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Evaluation of Low-Flow Correlations for Design of a Primary Heat Transport System in a Liquid Metal Reactor

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1. Introduction

When a reactor is shut down, the decay heat is removed by the natural circulation passing through the reactor core and IHX (Intermediate Heat Exchanger). In this situation the flow in the core and IHX is small compared with that in a normal operation. If one correctly simulates the fluid flow and heat transfer in this situation, adequate experimental correlations, which are accurate enough to model the low-flow, must be used. The objective of the present study is to evaluate the current correlations used in the design code for a reactor core and IHX thermal hydraulics. Only the pressure drop correlations are investigated due to the limited heat transfer correlations reported in the literature for a low-flow situation. The pressure drop correlations at the core inlet orifice, wire-wrapped fuel assembly and tube bundle in the IHX are evaluated through a comparison with the experimental data and new correlations.

2. Pressure Drop Correlations

2.1 Pressure Drop Correlation for Core Inlet Orifice

The pressure drop correlation for a core inlet orifice adopted in the present study is the correlation developed by Nam et al.[1]. The correlation can be written as follows;

$$\Delta P_{orifice} = f \frac{1}{2} \rho V_o{}^2 \tag{1}$$

$$f = F_g \left[1 + \frac{4.5\times10^6}{\left(\mathrm{Re}(\frac{A_{ot}}{A_d})^{1/4} \right)^{7/4}} \right] \tag{2}$$

$$V_o = \frac{Q}{N_o\, A_o}, \quad \mathrm{Re} = \frac{V_o d_h}{\nu}, \quad A_{ot} = N_o A_o \tag{3}$$

$$F_g = \left[1 + (1-\frac{A_o}{A_d})^2 + \tau(1-\frac{A_o}{A_d}) \right] \left(\frac{d_h^2}{A_d} \right)^{1/3} + 2.5\left(N_C - 1\right)^{2/3} \frac{A_o}{A_d} + 0.14(N_R - 1)^{1/4} \frac{N_C\, h\, P_S}{N_R\, w\, d_h} \tag{4}$$

$$\tau = 1.4 - 0.8 \frac{t_o}{d_h} \tag{5}$$

A detailed description of the variables in the correlation is reported in Nam et al. [1]

2.2 Pressure Drop Correlation for a Wire-Wrapped Fuel Assembly

The pressure drop correlation for a wire-wrapped fuel assembly investigated in the present study is that by Cheng and Todreas [2]. This correlation can be described as follows;

$$\Delta P = f \frac{L}{D_e} \frac{\rho V^2}{2} \tag{6}$$

$$f = \frac{C_{fL}}{\mathrm{Re}} \qquad \mathrm{Re} \le \mathrm{Re}_L \tag{7}$$

$$f = \frac{C_{fT}}{\mathrm{Re}^{0.18}} \qquad \mathrm{Re} \ge \mathrm{Re}_T \tag{8}$$

$$f = \frac{C_{fL}}{\mathrm{Re}}(1-\psi)^{\frac{1}{3}} + \frac{C_{fT}}{\mathrm{Re}^{0.18}}\psi^{\frac{1}{3}} \qquad \mathrm{Re}_L \le \mathrm{Re} \le \mathrm{Re}_T \tag{9}$$

$$\psi = \left(\log(\mathrm{Re}) - \left(1.7\frac{P}{D} + 0.78 \right) \right) \Big/ \left(2.52 - \frac{P}{D} \right) \tag{10}$$

$$C_{fL} = \left(-974.6 + 1612.0\left(\frac{P}{D}\right) - 598.5\left(\frac{P}{D}\right)^2 \right) \left(\frac{H}{D}\right)^{0.06-0.085(P/D)} \tag{11}$$

$$C_{fT} = \left(0.8063 - 0.9022\log\left(\frac{H}{D}\right) + 0.3526\left(\log\left(\frac{H}{D}\right)\right)^2 \right) \left(\frac{P}{D}\right)^{9.7} \left(\frac{H}{D}\right)^{1.78-2(P/D)} \tag{12}$$

2.3 Idelchik Pressure Drop Correlation [3] for IHX Inclined Flow

$$f = \frac{2\Delta P}{\rho U_m^2 N} = \Psi\left(3.2 + 0.66\left(1.7 - \frac{S_1 - d}{S_2^* - d} \right) \right) \mathrm{Re}_m^{-0.27} \frac{N+1}{N} \tag{13}$$

$$\Psi = 0.6135\ln(\theta) - 1.7462, \quad \mathrm{Re}_m = \frac{\rho U_m d}{\mu} \tag{14}$$

2.4 ESDU Pressure Drop Correlation [4] for IHX Inclined Flow

$$\frac{2\Delta P d}{\rho U^2 N S_2} = Y\left(\frac{D_v}{D}\right) \frac{1}{(X-1)^2} \Phi \tag{15}$$

$$\left(\frac{D_v}{D}\right) = \frac{2\sqrt{3}X^2}{\pi} - \frac{\mathrm{Re}_U}{\mathrm{Re}_U + 10} \tag{16}$$

$$Y = \left[\frac{3.61}{\mathrm{Re}_U^{0.7}}\left(1 + \frac{5}{\mathrm{Re}_U^{0.8}} \right)^2 + 0.0625(1-a)^2 + 0.01 \right]^{1/2} \tag{17}$$

$$a = \frac{\mathrm{Re}_U}{(\mathrm{Re}_U + 10^4)}, \quad \Phi = (\sin\theta)^{a_7}, \quad a_7 = 1 + 1.55\left(\frac{\mathrm{Re}_U}{\mathrm{Re}_U + 40} \right)^2 \tag{18}$$

$$\mathrm{Re}_U = \frac{\rho U d}{\mu}, \quad U = \beta U_m, \quad \beta = \frac{X-1}{X}, \quad X = \frac{S_2}{d} \tag{19}$$

3 Results and Discussion

Figure1 shows the comparisons of the pressure drop correlations for the inlet orifice and wire-wrapped fuel assembly with the experimental data. We can observe that the correlations agree very well with the measured data, especially in the low Reynolds number region.

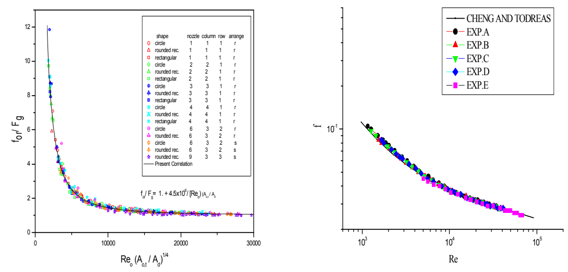
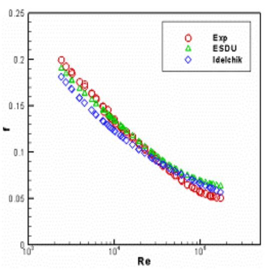
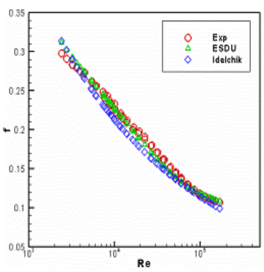


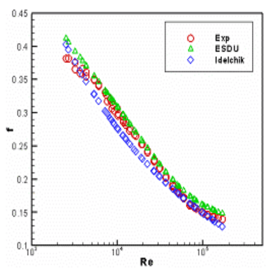
Figure 1. Pressure drop correlations for the inlet orifice (left) and wire wrapped fuel assembly (right) with experimental data



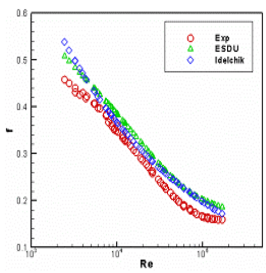
(a) 30°



(b) 45°



(c) 60°



(d) 90°

Figure 2.Comparison of Idelchik and ESDU correlations with measured data for different angles of inclination

Figure 2 shows that the Idelchik and ESDU correlations are accurate enough to be used for the engineering problems. It is noted that the correlation used in the ASTEEPL design code is Taborek's correlation. Since the Idelchik and ESDU correlations can be easily implemented in the ASTEEPL code, it is better to apply the three correlations to the calculations of the pressure drop in the IHX shell side and a change of mass flow rate during a pump coastdown. Figure 3 shows the comparison of the predicted pressure drop in the low-flow region in the IHX. We can observe that the three correlations result in nearly the same solutions while the Taborek's correlation (ASTEEPL in Figure) slightly under-predicts the pressure drop. Figure 3 also shows a change of the mass flow rate predicted using the three correlations during a pump coastdown. As shown in the figure, the three correlations produce nearly the same solutions.

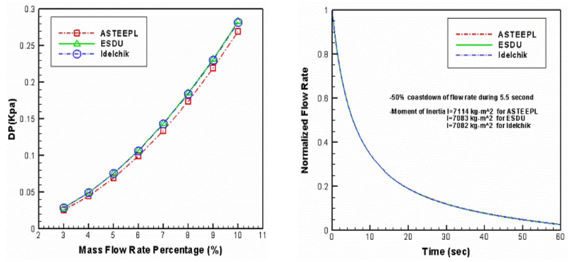


Figure 3. Pressure drop in IHX shell side (left) and the change of mass flow rate during the pump coastdown (right) predicted using the three correlations

4. Conclusions

An evaluation of experimental correlations for a pressure drop in a reactor core and IHX in a low-flow region is presented. It is shown that the correlation by Nam et al.[1] for the inlet orifice and that of Cheng and Todreas[2] for the wire-wrapped fuel assembly are accurate enough to be used in a design code. The Idelchik and ESDU correlations produce nearly the same solutions for four different inclinations. The correlations are also applied to the predictions of the pressure drop in the IHX shell side and a change of the mass flow rate during the pump coastdown, and it is shown that the three correlations produce nearly identical solutions.

REFERENCES

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