a and δ_b are estimated using the outer wall temperature from Eq. (7) and the average heat flux of the heater power from Eq. (6), as follows:

$$T_{w\ a\ est} = T_{w\ o\ est} + q''_{avg}\frac{r_o}{k_t}\ln\left(\frac{r_o}{r_o-\delta_a}\right) = T_{w\ a} + \Delta T_{w\ a}, \tag{8}$$

$$T_{w\ b\ est} = T_{w\ o\ est} + q''_{avg}\frac{r_o}{k_t}\ln\left(\frac{r_o}{r_o-\delta_b}\right) = T_{w\ b} + \Delta T_{w\ b}. \tag{9}$$

Here, the correction factors ($\Delta T_{w\ a}$ and $\Delta T_{w\ b}$) are introduced into the last terms of the above equations to correct each measured temperature ($T_{w\ a}$ and $T_{w\ b}$).

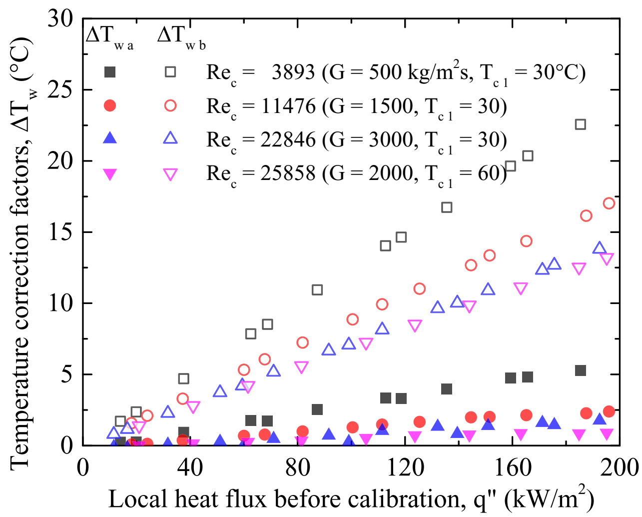
Fig. 7 respectively shows the tendencies of the correction factors for the local heat flux and the Reynolds number of the cooling water. Here, the Reynolds number of the cooling water in the annulus is defined as follows:

$$Re_c = \frac{2m_c}{\pi(r_o + r_a)\mu_c}, \tag{10}$$

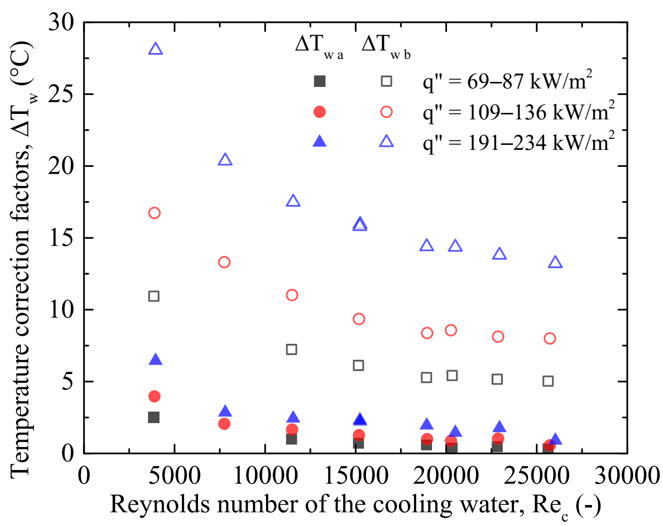
where r_a is the radius of the annulus channel and μ_c is the dynamic viscosity of the cooling water. It is worth noting that the effect of Reynolds number is asymptotically negligible when it exceeds 20000.

Fig. 8 shows the functional form of the empirical correlations for the correction factors, which are defined as follows:

$$\Delta T_{w\,a} = c_{1\,a} Re_c^{c_{2\,a}} q'', \tag{11}$$



(a) Local heat flux



(b) Reynolds number of the cooling water

Fig. 7. Effects of the experimental parameters on the temperature correction factors. (a) Local heat flux; (b) Reynolds number of the cooling water.

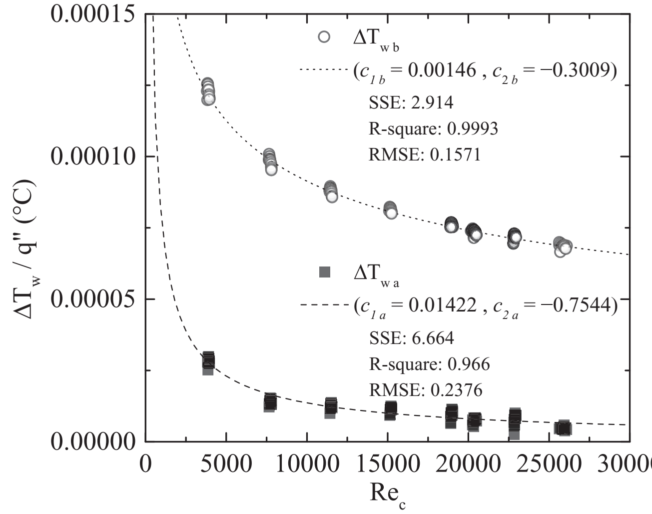


Fig. 8. Correlation of the temperature correction factors.

$$\Delta T_{w\,b} = c_{1\,b} Re_c^{c_{2\,b}} q'', \tag{12}$$

where q'' is the local heat flux before calibration and c_1 and c_2 are empirical coefficients obtained from the experimental data, as shown in Fig. 8.

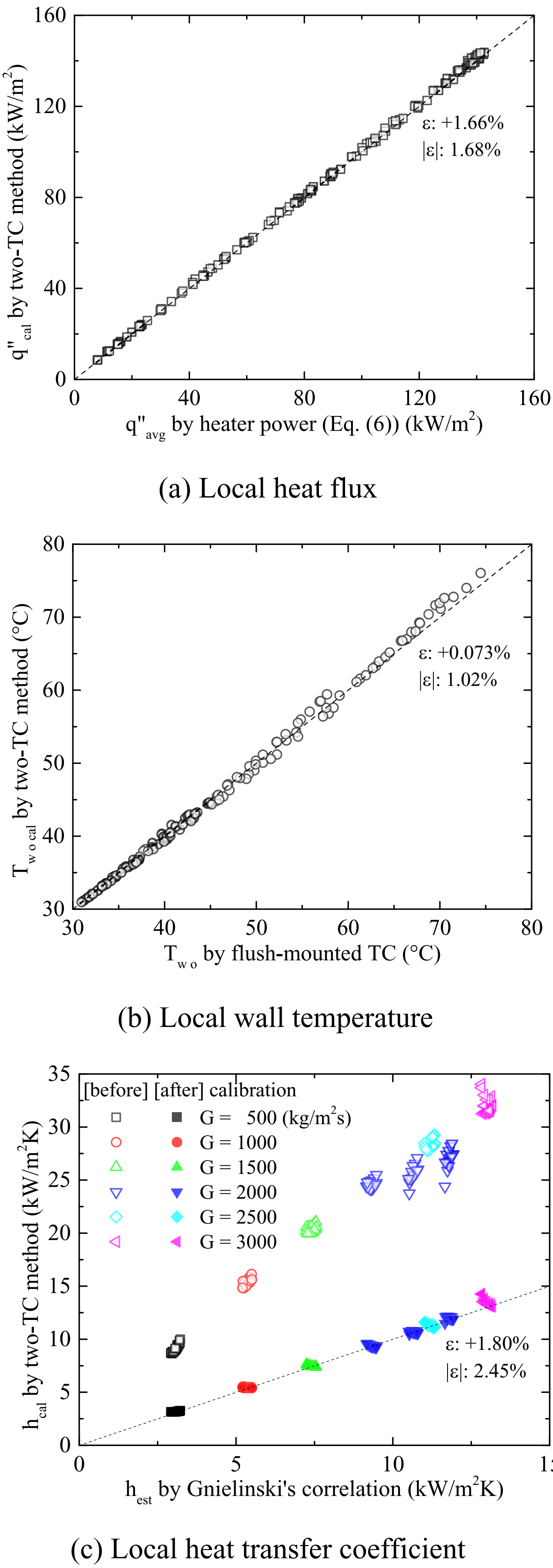
The correction factors of Eqs. (11) and (12) are applied to the wall temperatures measured by two-TC method to obtain the calibrated temperatures at δ_a and δ_b. Then, the calibrated local heat flux and wall temperature can be obtained by substituting the calibrated temperatures into Eqs. (1) and (2), respectively. Finally, the local heat transfer coefficient is calculated with the calibrated local heat flux (q''_{cal}) and wall temperature ($T_{w\,o\,cal}$) as follows:

$$h_{cal} = \frac{q''_{cal}}{T_{w\,o\,cal} - T_c}. \tag{13}$$

3.3. Evaluation of the calibration method

The calibration method was verified against 125 experimental data. Fig. 9(a) and (b) respectively compare the calibrated heat flux ($|\varepsilon| = 1.7\%$) and the wall temperature ($|\varepsilon| = 1.0\%$) with the average heat flux from the applied heater power and the wall temperature measured directly by the flush-mounted TC. Fig. 9(c) shows a comparison between the local heat transfer coefficients obtained from experiments and that calculated by Gnielinski's correlation [20]. The absolute average deviation of the calibrated heat transfer coefficient is approximately 2.5%. Among the calibrated heat transfer coefficients in Fig. 9(c), the largest heat transfer coefficient shows large deviations compared to others. The increased uncertainty of the heat transfer coefficient is caused by the small temperature difference between the wall surface and the cooling water in the cases with high heat transfer coefficients.

In addition, the applicability of this calibration method was evaluated for the single-phase flow convective heat transfer and condensation heat transfer inside the tube of a concentric double-tube test section [16]. The section consists of an inner tube with a length, inner diameter, and thickness of 3 m, 40 mm, and 5 mm, respectively, and an outer tube with an inner diameter of 80 mm. The two-TC method was applied on the outer surface of the inner tube through the outer tube at 10 local points along the axial



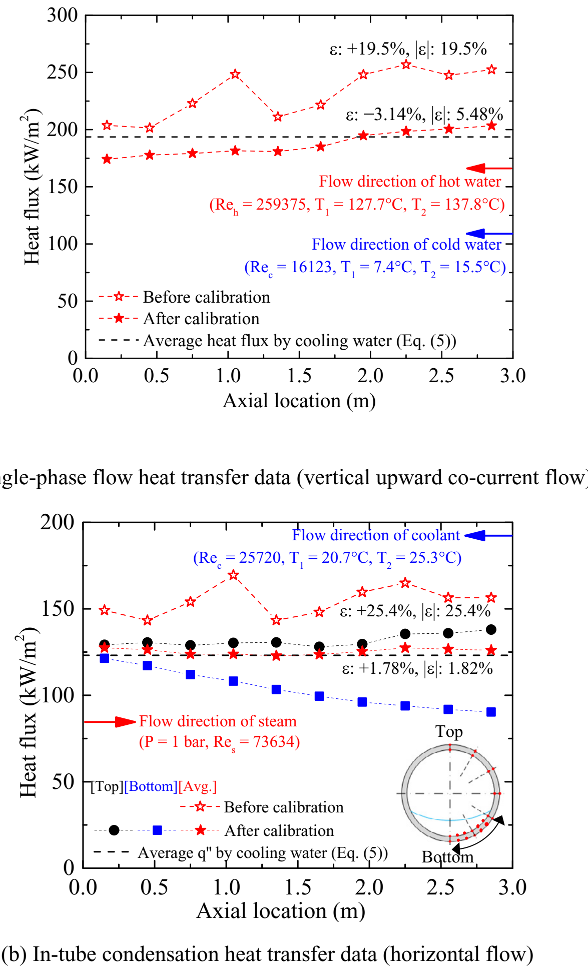


Fig. 10. Evaluation of the calibrated heat flux distribution [16]. (a) Single-phase flow heat transfer data (vertical upward co-current flow); (b) In-tube condensation heat transfer data (horizontal flow).

direction of the rotatable test section, and the correction factors for each measurement point were obtained through a calibration experiment with single-phase flow prior to the condensation experiment [16]. In the condensation test, steam flowed in the inner tube and cooling water flowed in the outer tube under the counter-current flow condition.

Fig. 10 shows that the calibrated heat flux is accurate for not only single-phase flow heat transfer but also in-tube condensation heat transfer. In Fig. 10(b), the average heat flux at each measurement plane was calculated as the circumferential average to consider the asymmetric distribution in horizontal stratified flow. Because the measurement error of the heat transfer parameters in the two-TC method are mainly caused by the installation of the TCs through the outer tube in which cooling water is flowing, the developed calibration method is applicable regardless of the heat transfer mechanism inside the tube.

4. Conclusions

Methods for measuring the local heat flux and the wall temperature of a heat transfer tube with TCs were investigated

Fig. 9. Evaluation of the calibrated values. (a) Local heat flux; (b) Local wall temperature; (c) Local heat transfer coefficient.

experimentally for an annulus channel in which an electrical heater rod was installed concentrically. The wall temperature measured by the flush-mounted TC that was installed along a groove in the outer wall surface of the tube showed good agreement with the true values. In contrast, the two-TC method showed significant bias errors in the measurements of both wall temperature and local heat flux. To eliminate the bias error, a calibration method was proposed: temperature correction factors for the two-TC method were introduced as a function of the local heat flux and the cooling water Reynolds number. Finally, the calibration method was evaluated against experimental data for the local heat flux and wall temperature. The proposed calibration method is also applicable to heat transfer tubes with two-phase flows in which condensation occurs because the measurement error is caused by the installation of the TCs on the outer wall of the heat transfer tube.

Acknowledgments

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