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Pressure drop modeling for helical tubes in SPACE

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1. Introduction

The utilization of once-through helical coiled tubes for steam generator makes reactor size to be small and simplified. The iSMR (innovative Small Modular Reactor) which has been developed in Korea employs helical tubes which coils the reactor vessel outside. The SPACE [1] code is used to perform the safety analysis of the iSMR.

The SPACE was originally developed to be used to the safety analysis of the large Pressurized Water Reactor and the code has the insufficiency for the physical phenomena occurring in a curved pipe. The pressure drop and heat transfer characteristics in a curved pipe is differed from those in a straight pipe due to the secondary flow with centrifugal force and torsion force in the cross section. It is well known that the secondary flow in a helically coiled tube is a significant factor affecting the frictional pressure drop.

This paper deals with the pressure drop model which has recently been implemented into the SPACE for the proper prediction of pressure drop in a curved pipe.

2. Frictional pressure drop model in SPACE

The SPACE uses two kinds of correlations to calculate the frictional pressure drop multiplier for two-phase in a pipe depending on the flow regime. The HTFS (Heat Transfer and Fluid flow Service) [2] correlation is used to calculate the multiplier in the bubbly and slug flow regimes and the Wallis correlation [3] is used in annular flow regime. Two multipliers are interpolated depending on the void fraction in the transition region between slug flow regime and annular flow regime.

The Lockhart-Martinelli [4] assumed that the liquid and gas pressure drops were considered equal irrespective of the details of the particular flow pattern.

$$\left(-\frac{dp}{dx}\right)_{2\phi} = \phi_k^2 \left(-\frac{dp}{dx}\right)_k \quad \left(\frac{dp}{dx}\right)_k = \frac{\lambda_k\left(\mathrm{Re}_k\right)G_k^2}{2D\rho_k} \tag{1}$$

Where ϕ is the pressure drop multiplier and 'k' means 'g' for gas-phase and 'f' for liquid-phase. D is the hydraulic diameter and ρ and λ are the density and friction factor, respectively. ϕ_g^2 and ϕ_f^2 are expressed as follows;

$$\phi_g^2 = 1 + \frac{C}{X} + \frac{1}{X^2},\ \phi_f^2 = 1 + CX + X^2,\ X^2 = \frac{\phi_g^2}{\phi_f^2} \tag{2}$$

The parameter 'C' is the correlation coefficient and is generally expressed in terms of mass flux (G) and dimensionless property index (Λ).

$$2 \le C = 2 + f_1\left(G\right) f_2\left(G,\Lambda\right) \tag{3}$$

$$f_1\left(G\right) = 28 - 0.3\sqrt{G}$$

$$f_2\left(G,\Lambda\right) = \exp\left[-\frac{\left(\log_{10}\Lambda + 2.5\right)^2}{2.4 - 10^{-4}G}\right] \tag{4}$$

$$\Lambda = \frac{\rho_g}{\rho_f}\left(\frac{\mu_f}{\mu_g}\right)^2$$

Where μ denotes fluid viscosity.

In SPACE, Churchill correlation [5] is used to calculate the friction factor (λ).

$$\lambda_k = 2\left[\left(\frac{8}{\mathrm{Re}_k}\right)^{12} + \frac{1}{\left(a+b\right)^{1.5}}\right]^{1/12} \tag{5}$$

$$a = \left[2.475\ln\left(\frac{1}{\left(7/\mathrm{Re}_k\right)^{0.9} + 0.27\,\varepsilon/D}\right)\right]^{16} \tag{6}$$

$$b = \left(\frac{37350}{\mathrm{Re}_k}\right)^{16} \tag{7}$$

Wallis correlation for the calculation of the frictional pressure drop multiplier in the annular flow is as follows;

$$\phi_f^2 = \frac{1}{\alpha_f^2} \tag{8}$$

3. new model

The important parameters determining pressure drop in a curved pipe are friction factor and two-phase pressure drop multiplier.

3.1. Friction factor in a curved pipe

Through the paper survey for frictional factor in a curved pipe two correlations were implemented into the SPACE code depending on the flow velocity. White correlation [6] was selected for the laminar flow and Ito correlation [7] for the turbulent flow. However, these correlations do not consider the wall roughness (ε in equation (6)). So, Churchill correlation is modified using White and Ito correlations.

White confirmed that the pressure drop in a curved pipe was increased by Dean flow through tests and he suggested an empirical multiplier considering the effect.

$$f_m^{-1} = 1 - \left[1 - \left\{ 11.6 / \left(\mathrm{Re}_k \sqrt{d_{tube} / D_{coil}} \right) \right\}^{0.45} \right]^{1/0.45} \quad (9)$$

Equation (9) is multiplied to friction factor of the straight pipe to describe the increased pressure drop in a curved pipe. The figure 1 compares friction factors in the curved pipe and straight pipe. Friction factor from a curved pipe is slightly higher than that from a straight pipe as Re number increases.

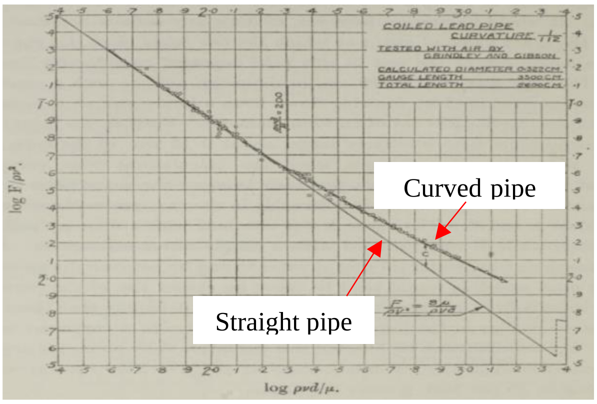

Fig.1 Comparison of friction factors[6]

The first term of right-hand side in equation (5) was devised to obtain friction factor for laminar flow. The factor 'f_m' is multiplied to the first term and the figure 2 shows the variation of friction factor for the laminar flow depending of diameter ratio of the curved pipes. The smaller diameter ratio means the smaller diameter of helical coil. Friction factor in a curved pipe with the smaller diameter represents the larger friction factor due to the Dean flow effect.

Ito suggested the critical Reynolds number of equation (10) for the transition from laminar flow to turbulent flow. Basically, the transition Reynolds number in a straight pipe is 2300, however this number depends on the diameter ratio in a curved pipe. Equation (10) has the Reynolds number of 2301.4 when the diameter ratio is equal to 860 and the number is 2300 in the case of the larger diameter ratio than 860.

$$\mathrm{Re}_{crit} = 20000 \times \left(\frac{d_{tube}}{D_{coil}} \right)^{0.32} \quad (10)$$

On the other hand, equation (7) was devised to represent the transition number and equation (7) is modified to present the critical Reynolds number in a curved pipe as equation (7').

$$b' = \left(\frac{37350\,\mathrm{Re}_{crit} / 2301.4}{\mathrm{Re}_k} \right)^{16} \quad (7')$$

Ito also suggested the friction factor for turbulent flow in a curved pipe.

$$\lambda_{k,turb} = \frac{0.029}{\left(D_{coil} / d_{tube} \right)^{0.5}} + \frac{0.304}{\mathrm{Re}_k^{0.25}} \quad (11)$$

Equation (11) is basically to consider the diameter ratio to Blasius correlation. The friction factor by Blasius correlation is very close to that by Churchill correlation when roughness (ε) is equal to 10^{-6} m. The first term of equation (11) is added to equation (6). Equation (12) presents the final modified Churchill correlation and it is applied in the helical coiled steam generator tubes. Upper equation in equation (12) is used to calculate the friction factor for laminar flow when $\mathrm{Re}_k < \mathrm{Re}_{crit}$ and lower equation is used when $\mathrm{Re}_k \geq \mathrm{Re}_{crit}$.

$$\lambda_k' = \left| \begin{array}{l} 2\left[\left(\dfrac{8 f_m}{\mathrm{Re}_k} \right)^{12} + \dfrac{1}{(a+b)^{1.5}} \right]^{1/12} \\ 2\left[\left(\dfrac{8 f_m}{\mathrm{Re}_k} \right)^{12} + \dfrac{1}{(a+b)^{1.5}} \right]^{1/12} + 0.00725 \left(\dfrac{d_{tube}}{D_{coil}} \right)^{0.5} \end{array} \right. \quad (12)$$

Figure 2 compares the friction factors depending on diameter ratio. The bigger helical coil diameter is the smaller friction factor is calculated.

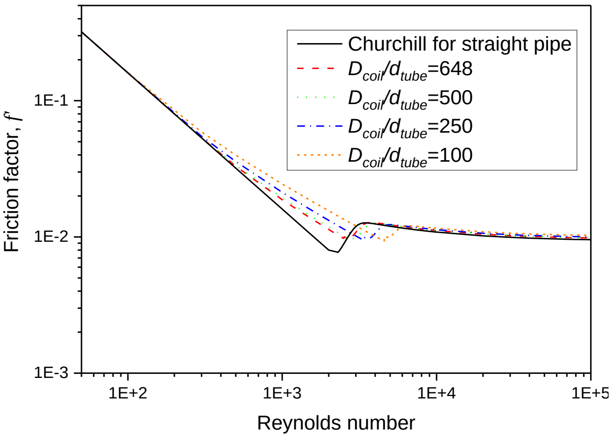

Fig.2 Comparison of friction factors with D_{coil}/d_{tube}

3.1. two-phase pressure-drop multiplier

Flow characteristics in a curved pipe is generally differed from those in a straight pipe due to the bending of pipe, the centrifugal force, and the force of gravity. When the pressure drop is calculated in a curved pipe above three factors should be considered. The parameters representing those factors are the coiled elevation angle, diameter ratio, and the Froude number.

Xin et. al [8] presented the modified Lockhart-Martinelli multiplier (ϕ) considering three factors.

$$\begin{array}{l} \phi_f \Big/ \left(1 + \dfrac{20}{X} + \dfrac{1}{X^2} \right)^{1/2} = 1 + \dfrac{X}{65.45 F_d^{0.6}},\ F_d < 0.1 \\ \phi_f \Big/ \left(1 + \dfrac{20}{X} + \dfrac{1}{X^2} \right)^{1/2} = 1 + \dfrac{X}{434.8 F_d^{1.7}},\ F_d < 0.1 \end{array} \quad (13)$$

$$F_d = Fr \sqrt{\frac{d_{tube}}{D_{coil}}} \left(1 + \tan\beta \right)^{0.2} \quad (14)$$

Pressure drop should be generally decreased as the coil diameter is increased. However, pressure drop by equation (13) is reverse to above general presumption due to the diameter ratio and thus parameters in the diameter ratio should be inverted. Conclusively equation (14) is modified as equation (15)

$$F_d = Fr\sqrt{\frac{D_{coil}}{d_{tube}}}(1+\tan\beta)^{0.2} \tag{15}$$

4. Calculation results

A sample problem was prepared to investigate how much pressure drop increases in a curved pipe. The helical coil diameter (D_{coil}) is 0.5 m while the tube diameter (d_{tube}) is 0.01 m and the inclination angle (β) is 10 degree. The pipe with the length of 0.8 m is divided into 20 cells. The tube is initially pressurized to 5 bar and filled with 100 ℃ water. Pressure boundary condition of 5 bar is applied to the outlet boundary cell of 210 and flow boundary condition is applied at the inlet cell of 200 in Figure 3.

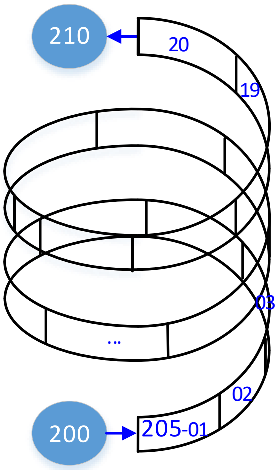

Fig.3 Node system for Sample problem

Velocities for liquid and vapor were linearly increased from 0.0 m/s to 3.0 m/s and 4.0 m/s during the initial 10.0 seconds and were maintained by 50.0 seconds. Figure 4 compares the calculation results using different wall friction models for pressure drop.

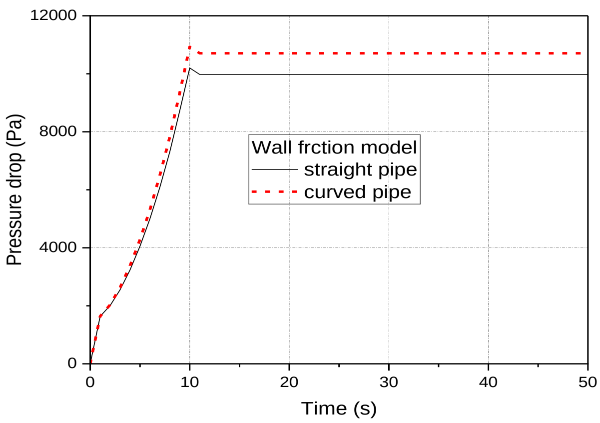

Fig.4 Pressure drop comparison at constant velocity

The void fraction was about 0.2. Pressure drop for the whole pipe is 9976.0 Pa when the wall friction models for the straight pipe is applied and 10705 Pa for the models of curved pipe. The deviation of 7.8 % is slightly small compared with its of other reports in which is predicted as above 15 %. However, their experimental data were ranged from 0 % to about 30 % and thus the calculation results are reasonable.

5. Conclusion

The wall frictional pressure drop models for the curved pipe were implemented into the SPACE code safety analysis for iSMR. Churchill friction factor correlation was modified using White correlation and Ito correlation. And the HTFS model for two-phase pressure drop was also modified using the corrected Xin correlations. Calculation using the modified correlations represented the reasonable results with the 7.8 % higher pressure drop than those using the original correlations.

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