Numerical studies of thermal hydraulic characteristics through rectangular channels

Daeseong Jo[*], Jongharh Park, Heetaek Chae
Korea Atomic Energy Research Institute, 1045 Daeduk-Daero, Yuseong-Gu, Daejeon, 305-353, Republic of Korea
[*]Corresponding author: djo@kaeri.re.kr

1. Introduction

A typical open pool type research reactor utilized with plate type fuel elements is modeled to analyze steady state thermal hydraulic characteristics and thermal margins for reactor safety and design purposes. The forced convection cooling by the primary cooling pump system (PCS) is a normal operation mode when the reactor is operated at a nominal power. The coolant flowing downward through the core during the forced convection cooling is only considered in this model development. The predictions by the present numerical studies are compared with experimental data taken by Sudo et al. (1984).

2. Model development

Because coolant channels of plate type research reactors are independent (no cross flow from a channel to another channel), steady state thermal hydraulics through the coolant channels can be analyzed by one-dimensional computational calculations. The coolant temperature distribution along the axial direction from the inlet is determined by solving the simplified one-dimensional energy equation given as

$$\dot{m}C_p \frac{dT_b}{dz} = P_h q'' \tag{1}$$

Since the coolant is incompressible, the coolant velocity change through the core due to the coolant temperature change is determined by the conservation of mass given as

$$v = \frac{\dot{m}}{\rho A} \tag{2}$$

Pressure drop is estimated as

$$dp = \rho g\left(-dz + f\frac{v^2}{2gD_h}dz \right) \tag{3}$$

The first term considers the hydrostatic pressure change due to the elevation change, and the second term considers the friction loss through the distance *dz*.

The friction factor *f* in Eq.3 is estimated as

$$f = 0.316\,\mathrm{Re}^{-0.25} \quad \text{for } \mathrm{Re} \geq 2000 \tag{4}$$

$$f = C_f\,\mathrm{Re}^{-1} \quad \text{for } \mathrm{Re} < 2000 \tag{5}$$

Eq.4 is the Blasius friction factor for Re is larger than 2000. The friction factor constant C_f in Eq.5 developed by Eckert and Irvine (1957) for incompressible fluids flowing through rectangular cross sectional ducts is listed in Table1.

Table 1. Friction factor constant

Channel Ratio (width/thickness)	C_f
1	58
2	63
3	69
4	72.5
5	77
6.3	80
8	83
11	85
15	88
18	89
100	96

The wall temperature is determined as

$$T_w = T_b + \frac{q''}{h} \tag{6}$$

The convective heat transfer coefficient *h* in Eq.6 can be determined as

$$h = \frac{K_{th}}{D_h}Nu \tag{7}$$

where, K_{th} is the thermal conductivity of the fluid, D_h is the hydraulic diameter, and *Nu* is the Nussult number.

Since single phase heat transfer is strongly dependent on flow conditions and geometry, a different single phase heat transfer correlation may be applied to each flow region. Nussult number for rectangular channels have been empirically developed by Colburn (1933), Dittus and Boelter (1930), Sieter and Tate (1936), and Sudo et al. (1985). Sudo et al. (1985) compared predictions by Dittus-Boelter, Sieder-Tate, and Colburn correlations with their experimental data, and concluded that Dittus-Boelter correlation shown in Eq.8 is still applicable to downward flows for Re is larger than 3000.

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{8}$$

For downward flows (Re < 3000), Sudo et al. (1985) proposed the convective heat transfer correlation given as

$$\begin{aligned} Nu &= 0.915Gz^{0.4} && \text{for}\,\mathrm{Gz} \geq 40 \\ Nu &= 4.0 && \text{for}\,16 < \mathrm{Gz} < 40 \end{aligned} \tag{9}$$

where, $Gz = RePrD_h/z$ and *z* is the distance in the axial direction.

3. Experiment

In 1984, Sudo et al. performed experimental studies of forced convection heat transfer characteristics of a rectangular channel for upward and downward flows. Experiments were carried out in which flow velocity was changed from 0.07 to 7 m/s for the flow channel thickness of 2.25 mm. The flow channel was made of two flat heating plates which were 750 mm long, 1 mm thick, and 40 mm wide. Their experimental studies reported coolant and wall temperatures, channel thickness, flow velocity, Nu, Re, etc along the axial direction. For a comparison study, four cases are reviewed and used to compare against predictions by Thermal hydraulic Margin Analysis code for Plate type research reactor (TMAP). In Table 2, the experimental conditions of the forced convective cooling for downward flows are listed.

Table 2. Experimental conditions

	Case1	Case2	Case3	Case4
Mass flux [kg/(m^2 s)]	884.0	2405.5	3666.2	5173.3
Avg. heat flux [kW/m^2]	158.27	303.52	163.17	495.87
Inlet temperature [C]	12.8	21.3	20.2	34.3

Fig.1 shows the coolant and wall temperature distributions along the axial direction. The temperatures predicted by TMAP are indicated as solid lines, and the temperatures measured by Sudo et al. (1984) are indicated as dots. The coolant temperatures do not have errorbars because they are not measured values. The errorbars of the wall temperatures measured by Sudo et al. (1984) are added from the error analysis of the experimental data. With +30% and -10% Nu correlation error and +5% and -10% heat flux error, the resulting error of the wall temperature is approximately +30.6% and -11.7%.

4. Conclusion

As shown in Fig.1, the predictions by TMAP sit within the experimental errors except for the exit temperatures of Cases 2, 3, and 4. This may be resulted due to the proximity of the exit. Therefore, thermal hydraulic characteristics through thin rectangular channels can be analyzed by using one-dimensional computational calculations.

REFERENCES

[1] Eckert, E.R.G., Irvine, Jr., T.F., 1957. Incompressible friction factor, transition and hydrodynamic entrance length studies of ducts with triangular and rectangular cross sections. WADC Tech. Report 58-85

[2] Sudo, Y., Miyata, K., Ikawa, H., Ohgawara, M., Kaminaga, M., 1984. Core heat transfer experiment for JRR-3 to be upgrated at 20 MWt: Part1 Differences between upflow and downflow for rectangular vertical flow channel. JAERI-M 84-149 (in Japanese)

[3] Sudo, Y., Miyata, K., Ikawa, H., Ohkawara, M., Kaminaga, M., 1985. Experimental study of differences in single-phase forced-convection heat transfer characteristics between upflow and downflow for narrow rectangular channel. Journal of Nuclear and Technology 22, 202 – 212

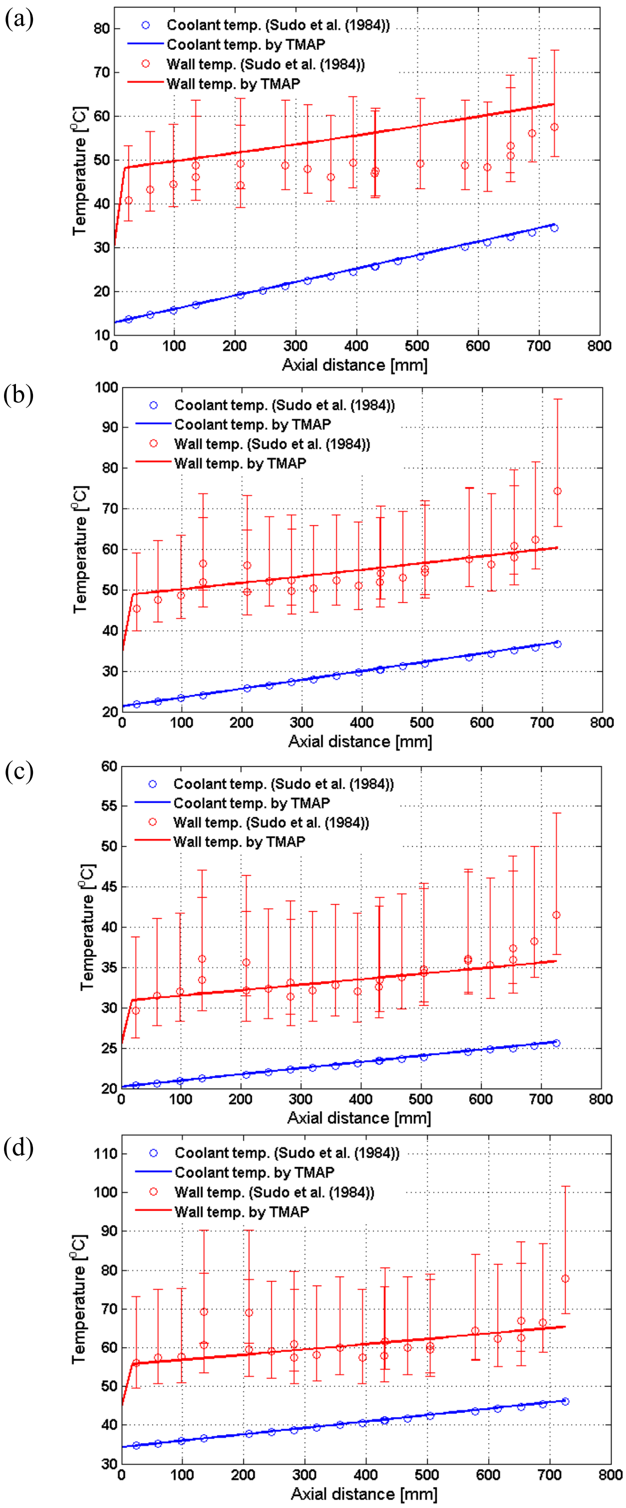

Fig.1. Coolant and wall temperature distributions: (a) Case1, (b) Case2, (c) Case3,and (d) Case