Proceedings of the Korean Nuclear Society Spring Meeting
Pohang, Korea, May 1999

Heat Transfer in a One-Dimensional Mixed Convection Loop

Min-Joon Kim, Yong-Bum Lee, Yong-Kyun Kim, Jong-Man Kim, and Ho-Yun Nam

Korea Atomic Energy Research Institute
150 Dukjin-dong, Yusong-gu, Taejon, Korea 305-353

Abstract

Effects of non-uniform heating in the core and additional forced circulation during decay heat removal operation are studied with a simplified mixed convection loop. The heat transfer coefficient is calculated analytically and measured experimentally. The analytic solution obtained from a one-dimensional heat equation is found to agree well with the experimental results. The effects of the non-uniform heating and the forced circulation are discussed.

Ⅰ. Introduction

During normal operation of a nuclear reactor, heat transfer phenomena can be treated as forced convection because the external flow rate is large enough. But, in some situations, natural convection dominates. One example is decay heat removal[1-3]. Natural convection is frequently used for decay heat removal. The natural circulation operation is so passive that it can be easily applied to decay heat removal in various systems. But the natural circulation phenomena are still unstable and subtle, so it can cause instability[4-5]. In order to resolve the stability problem, flow is often provided externally[6]. For the case that the effect of the external flow supply is comparable to the effect of the natural convection, competition of buoyancy effect and the external flow is very important

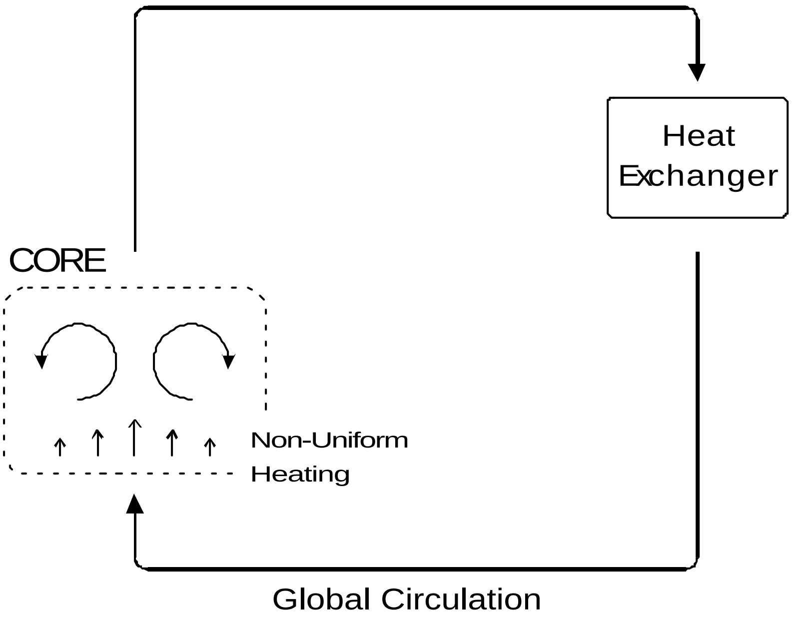

Figure 1. Schematic diagram of heat transfer in a nuclear reactor

and the heat transfer phenomena can be classified as a "mixed convection."

In this paper, we consider a simple mixed convection system. Idea of the target system is obtained from heat transfer in the core of a nuclear reactor during decay heat removal operation(Fig. 1)[7,8]. In the core, generally, the heat generation rate is not uniform and the non-uniform heating may induce natural convection. There also exists global forced(or natural) circulation between the core and a heat exchanger. When the two effects, the non-uniform heating and the global circulation, are comparable, the heat transfer should be treated as a mixed convection phenomenon.

To simulate the heat transfer in the core of a nuclear reactor, we design a simple model system(Fig. 2). It is composed of a circulation loop with an inlet through which flow is provided externally and an outlet through which the provided flow overflows. The model system is also considered as two geometrically symmetric vertical channels whose inlets and outlets coincide respectively. The non-uniform heating in the core is

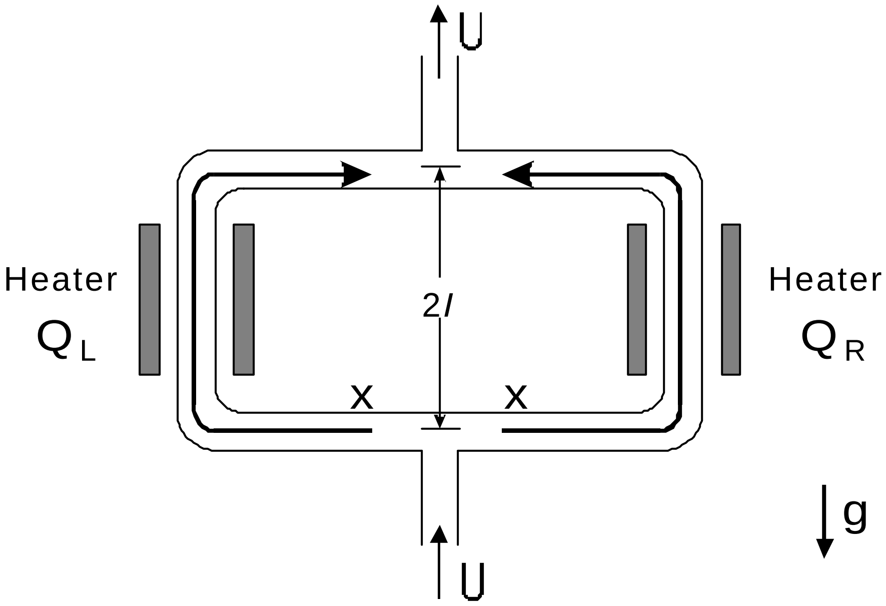

Figure 2. The simplified mixed convection loop

represented simply with two heaters of different powers, Q_L and Q_R, installed at the centers of the left channel and the right channel(Without loss of generality, we assume $Q_L > Q_R$). The velocity of the fluid provided at the inlet is denoted by U. The heights of the both channels are $2l$. In both channels, the axial axes are denoted by x and the radial and azimuthal axes by (r, θ). For each channel, the direction of the axial axis x is from the inlet to the outlet, individually.

By considering asymptotic cases, a qualitative prediction can be made. When the buoyancy effect dominates, a circulation loop forms. But, when the provided flow dominates, the circulation loop disappears and fluid flows upwards in both channels. In this paper, formation and deformation of the local circulation loop and heat transfer are studied analytically and experimentally. The analytic and experimental results are compared with each other and the heat transfer characteristics are discussed.

Ⅱ. Analytic Calculations

For simplicity, we introduce several assumptions. The most important assumption is that the flow in the loop is one-dimensional except at the inlet and the outlet. Under the one-dimensional flow assumption, the governing equations can be simplified by averaging the three-dimensional equations with respect to the cross-sectional plane, *i. e.* (r, θ) plane.

Especially, the continuity equation can be written with the average axial velocity u except at the inlet and the outlet and implies the average velocity is constant throughout each channel, so that

$$u = \begin{cases} u_L & \text{for the left channel,} \\ u_R & \text{for the right channel,} \end{cases} \tag{1}$$

where, u_L and u_R are constants. Note that the mass conservation at the inlet and at the outlet must be satisfied.

For steady solutions, the momentum equation implies force balance. For this system, the force balance can be replaced by buoyancy balance assuming no pressure drop. The effect of pressure drop is found so small compared with the buoyancy effect that it can be ignored for this system. If we assume that the coefficient of expansion is constant, the buoyancy balance can be replaced by the following equation:

$$\int T_L \, dx = \int T_R \, dx. \tag{2}$$

Here, T_L and T_R are the temperatures in the left and right channels. Note that zero horizontal lengths of the channels were assumed. Moreover, we assume volumeless heat sources and no heat loss to surroundings.

For boundary conditions, first, temperature is continuous everywhere, including at the inlet, at the outlet, and at the heat source positions. And the first derivative of temperature, dT/dx is also continuous everywhere except at the inlet and at the heat source positions. Note that dT/dx is continuous at the outlet because there is no external constraints on temperature at the outlet.

From the continuity of dT/dx at the outlet and the buoyancy balance

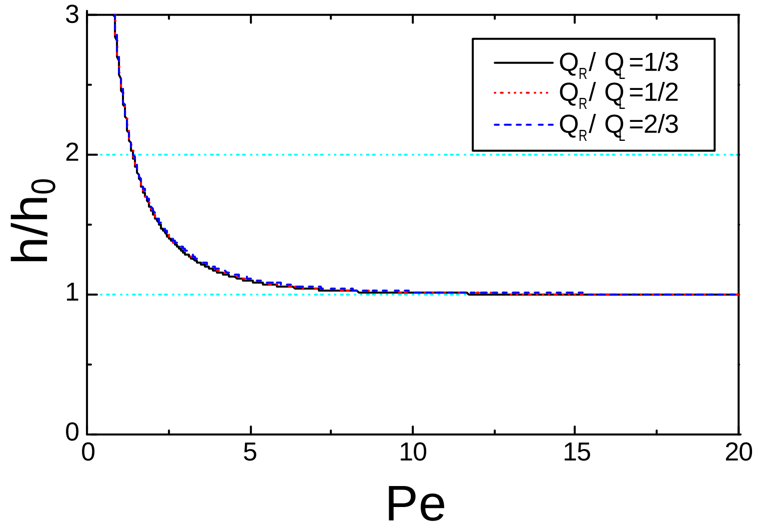

Figure 3. Normalized overall heat transfer coefficient(analytic results)

we can find a solution. The details can be found elsewhere[9]. The normalized overall heat transfer coefficient h/h_0 with respect to Pe is shown in Fig. 3 where h_0 is the overall heat transfer coefficient for forced circulation limit. The overall heat transfer coefficient and Pe are defined as

$$h \equiv \frac{(Q_L+Q_R)}{A(T_{out}-T_{in})}, \tag{3}$$

$$Pe \equiv \frac{Ul}{k}, \tag{4}$$

where T_{in} and T_{out} are the temperature at the outlet and at the inlet, respectively. And A is the flow area and k is heat diffusivity. The heat transfer characteristics will be discussed in later sections.

Ⅲ. Experiments and Results

The test loop is square-shaped with a peripheral length of 3600 mm(height: 800 mm, width: 1000 mm). The inner diameter is 16.7 mm. Two 600 mm long heaters were equipped on the left and right side at the same height(400 mm distant from the bottom). The heater power inputs were controlled within 0~1000 W. Liquid sodium flow was

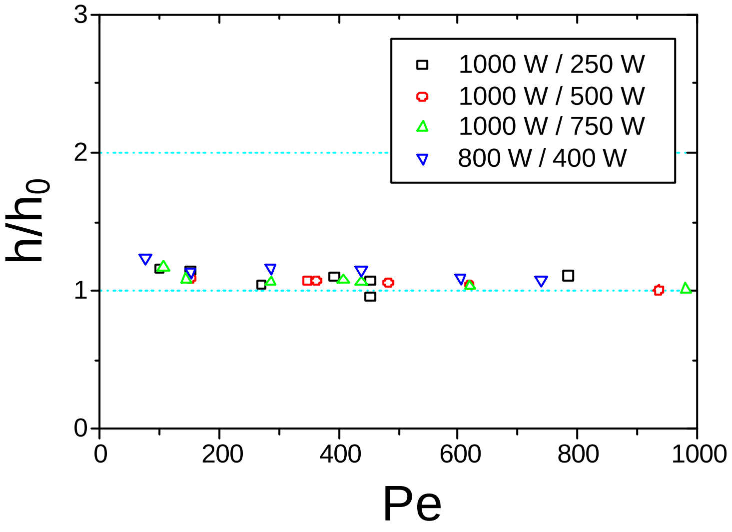

Figure 4. Normalized overall heat transfer coefficient(experimental results)

provided through the inlet at the bottom. The inlet flow rate was controlled by electro-magnetic pumps and measured by flow meters. The inlet temperature was kept constant by pre-heaters and coolers. The temperature profile inside the loop was monitored with 10 thermocouples inside and outside the loop. The thermocouples L1, L2, LH, LL, and L6 were 100 mm, 300 mm, 590 mm, 1210 mm, and 1500 mm distant from the outlet in the peripheral direction, respectively. For the right side, the thermocouples, R1, R2, RH, RL, and R6 were located at the symmetric positions to the left side thermocouples. The measured data were recorded in a HP715 workstation through a HP3852A device.

The parameters for the heater power ratio were 1000 W / 250 W, 1000 W / 500 W, 1000 W / 750 W, and 800 W / 400 W. The injection flow rate was varied from 0.000 to 0.050 m^3/hr. We considered a steady state where the measured temperature fluctuations were within 1 K.

The normalized overall heat transfer coefficient is shown in Fig. 4. For the heat transfer coefficient calculation, $\Delta T = T_{LH} - T_{LL}$ was used, where T_{LH} and T_{LL} are the temperatures measured at the top(LH) and at the bottom(LL) of the heater in the left channel. For h_0, the results of uniform heating cases are used.

Ⅳ. Discussions

In the two results, it can be found that as Pe increases, h decreases and soon converges to h_0. Although the two results are different slightly from the quantitative point of view, the coincidence of the two results seems remarkable considering the assumptions introduced for the analytic calculation. The coincidence also supports the validity of the analytical approach. The quantitative difference of the two results is thought to be due to the zero horizontal length assumption and the usage of $\Delta T = T_{LH} - T_{LL}$ for the heat transfer coefficient determination.

Moreover, the heat transfer characteristics are enhanced by decreasing Pe. The enhancement of the heat transfer characteristics has been already reported for the similar systems[6]. It should be also noted that the convergence rates are almost the same in spite of the different heating conditions[9].

Fortunately, because the parameters for the natural circulation operation for the decay heat removal of liquid metal reactors lies between Pe = 300 and Pe = 500, which was found to be located in the forced circulation dominant region, we don't have to consider the effects of non-uniform heating seriously.

Ⅴ. Summary

The decay heat removal system was simplified and treated as a one-dimensional loop and competition of the forced circulation and the buoyancy effect induced by the non-uniform heating was investigated analytically and experimentally.

The analytic solution obtained from a one-dimensional heat equation was found to agree well with the experimental results. It was also found that, for the forced circulation dominant region, the heat transfer coefficient converges to h_0, which is governed by Q_{tot}/U only. And for small Pe, enhancement of the heat transfer characteristics was also found.

Acknowledgments

This work has been supported by the Nuclear R & D Program, Ministry of Science and Technology.

References

1. Astegiano, J.C., Martin, R., and Gesi, E., 1981, Theoretical and Experimental Analysis of SUPER PHENIX 1 Thermohydraulique Problems in Natural Convection, in *Decay Heat Removal and Natural Convection in Fast Breeder Reactors*, ed. Agrawal, A.K. and Guppy, J.G., pp. 275-287, Hemisphere, Washington.

2. Rosegen, F., Dueweke, M., Timmermann, F., and Vossebrecker, H., 1981, Decay Heat Removal of the SNR-300 with Special Consideration of the Natural Convection Effects, in *Decay Heat Removal and Natural Convection in Fast Breeder Reactors*, ed. Agrawal, A.K. and Guppy, J.G., pp. 253-261, Hemisphere, Washington.

3. K. S. Han and J. H. Song, J. Kor. Nucl. Soc. **27,** 645 (1995).

4. Singler, R.M., Betten, P.R., *et al.*, 1980, Studies of Thermal-Hydraulic Phenomena in EBR-Ⅱ, *Nucl. Eng. Design*, vol. 62, pp. 219-232.

5. Takeda, H. and Koga, T., 1993, Study on Similarity Rule for Natural Circulation Water Test of LMFBR, IAEA Specialist Meeting on "Evaluation of Decay Heat Removal by Natural Convection," held at O-arai Engineering Center/PNC, 22-25, Feb. 1993.

6. H. Kamide, K. Hayashi, and K. Momoi, *Proceedings of NURETH-8*, 922 (1997).

7. Y-B. Lee, M-J. Kim, S-K. Choi, Y-K. Kim, and H-Y. Nam, *Proceedings of 11th IHTC*, Vol. 6, pp. 57-62 (1998).

8. M-J. Kim, Y-B. Lee, S-K. Choi, Y-K. Kim, and H-Y. Nam, *Proceedings of ICONE-6,* 6489 (1998).

9. M-J. Kim, Y-B. Lee, Y-K. Kim, B-H. Choi, and H-Y. Nam, Mixed Convection in an Un-Equally Heated Loop: Steady Solutions, J. Kor. Phys. Soc., *submitted.*