Thermo-flow characteristics in a corrugated plate heat exchanger considering plate deformation

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Abstract. Heat transfer and pressure drop characteristics were numerically investigated in a corrugated plate heat exchanger, considering the operating conditions for the nuclear power system. The plate deformation which is induced by the large pressure difference between the hot fluid side and cold fluid side was examined using the two-way fluid-structure interaction (FSI), and then the friction factors and Colburn factors were investigated for the deformed geometry. The Colburn factors for the deformed geometry were similar to those of the previous correlations, while the friction factors for the deformed geometry were about 7% higher than those of the previous correlations in large pressure difference regime.

1. Introduction

To ensure the safety in nuclear power systems, it is important to transfer the heat from the reactor core to the ultimate heat sink. For this reason, various types of heat exchanger (shell and tube type heat exchanger, plate type heat exchanger, etc.) are installed in the system. Especially, the corrugated plate heat exchanger has a large surface area for heat transfer per unit volume, which leads to a high thermal performance with counter-flow operation. Moreover, their geometries make the heat exchangers highly durable. However, the large pressure difference between the hot and cold fluid sides induces the plate deformation, which alters the performance of the heat exchangers. Therefore, to investigate the performance of heat exchangers, studies considering the geometric deformation should be carried out.

Many researchers have studied corrugated plate heat exchangers using experiments or numerical analyses. Focke and Knibbe [1], Gaiser and Kottke [2], and Dovic et al. [3] investigated the flow patterns experimentally for different corrugation angles using flow visualization at a macroscopic level. Lee and Lee [4] numerically investigated the time-dependent flow characteristics using large-eddy simulation. Focke et al. [5] proposed friction and Colburn factor correlations as functions of the corrugation angle. Muley and Manglik [6], Okada et al. [7], and Heavner et al. [8] also reported friction factor and Nusselt number correlations based on experimental investigations, and Lee and Lee [9] derived friction factor and Colburn factor correlations considering various geometric conditions and working fluids. Nevertheless, although various studies [1-9] have examined the heat transfer and flow friction for the corrugated plate heat exchangers, the deformation of the geometry has not been considered.

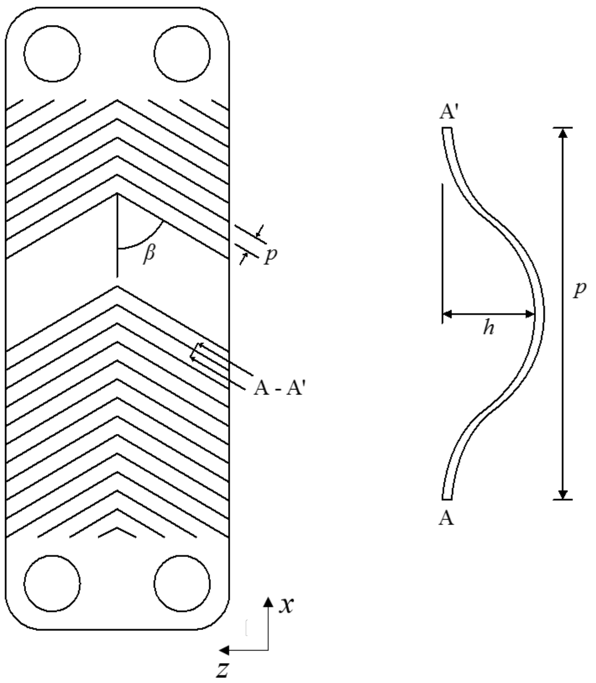

Figure 1. Schematic diagram of a corrugated plate heat exchanger

This study examined the plate deformation induced by the large pressure difference between the hot and cold fluid sides using the two-way fluid-structure interaction (FSI), and then investigated the friction and Colburn factors for the deformed geometry.

2. Problem Formulation

Figure 1 shows a schematic diagram of a corrugated plate heat exchanger. Sinusoidal corrugations are repeated in the *x*- and *z*-direction, with corrugation angle *β*, pitch *p*, and height *h*. The unit section was used as the computational domain, as shown in figure 2. Periodic boundary conditions were used in the streamwise and spanwise directions. The hot and cold fluids exchange heat in a counter flow arrangement, and the hot fluid flows between two layers of cold fluid. In this paper, the numerical results for the hot fluid side were presented. The pressure gradient condition was applied in the streamwise direction. No-slip boundary condition was applied at the walls. The plate was of 0.6-mm-thick.

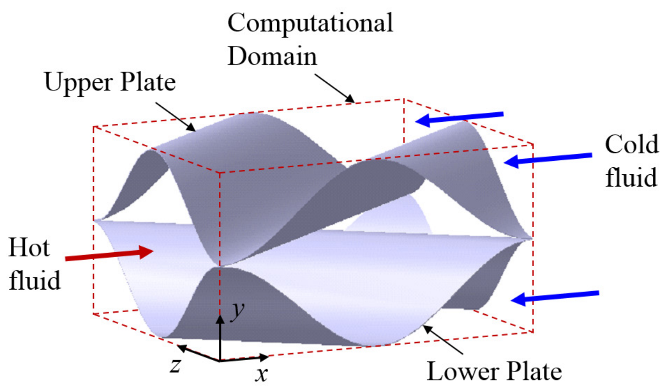

Figure 2. Computational domain

Reynolds number is defined as follows:

$$\mathrm{Re} = \frac{\rho u D_{eq}}{\mu} \tag{1}$$

where D_{eq} [6, 9] is the equivalent diameter, which is defined as

$$D_{eq} = 2h \tag{2}$$

2.1. Governing Equations

In this study, the numerical analysis using shear stress transport (SST) *k-ω* turbulent model [10] was carried out to investigate the friction and Colburn factors. The SST *k-ω* turbulence model employs the *k-ω* turbulence model in the near-wall region, and the *k-ε* turbulence model in the free-stream region, which provides both accuracy and efficiency. Kim et al. [11] and Kim and Lee [12] showed that numerical results using the SST *k-ω* turbulence model were in good agreement with experimental data for plate heat exchangers. Lee and Lee [4] investigated the variation in the Strouhal number as a function of the Reynolds number. As a results, the critical Reynolds numbers were in the range 170~330 for various values of p/h, meaning that the flow was turbulent at relatively low Reynolds numbers. Therefore, in this work, the numerical analysis using the SST *k-ω* turbulence model is appropriate. The following assumptions were made:

(1) The fluid flow is three-dimensional, steady-state, and incompressible.
(2) The hot and cold side fluids are water, and their properties are constant.
(3) Natural convection and radiation heat transfer are neglected.

The Navier–Stokes equations for the steady-state analysis using SST *k-ω* turbulent model are as follows.

Continuity:

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right) = 0 \tag{3}$$

Momentum:

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\left(\mu + \mu_t\right)\frac{\partial u_i}{\partial x_j}\right] \tag{4}$$

Turbulent kinetic energy:

$$\frac{\partial}{\partial x_j}\left(\rho u_i k\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\beta^* k\omega \tag{5}$$

Specific dissipation rate:

$$\frac{\partial}{\partial x_j}\left(\rho u_i \omega\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + \frac{\alpha}{\nu_t}G_k - \rho\beta_t\omega^2 + 2(1-F_1)\rho\sigma_{\omega,2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{6}$$

Energy:

$$\rho C_p \frac{\partial}{\partial x_j}\left(u_j T\right) = k_{eff}\frac{\partial^2 T}{\partial x_j^2} + \left(\tau_{ij}\right)_{eff}\frac{\partial u_i}{\partial x_j} \tag{7}$$

2.2. *Numerical analysis procedure*

The semi-implicit pressure linked equations (SIMPLE) algorithm was employed to couple the velocity and pressure fields. The momentum and energy equations were discretized via the second-order upwind scheme. Tetrahedral grids were generated, and the grid-size dependence test in the undeformed condition was performed; the results showed that a grid size of $y^+ < 5$ was sufficient, as shown in figure 3.

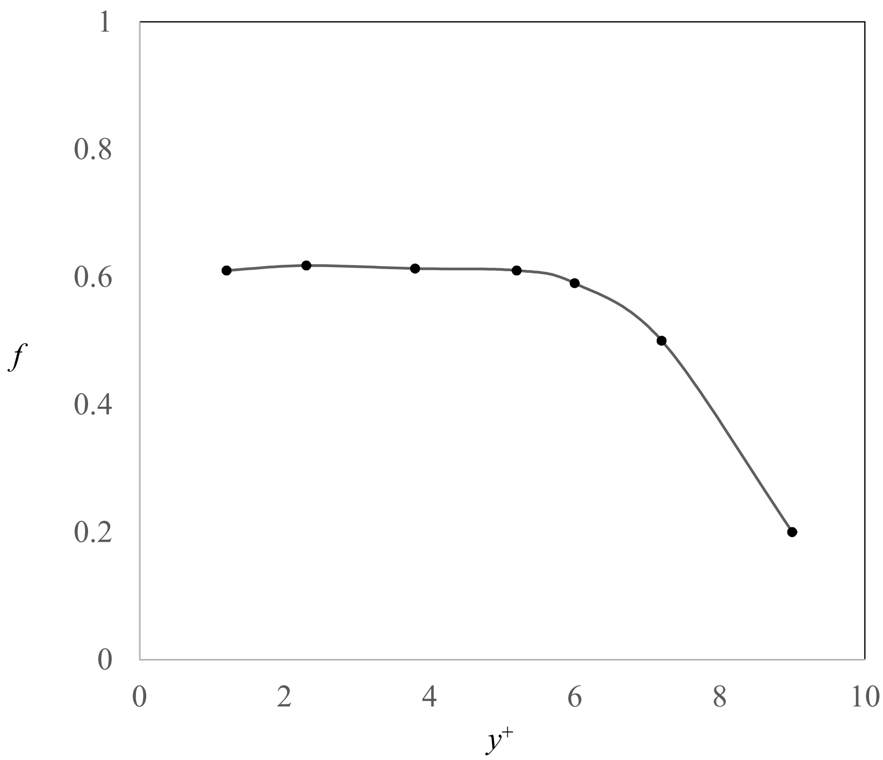

Figure 3 Grid dependence test

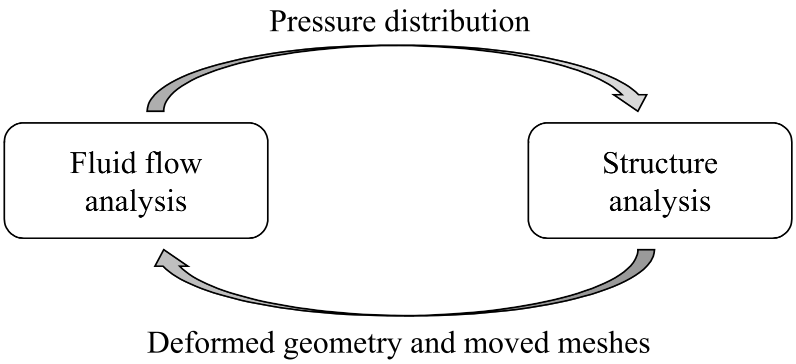

Figure 4 Procedure of the fluid-structure interaction

2.3. Predicting the plate deformation

The plate heat exchanger transfers the heat from the hot fluid side to the cold fluid side via the plate, and the large pressure difference between the hot and cold fluids induces the plate deformation. In this study, the pressure difference-induced plate deformation was predicted by using the two-way fluid-structure interaction (FSI), as shown in figure 4. The values of pressure and temperature were selected considering those of a nuclear power system. First, the pressure distribution in the fluid flow field was calculated. Then the plate deformation was predicted using the calculated results. Finally, the heat transfer coefficient and pressure drop in the deformed geometry using the moved meshes was investigated, and the friction and Colburn factors were calculated.

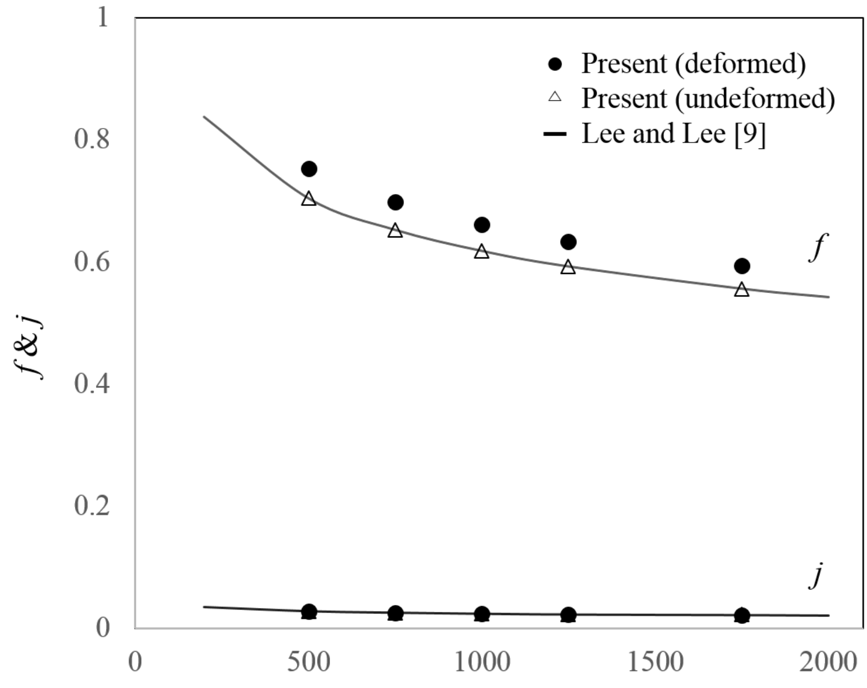

Figure 5 Friction and Colburn factors according to Reynolds number

3. Results

3.1. Friction factor and Colburn factor considering the plate deformation

Figure 5 shows the friction and Colburn factors in the deformed geometry for a pressure difference of 2.5 MPa. These were compared with the correlations of Lee and Lee [9], which were derived for undeformed corrugated plate heat exchangers. The Colburn factors considering the plate deformation were similar to those of Lee and Lee [9], while the friction factors considering the plate deformation were about 7% higher than those of Lee and Lee [9]. As shown in Lee and Lee [4], the fluid in the corrugated plate heat exchanger flows along the streamwise direction and in the directions of the furrows, which makes the flow turbulent even at a low Reynolds number. Deformation of the plates affects this fluid flow pattern, resulting in a slight increase in the pressure drop. However, the effects on the heat transfer coefficient were not significant.

3.2. Friction factor and Colburn factor according to pressure difference

Figure 6 shows the friction and Colburn factors according to the pressure difference between the hot and cold fluids at Re = 1000. The Colburn factors for the deformed geometry had the almost same values with those of Lee and Lee [9], regardless of the pressure difference. The friction factors matched those of Lee and Lee [9] in the regime with low pressure differences. As the pressure difference increased, however, the difference in the friction factors between the deformed and undeformed conditions increased; the friction factors for the deformed condition were about 7% higher than those of the correlations of Lee and Lee [9]. Therefore, to investigate the pressure drop in plate heat exchangers with a large pressure difference between the hot and cold fluids, deformation of the plate should be taken into account in the numerical analysis.

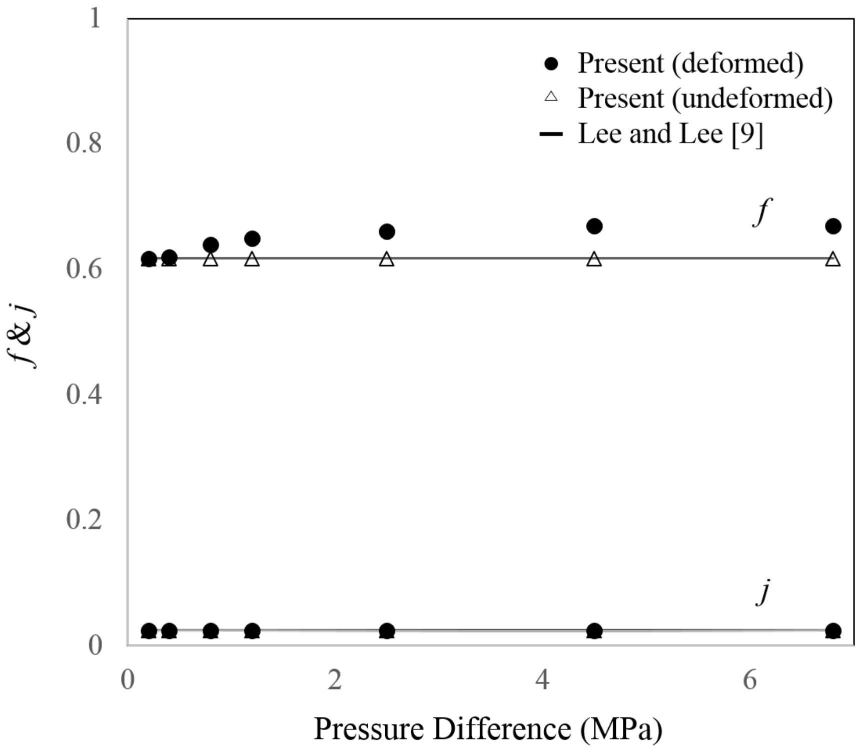

Figure 6 Friction and Colburn factors according to pressure difference

4. Conclusion

In this study, the numerical analysis was carried out to investigate the heat transfer and pressure drop characteristics in a corrugated plate heat exchanger, using the two-way fluid-structure interaction (FSI) to consider the pressure difference that induced plate deformation. The Colburn factors for the deformed geometry were similar to those of the correlations of Lee and Lee [9] (for undeformed conditions), regardless of the pressure difference. However, in large pressure difference regime, the friction factors for the deformed condition were about 7% higher than those of the correlations of Lee and Lee [9]. Therefore, to investigate the pressure drop in plate heat exchangers with a large pressure difference between the hot and cold fluids, the plate deformation should be taken into account in the numerical analysis.

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