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Calculation of Shell Side Pressure Drop in the Experiment Simulating Typical Heat Exchanger Using MULTID Component Model of MARS-KS Code

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1. Introduction

Predicting the pressure drop on the shell side of the shell-and-tube type heat exchanger is the starting point of the design [1]. It is a key part of the design of NRHES (Nuclear Renewable Hybrid Energy System) [2]. The pressure drop is caused by the flow passing through inlet nozzle, tube bundle, baffle cut, outlet nozzle, etc. In the design of heat exchangers such as feedwater heaters based on the Delaware method [3], pressure drop has been estimated through empirical equations.

Use of system thermal-hydraulic code in predicting the pressure drop is a very effective process to verify the performance of the design. To this end, the system code should be able to model the geometrical configuration inside the heat exchanger, such as tube bundle, segmental baffles, baffle cuts, impingement baffle, etc. Especially, appropriate pressure loss coefficients should be specified.

In this study, calculation of the experiment simulating a typical shell-side pressure drop with a system code is discussed and how to get the pressure loss coefficient to be involved in the calculation is also presented. To this end, the experiment of pressure drop in the heat exchanger performed by Halle et al. [4] is selected and the MARS-KS code [5] is applied to the calculation. In addition, based on the calculation results, it is investigated whether the pressure loss coefficient could be correlated with the height of the baffle cut.

2. Experiment

Fig.1 shows overall configuration of the experimental heat exchanger of Halle's experiment [3].

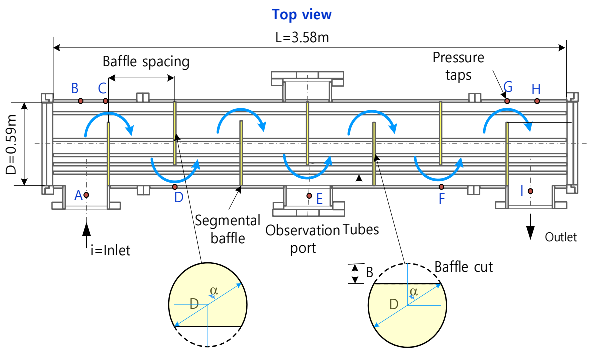

Fig. 1. Overall configuration of the experiment heat exchanger in 8 cross-passes

The experiment was conducted in a heat exchanger having 245~499 straight tubes with an outer diameter of 19.1 mm. In the experiment, a typical type of segmental baffle (truncated circle plate) was used. The experiment was carried out for the range of 0.037~0.394 m^3/s of water flow in shell-side. No flow was at the tube side. Measured data was presented for 24 tests having the various conditions including number of cross passes by segmental baffle, inlet/outlet nozzle size, and sizes of baffle cut height. The accuracy of measurements of pressure drop and the flow rate are ± 1.4 kPa and ± 0.002 m3/s, respectively.

The following four tests were selected for the purpose of the present study. No tube was in the baffle cut region, and effect of baffle cut height can be investigated with the selected tests.

Table I: Test conditions

Test ID	Tub-ing, deg	No of tubes	No of Cross -pass	Nozzle size, in	Baffle cut height, %
N-P-8-10-30-26	30	333	8	10	26
N-P-8-14-30-26	30	333	8	14	26
N-P-6-14-60-16	60	425	6	14	16
N-P-6-14-60-30	60	275	6	14	30

3. Code and Modeling

MARS-KS version1.5 [4] has been used in the present calculation.

3.1 MULTID modeling

Figure 3 shows the MARS-KS nodalization for the test heat exchanger.

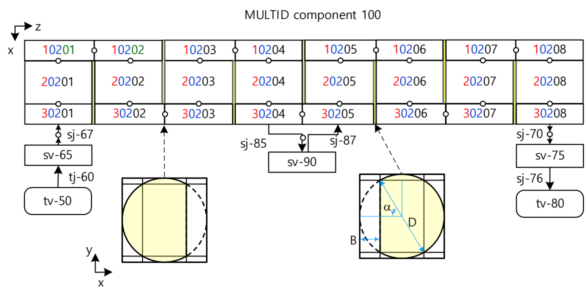

Fig. 2. MARS-KS noding diagram of test heat exchanger

A rectangular MULTID component having 3, 3, and 8 (6 for some experiments) nodes in x, y, and z directions was used to describe the heat exchanger shell side, respectively. The reason for this noding, 3x3 in the x-y plane, is effectiveness in implementing the circular baffle cut with a shape of the truncated circle. The number of nodes in the longitudinal direction (z) was set to be equal to the number of cross passes formed by the segmental baffles. In this way, crossflow passing between the segmental baffles is established, and it passes through the baffle cut with an appropriate pressure drop. The blocked part of the baffle plate can be modeled by setting the junction's area fraction to 0, while the baffle cut part is considered to be the area fraction of the truncated circle to the rectangle covering the truncated circle. This distinguishes the part blocked by the baffle from the part opened by the baffle cut, and the shape of the flow path can be described most closely.

3.2 Determination of pressure loss coefficients

Fig. 3 shows the shape of junctions of the MULTID component with tubes.

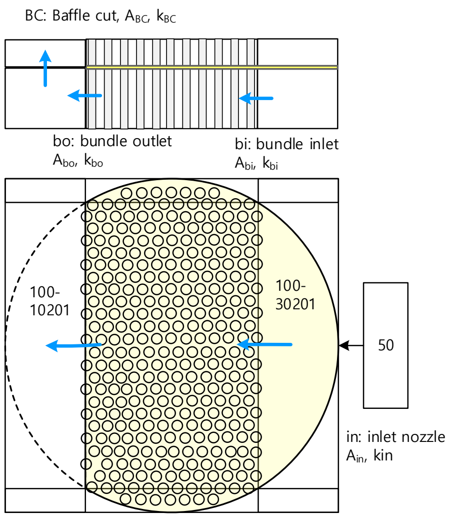

Fig. 3. Major junctions in MULTID of MARS

For the heat exchanger having a number of segmental baffles (N_B), the total pressure drop (Δp_G) of shell side is a sum of pressure drop at several elements such as the inlet nozzle (Δp_{in}) and the outlet nozzle (Δp_{out}), the tube bundle entrance (Δp_{bi}), the tube bundle exit (Δp_{bo}), and the baffle cut (Δp_{BC}) at each cross pass,

$$\Delta p_G = \Delta p_{in} + \sum_{k=1}^{N_B+1} (\Delta p_{bi} + \Delta p_{bo})_k + \sum_{k=1}^{N_B} \Delta p_{BC_k} + \Delta p_{out} \quad (1)$$

Assume the same pressure drop through each cross pass, then,

$$\Delta p_G = \Delta p_{in} + (N_B+1)(\Delta p_{bi} + \Delta p_{bo}) + N_B \Delta p_{BC} + \Delta p_{out} \quad (2)$$

Now, consider only pressure loss coefficients at each junction, k, in one-dimensional manner, neglecting the wall frictional pressure drop, then

$$\Delta p_G = \frac{1}{2}\rho k_{in} v_{in}^2 + (N_B+1)\left(\frac{1}{2}\rho k_{bi} v_{bi}^2 + \frac{1}{2}\rho k_{bo} v_{bo}^2\right) + N_B \frac{1}{2}\rho k_{BC} v_{BC}^2 + \frac{1}{2}\rho k_{out} v_{out}^2 \quad (3)$$

Inserting the definition of volumetric flow rate, $Q = Av$ at each junction into equation (3), and organizing, then

$$\frac{2\Delta p_G}{\rho Q^2} = \frac{k_{in}}{A_{in}^2} + (N_B+1)\left\{\frac{k_{bi}}{A_{bi}^2} + \frac{k_{bo}}{A_{bo}^2}\right\} + N_B \frac{k_{BC}}{A_{BC}^2} + \frac{k_{out}}{A_{out}^2} \quad (4)$$

From the experiment, almost linear pressure drop along the shell was found. Thus, we assume the same pressure drop for *bi*, *bo*, and *BC*,

$$\frac{k_{bi}}{A_{bi}^2} = \frac{k_{bo}}{A_{bo}^2} = \frac{k_{BC}}{A_{BC}^2} \quad (5)$$

Inserting this equation into equation (4), then

$$\frac{2\Delta p_G}{\rho Q^2} = \frac{k_{in}}{A_{in}^2} + (3N_B+2)\frac{k_{bi}}{A_{bi}^2} + \frac{k_{out}}{A_{out}^2} \quad (6)$$

If the form loss coefficients at the inlet nozzle and outlet nozzle are given, we can obtain the form loss coefficients at three junctions.

$$k_{bi} = \frac{A_{bi}^2}{3N_B+2}\left\{\frac{2\Delta p_G}{\rho Q^2} - \left(\frac{k_{in}}{A_{in}^2} + \frac{k_{out}}{A_{out}^2}\right)\right\}$$
$$k_{bo} = \frac{A_{bo}^2}{A_{bi}^2} k_{bi} \quad (7)$$
$$k_{BC} = \frac{A_{BC}^2}{A_{bi}^2} k_{bi}$$

Incorporating the pressure loss coefficient determined in this way into the initial guess of the input of calculation, the MARS-KS code run is conducted. The calculated total pressure drop may be greater than the experiment data for the corresponding flow rates, which due to several reasons including multi-dimensional effect, wall friction, etc. In such a case, the desired value can be obtained through the repeated calculation with the adjusted k_{bi}, k_{bo}, and k_{BC} .

4. Results and Discussion

4.1 Result for 26% baffle cut experiment

The MARS-KS calculation for the N-P-8-10-30-26 experiment was performed using the loss coefficients obtained by the method described above. And the final results as shown in Figure 3 could be obtained. As shown in this figure, the pressure drop is well consistent with the experimental data for most flow rates.

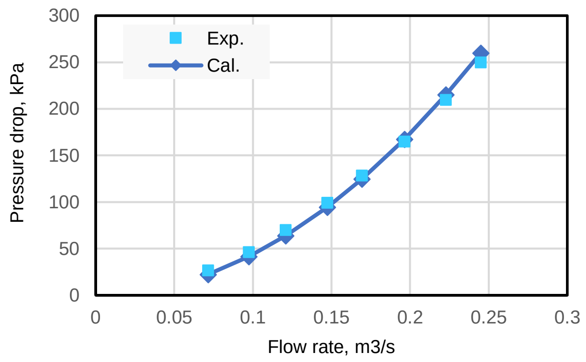

Fig. 4. Comparison of pressure drop for test N-P-8-10-30-26

Figure 5 shows a comparison of the calculated distribution of pressure drops with the same experiment. The x-axis represents the relative distance from the inlet nozzle to each measurement position in Figure 1. The y-axis is a normalized pressure drop based on the total pressure drop. The distribution of pressure drops calculated for the three flow rates generally converges to one curve, which is well consistent with the measured data. Also, it can be reconfirmed that the distribution of pressure drops is linear in both experiments and calculations.

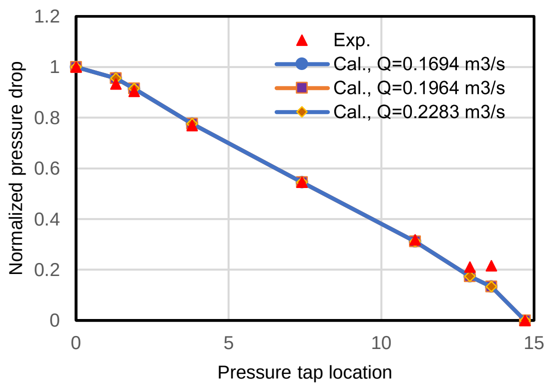

Fig. 5. Comparison of pressure drop distribution over shell side for test N-P-8-10-30-26

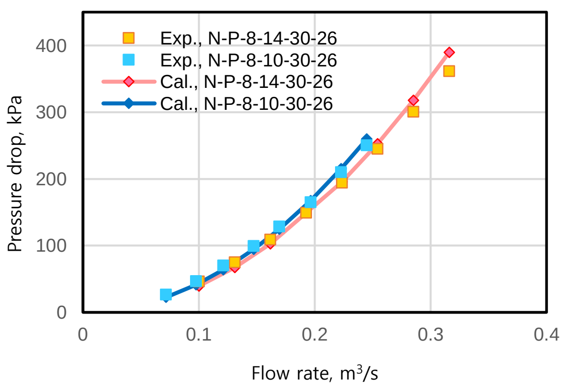

Fig. 6. Comparison of pressure drop for sizes of nozzle of inlet and outlet (14 inches and 10 inches)

4.2 Effect of size of nozzle at inlet and outlet

Figure 6 compares the calculated total pressure drop for two experiments, N-P-8-10-30-26 with 10-inch nozzle and N-P-8-14-30-26 with 14-inch nozzle. Both experiments and calculations show that the larger the nozzle size, the lower the pressure drop up to 0.25 m^3/s in flow rate. Also, the same effect can be expected at a flow rate greater than this value from the figure. Overall, the results are generally well agreed to the experiment, but the pressure drop is predicted slightly large in the high-flow region.

4.3. Effect of height of baffle cut

Figure 7 compares the calculated total pressure drop for three experiments having different baffle cut height, N-P-8-10-30-26 (26%), N-P-6-14-60-30 (30%), and N-P-6-14-60-16 (16%). Although the tube arrangement, nozzle size, and number of tubes in the experiment with a height of 26% of the baffle cut differ from the other two experiments, it is clearly shown that the pressure drop increases as the height of the baffle cut decreases for the same flow in both experiments and calculations.

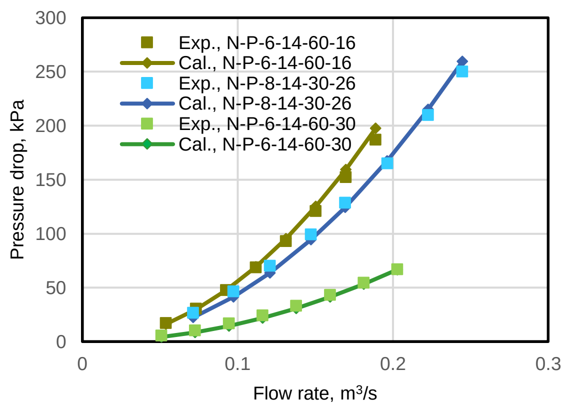

Fig. 7. Comparison of pressure drop for three heights of baffle cut

4.4. Correlation with height of the baffle cut

Figure 8 shows a plot between the corrected pressure drop versus the pressure loss coefficient and the estimated curve based on it. The loss coefficients in the figure were the values that provided the result closest to the experimental value through repeated calculations. As shown in Table 1, in Halle's experiment, effect of the height of the baffle cut under the same condition can be evaluated by only two sets of tests (16 % and 30 %). Therefore, it is necessary to convert the calculation results for the 26 % baffle cut experiment into the value for those same condition. The used correction equation is as follows.

$$\Delta p_{G_j}^{\ *} = \Delta p_{G,cal,j} \frac{1}{1-B_j^{\ 2}} \frac{6}{N_{B,j}} \frac{A_{x,N_B=6}}{A_{x,j}} \qquad (2)$$

where, asterisk means corrected values, j means the experiment to be corrected, A_x means area of node in x direction, respectively. According to this equation, the calculation results for the experiment with an N_B of 6 are only corrected according to the height of the baffle cut.

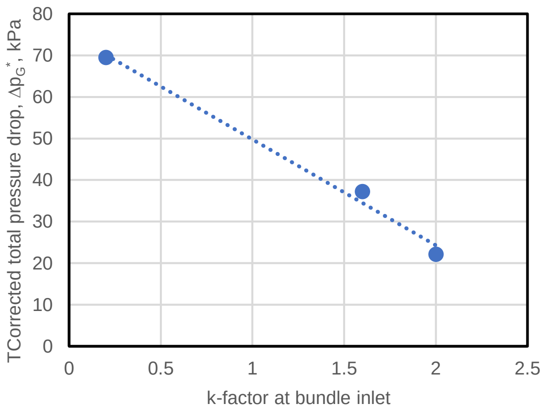

Fig. 8. Relation between the corrected total pressure drop and loss coefficient

As shown in the figure, it can be estimated that the corrected pressure drop has a linear relationship with the pressure loss coefficient. The calculation results for the baffle cut height 26% experiment appear to be slightly deviated from this linear relationship due to the fact that the correction equation is not yet complete enough. There are still need of improvement, but using this correlation, the pressure drop and loss coefficient can be estimated for the number of baffle plates and the height of baffle cuts for a heat exchanger similar to Halle's experiment.

5. Conclusions

Calculations of the experiment simulating a typical shell-side pressure drop by Halle et al. [3] were made using MARS-KS code and MULTID component model. The conclusions are as follows:

(1) The MULTID component model of MARS-KS code and the pressure loss coefficients guessed by the present method and modified by iterative calculations made it possible to predict the total pressure drop of the experiment with relatively acceptable accuracy.

(2) The present modeling scheme consistently predicts the effect of the inlet and outlet nozzle size and the height of the baffle cut on the total pressure drop as observed in the experiment.

(3) The pressure loss coefficient may be correlated in linear manner with the total pressure drop corrected by ratio of the height of the baffle cut, the number of baffle cut, and the flow rate.

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