Pressure Drop Characteristics in Tight-Lattice Bundles for Reduced-Moderation Water Reactors*

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The reduced-moderation water reactor (RMWR) consists of several distinctive structures; a triangular tight-lattice configuration and a double-flat core. In order to design the RMWR core from the point of view of thermal-hydraulics, an evaluation method on pressure drop characteristics in the rod bundles at the tight-lattice configuration is required. In this study, calculated results by the Martinelli-Nelson's and Hancox's correlations were compared with experimental results in 4×5 rod bundles and seven-rod bundles. Consequently, the friction loss in two-phase flows becomes smaller at the tight-lattice configuration with the hydraulic diameter less than about 3 mm. This reason is due to the difference of the configuration between the multi-rod bundle and the circular tube and due to the effect of the small hydraulic diameter on the two-phase multiplier.

Key Words: Pressure Distribution, Constitutive Equation, Multi-Phase Flow, Friction Loss, Tight-Lattice Bundle

1. Introduction

The reduced-moderation water reactor (RMWR)[1,2] has been proposed as one of advanced water-cooled reactors at the Japan Atomic Energy Research Institute (JAERI). In order to attain a high conversion ratio more than 1.0 and a negative void reactivity coefficient, the RMWR core has the following structural features; a triangular tight-lattice configuration and a double-flat core. For design of the RMWR core from the point of view of thermal-hydraulics, an evaluation method on pressure drop characteristics in multi-rod bundles at the tight-lattice configuration is required. The pressure loss in a two-phase flow through the BWR core has been generally evaluated using correlations on friction factors for circular tubes with the same hydraulic diameter as the BWR core. This fact derives the following two outstanding problems. One is that the hydraulic diameter of the RMWR core is much smaller than that of the BWR core. Few correlations are therefore applicable to the evaluation of the pressure loss in the RMWR core without any verification. The other is the difference of the configuration between the multi-rod bundle and the circular tube. In the RMWR core the difference of flow area among each sub-channel is large. The objective of this study is to investigate whether the general evaluation methods proposed by Martinelli & Nelson[3] and Hancox & Nicoll[4] can apply to the prediction of the friction loss in the two-phase flow at the tight-lattice configuration. As the experimental data with the triangular tight-lattice configuration, we could use the results of 4×5 rod bundle experiments at the Bettis Atomic Power Laboratory. In addition, the pressure losses in two types of seven-rod bundles were measured under the tight-lattice configuration and the operating condition of the RMWR core at the JAERI.

2. Friction Loss at Tight-Lattice Configuration

The RMWR core has the triangular tight-lattice configuration to attain the high conversion ratio. At the configuration a pressure gradient becomes larger because of a short distance between each rod, in other words, because of a small hydraulic diameter. The friction loss in a two-phase flow, in general, is evaluated using correlations for a two-phase multiplier, proposed by Martinelli & Nelson[3], Hancox & Nicoll[4], Lockhart & Martinelli[5] and Chisholm[6]. However, since almost the correlations were developed based on the experiments for circular tubes with a larger diameter than 5 mm, it is not obvious

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whether these correlations can apply to the calculation of the friction loss at the tight-lattice configuration with the small hydraulic diameter. Mishima and Hibiki[7] investigated the two-phase pressure loss in small diameter vertical tubes under the atmospheric pressure condition and confirmed that the Chisholm's parameter C decreases with the hydraulic diameter less than about 3 mm.

An evaluation of a pressure loss at a spacer is important to enhance the prediction accuracy on a pressure loss in multi-rod fuel bundles. However, since the spacers have a lot of shapes such as honeycomb-type, ring-type, wire-wrapped-type and so on, it is difficult to predict the spacer loss without empirical correlations. A simple evaluation method for the spacer loss is therefore useful for the design of the reactor cores with the multi-rod bundles. Rehme[8] investigated the pressure loss at the several types of spacers experimentally. He indicated that the loss coefficient for the grid-type spacers is dependent on the relative plugging of a flow cross section, whereas the pressure loss coefficient for the wire-wrapped rod bundle is dependent on the lead of wire wraps. Yano, et al.[9] also pointed out that the local pressure loss at the spacer increases with the spacer thickness. Okubo, et al.[10] measured the spacer loss in the tight-lattice rod bundles and confirmed that the spacer loss coefficient depends also on a length of a grid-type spacer. As shown in Fig. 1, they suggested that the pressure loss at the space ΔP_{SP} can be expressed as a sum of the loss due to the contraction ΔP_C, the friction loss ΔP_F and the loss due to the expansion ΔP_E as follows:

$$\Delta P_{SP} = \Delta P_C + \Delta P_F + \Delta P_E \tag{1}$$

From this concept, the coefficient of the pressure loss at the spacer K is given by

$$K = \left(\zeta_C + f\frac{L}{D_2} + \zeta_E\right)\left(\frac{A_2}{A_1}\right)^{-2} \tag{2}$$

Here, the subscript 1 denotes the normal flow section and 2 the flow section at the spacer, A the flow area, L the length of a spacer, D the hydraulic diameter, f the friction loss coefficient, ζ_C the coefficient of the pressure loss due to the contraction, ζ_E the coefficient of the pressure loss due to the expansion. Results of K calculated by Eq. (2) are shown in Fig. 2. In this figure, the Reynolds number Re $(= V_1 D_1/\upsilon)$ is 20 000, the hydraulic diameter at the spacer D_2 is 2.0 mm and the coefficient of the friction loss f is calculated by the Blasius equation. Here, V is the velocity, υ the kinetic viscosity. Figure 2 displays that K is strongly dependent on the ratio of flow areas A_2/A_1 and the length of a spacer, as described by Rehme[8] and Okubo, et al.[10] When A_2/A_1 is between 0.7 and 0.8, K ranges from 0.5 to 1.0. The K value is usually adopted in the pressure loss calculation of the reactor core with multi-rod fuel bundles. Figure 3 shows the dependence of K on Re. K decreases with increasing Re. This is also confirmed by Rehme[8], Okubo, et al.[10] and LeTourneau, et al.[11] Consequently, the pressure loss coefficient at the spacer is given by the evaluation method based on Eq. (2) easily.

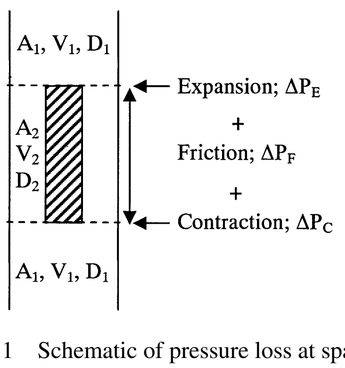


Fig. 1 Schematic of pressure loss at spacer

In order to evaluate the applicability of the Martinelli-Nelson's and Hancox's correlations, the calculated results by each correlation was compared with several experimented results. Both the correlations are often applied for the calculations in the vapor-water two-phase flow under high pressure condition. As the experimental data at the triangular tight-lattice configuration, the results of 4×5 rod bundle experiments at the Bettis Atomic Power Laboratory[11] were used.

Figure 4 shows the experimental configuration. Two kinds of ratios of a pitch to diameter with the triangular tight-lattice configuration were provided; 1.22 and 1.36.

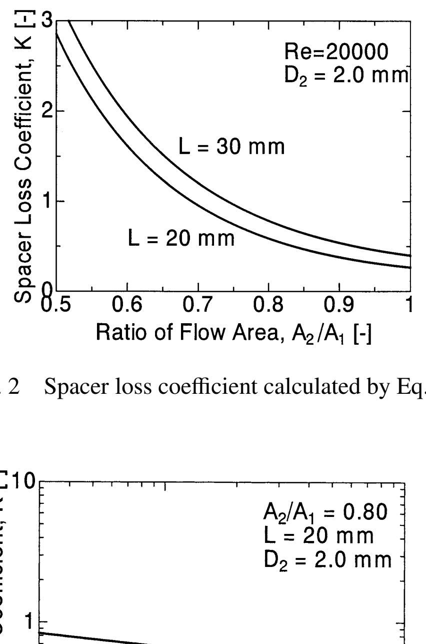


Fig. 2 Spacer loss coefficient calculated by Eq. (2)

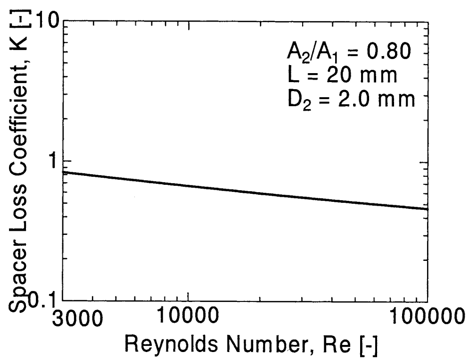


Fig. 3 Dependence of spacer loss coefficient on Reynolds number

The hydraulic diameters D_e of the two configurations were 3.94 and 6.02 mm, respectively. The experiments were conducted under the conditions of pressure $P = 2.8 - 13.8$ MPa and mass velocity $G = 70 - 5\,400$ kg/m^{2}s. Only the experimental data with a uniform heat flux distribution and a boiling length beyond 30% of the heating length were selected and compared with calculated results by the Martinelli-Nelson's and Hancox's correlations. Both calculations by the homogeneous model and the drift-flux model[12] were performed. Each model can evaluate axial distributions of void fraction α and velocities V_v & V_l. Here, the subscripts v and l denote the vapor and liquid, respectively. The distribution parameter C_0 and the drift velocity V_{gj} in the drift-flux model were calculated by the Ishii's correlation[13]. For the calculation of the pressure loss at the spacer in the two-phase flow ΔP_{SP_TP}, several models were proposed[9],[14]. In this study, ΔP_{SP_TP} was evaluated by

$$\Delta P_{SP\_TP} = K\frac{1}{2}\rho V_l^2 \frac{\rho_l}{\rho_m} \tag{3}$$

Here, ρ_m is the homogeneous mixture density. The coefficient of the pressure loss at the spacer K was evaluated based on Eq. (2).

The experimental and calculated results by the

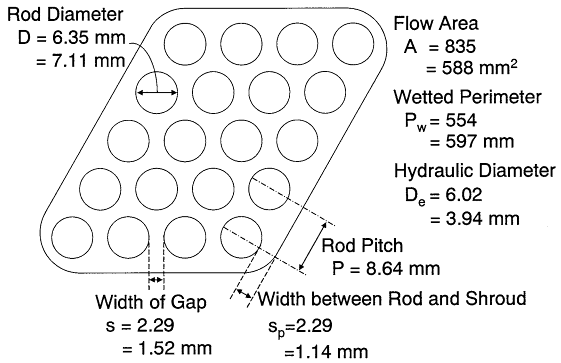
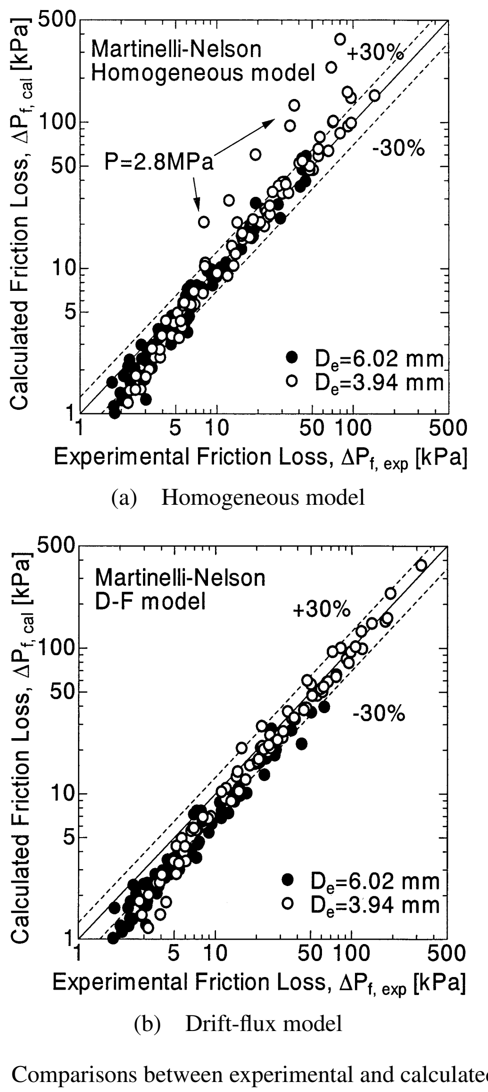


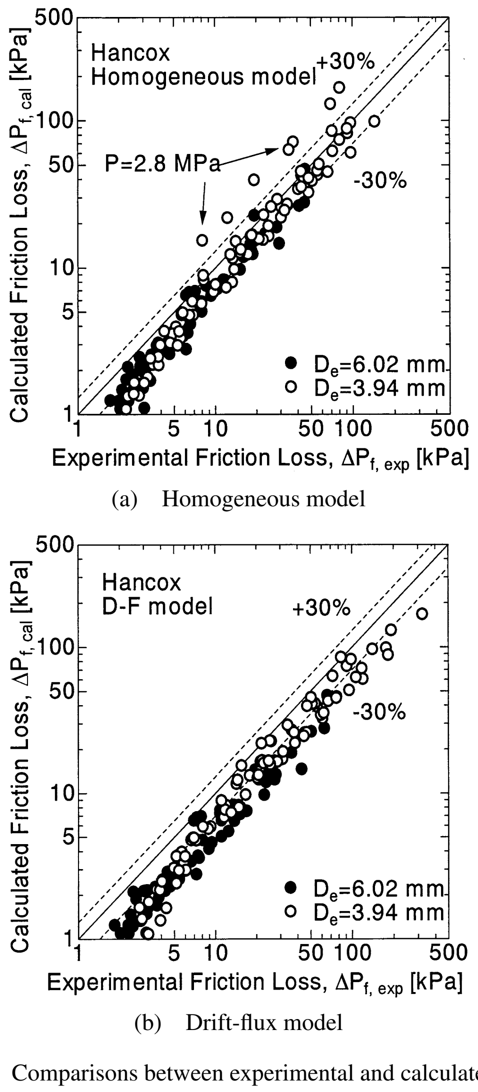
Fig. 4 4×5 rod bundle configuration at Bettis Atomic Power Laboratory[11]



(a) Homogeneous model

(b) Drift-flux model

Fig. 5 Comparisons between experimental and calculated friction losses by Martinelli-Nelson's correlation.



(a) Homogeneous model

(b) Drift-flux model

Fig. 6 Comparisons between experimental and calculated friction losses by Hancox's correlation.

Martinelli-Nelson's and Hancox's correlations are shown in Figs. 5 and 6, respectively. The calculated results based on the homogeneous model, as can be seen in Figs. 5 (a) and 6 (a), are larger than those based on the drift-flux model in Figs. 5 (b) and 6 (b), particularly in case of a low pressure condition; $P = 2.8$ MPa. This is because the homogeneous model overestimates a liquid velocity in the two-phase flow. All figures show that there is no difference between results of $D_e = 6.02$ mm and $D_e = 3.94$ mm.

The comparison between Figs. 5 (b) and 6 (b) clearly shows that the Hancox's correlation evaluates the friction loss in a two-phase flow lower than the Martinelli-Nelson's correlation. Furthermore, the Martinelli-Nelson's correlation can predict the pressure loss within the error less than ±30%, except for the pressure loss less than about 10 kPa, i.e. the low flow rate condition ($G < 1000$ kg/m^{2}s).

The another experiments by the Bettis Atomic Power Laboratory[15] were available for the database of the pressure loss at the triangular tight-lattice configuration with the smaller hydraulic diameter. Figure 7 shows a horizontal layout of the 4×5 rod bundle configuration. The spacing between each adjacent rod was maintained by warts.

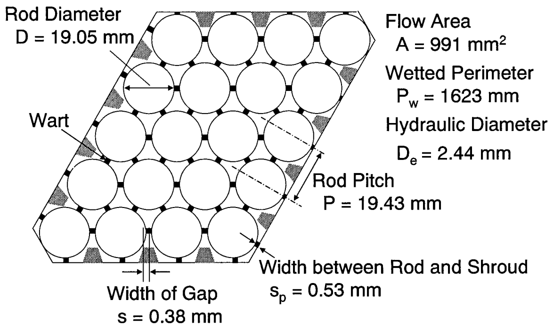


Fig. 7 4×5 rod bundle configuration at Bettis Atomic Power Laboratory[15]

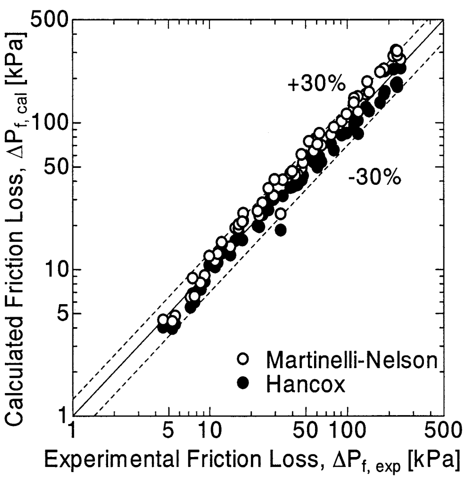


Fig. 8 Comparisons between experimental and calculated friction losses for the configuration in Fig. 7

The hydraulic diameter D_e of the rod bundle configuration was 2.44 mm. The measurements of the pressure loss were conducted under the conditions of pressure $P = 8.3 - 13.8$ MPa and mass velocity $G = 340 - 4000$ kg/m^{2}s. Figure 8 shows the comparisons between the experimented and calculated results by the Martinelli-Nelson's and Hancox's correlations based on the drift-flux model. In this configuration the Martinelli-Nelson's correlation overestimates the friction loss whereas the Hancox's correlation can give good calculated values.

The experiments referred to above were conducted at the configurations with the different rod diameters and widths of gap from those in the RMWR core. Then the pressure losses in two types of seven-rod bundles with the triangular tight-lattice configurations were measured by the JAERI. The experimental configurations are shown in Figs. 9 and 10. Each seven-rod bundle consists of a

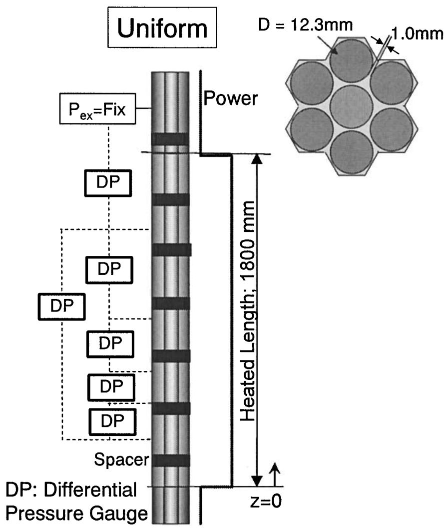


Fig. 9 7-rod bundle geometry with a uniform axial power distribution

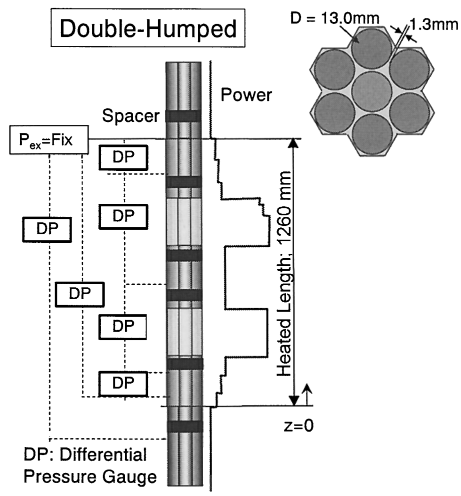


Fig. 10 7-rod bundle geometry with a double-humped axial power distribution

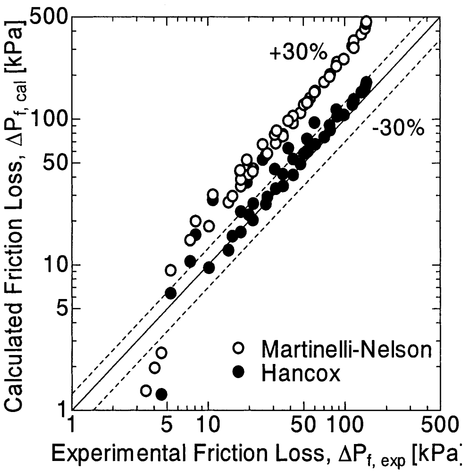


Fig. 11 Comparisons between experimental and calculated friction losses for the configuration in Fig. 9

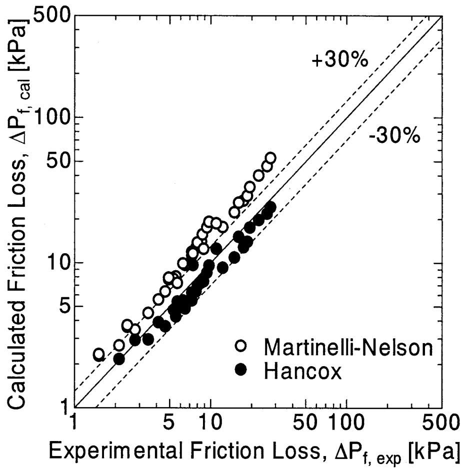


Fig. 12 Comparisons between experimental and calculated friction losses for the configuration in Fig. 10

central rod and six surrounding rods and it simulates the structure of the RMWR core. One of both rod bundles has a uniform axial power distribution and the other has a double-humped axial power distribution, which simulates the double-flat core in the RMWR. The rod diameters are 12.3 and 13.0 mm, the widths of gap are 1.0 and 1.3 mm, and the hydraulic diameters are 2.36 and 2.86 mm, respectively. The experiments were conducted under the conditions of $P = 7.2$ MPa, $G = 400 - 2\,500$ kg/m^{2}s and the initial temperature $T_{in} = 556$ K. A local peaking factor of center rod was set on 1.30.

The comparisons between experiments and calculations at the two test configurations are shown in Figs. 11 and 12. In the calculations the coefficient of the pressure loss at the spacer in the two-phase flow was calculated by Eqs. (2) and (3), and the velocities and void fraction were evaluated based on the drift-flux model[(12)] and the Ishii's correlation[(13)]. The results obtained by Hancox's correlation could derive better predictions on the friction loss

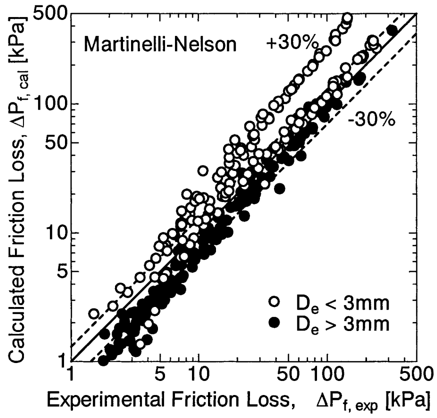


Fig. 13 Comparisons between experimental and calculated friction losses for all data based on Martinelli-Nelson's correlation

than Martinelli-Nelson's.

All results were summarized in Fig. 13. From this figure, in case of the hydraulic diameter less than about 3 mm, Martinelli-Nelson's correlation tends to overestimate the friction loss. One of the reasons is the effect of the small hydraulic diameter on the two-phase multiplier and the distribution parameter in the drift-flux model. Mishima and Hibiki[(7)] investigated the friction loss and void fraction on an air-water two-phase flow in capillary tubes with inner diameters in the range from 1 to 4 mm. They displayed that the two-phase multiplier quickly decreases and the distribution parameter increases in the hydraulic diameter less than about 3 mm.

As the other reason, the friction loss in a single-phase flow at the tight-lattice configuration is considered. Rehme[(16)] carried out systematic investigations on the friction loss in a single-phase flow on about 60 types of rod bundles. He pointed out that the coefficient of the pressure loss decreases to approximately 60% of the circular tube with decreasing the ratio of a pitch to diameter in the bundles. This is because fluid trends to flow through the channel with the larger flow area and that the local turbulence intensity is strong in the narrow channel at the tight-lattice configuration.

3. Conclusion

In order to investigate the applicability of the evaluation methods for the friction loss at the tight-lattice configuration, calculated results by the Martinelli-Nelson's and Hancox's correlations were compared with experimental results in 4×5 rod bundles and seven-rod bundles. The friction loss in the two-phase flow becomes smaller at the tight-lattice configuration with the hydraulic diameter less than about 3 mm. This reason is due to the difference of the configuration between the multi-rod bundle and the circular tube and due to the effect of the small equivalent diameter on the two-phase multiplier and the distribution parameter in the drift-flux model.

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