Proceedings of the Korean Nuclear Society Spring Meeting
Seoul, Korea, May, 1998

Single and Two-Phase Flow Pressure Drop for CANFLEX Bundle

Joo Hwan PARK, Ji Su JUN, Ho Chun SUK,
Korea Atomic Energy Research Institute

G.R. Dimmick, D.E. Bullock,
Atomic Energy of Canada Limited

ABSTRACT

Friction factor and two-phase flow frictional multiplier for a CANFLEX bundle are newly developed and presented in this paper. CANFLEX as a 43-element fuel bundle has been developed jointly by AECL/KAERI to provide greater operational flexibility for CANDU reactor operators and designers. Friction factor and two-phase flow frictional multiplier have been developed by using the experimental data of pressure drops obtained from two series of Freon-134a (R-134a) CHF tests with a string of simulated CANFLEX bundles in a single phase and a two-phase flow conditions. The friction factor for a CANFLEX bundle is found to be about 20 % higher than that of Blasius for a smooth circular pipe. The pressure drop predicted by using the new correlations of friction factor and two-phase frictional multiplier are well agreed with the experimental pressure drop data of CANFLEX bundle within ± 5 % error.

1. INTRODUCTION

Most friction factors and two-phase frictional multipliers have been developed for circular tubes. These can not be applied directly for the complicated geometry of nuclear fuel bundles. The friction factor or two-phase frictional multiplier for a new geometric bundle as well as for an LWR fuel assembly having a uniform pitch-to-diameter (P/D) ratio would be modified with a correction factor based on the pressure-drop experiment corresponding to the specific bundle or assembly. A CANDU fuel bundle has 37- or 43-elements, end plates and appendages such as spacer pads, bearing pads, endplates, and buttons to configure the geometry. The appendages enhance the heat transfer or CHF. The CANDU fuel elements are arranged to have a non-uniform P/D ratio. Song et al.[1] experimentally showed that the friction factor for the CANDU 37-element bundle was 20 % lower than that of the smooth tube for the Blasius equation. Therefore, either a correction factor to a Blasius type equation or new correlation for the friction factor should be found in order to apply to a complex geometry of CANDU or LWR fuel assemblies.

This paper presents new friction factor and two-phase frictional multiplier equation for a CANFLEX bundle, based on the experiments of the single- and two-phase pressure drops in R-134a tests with a CANFLEX bundle. The friction factor for the CANFLEX bundle without buttons was compared with Blasius equation. Also the two-phase pressure drop predicted by using new two-phase frictional multiplier are compared with experimental data for the CANFLEX bundle

2. TEST SECTION AND EXPERIMENTS

The R-134a CHF and pressure drop experiments for the CANFLEX bundle have performed in MR-3a Test Loop at AECL(Atomic Energy Canada Limited)-CRL(Chalk -River Laboratory). The pressure drop experiments are distinguished into two types as one for the 12 buttoned CANFLEX bundle string and the other for the 12 unbuttoned CANFLEX bundle string. In a CANDU-6 fuel channel, there are eleven junction planes. One fuel bundle in a junction could be rotated with respect to the adjacent bundle. The junction pressure drop and so the string pressure drop would be different and depended on the aligned angle of adjacent bundles in the junction. In present experiments, however, a string of twelve simulated test bundles was fully aligned because of direct heating the fuel rods. The heating rods was made of Inconel-718, and have uniform axial heat flux profile, but non-uniform radial heat flux profile in the bundle string. The coolant is non-toxic R-134a as a modelling fluid and flows upward. The bundle was eccentrically mounted by lift spring in a vertical flow tube to simulate the horizontal flow geometry existing in a CANDU reactor [2]. Pressure drops are measured for each flow condition by setting six pressure taps in every two bundles in the channel.

3. TEST RESULTS

There are two parts of pressure drop data for CANFLEX bundles without buttons and with buttons. Although the axial flow properties is changing by pressure drop along the channel regardless of heating the rod, the averaged flow condition in each axial step is used for the evaluation of pressure drop in each axial step. The change of flow properties in the heating and unheating conditions is considered with the pressure distribution along the fuel channel. Since the channel entrance and exit sections partly have no bundles, the first and last nodes corresponding the entrance and exit sections respectively are excluded for the pressure drop evaluation of two bundles, but included for evaluation of the channel pressure drop.

3.1 Friction Factor and Single Phase Pressure Drop

CANDU-6 reactor has 380 horizontal pressure tubes. Each horizontal pressure tube is loaded with twelve bundles. The pressure drop in a channel is generated by skin friction, form loss caused by the appendages on fuel bundle and bundle-to-bundle junction. It can be expressed as follows:

$$\Delta P_{channel} = \Delta P_{fric} + \Delta P_{app} + \Delta P_{jun} \tag{1}$$

where ΔP_{fric}, ΔP_{app} and ΔP_{jun} are frictional, form loss and junction pressure drops, respectively. The pressure drop by appendages is consisted of those for spacer planes, ΔP_{sp}, bearing-pad planes, ΔP_{bp}, and button planes, ΔP_{button}. Hence, ΔP_{app} is

$$\Delta P_{app} = \Delta P_{sp} + \Delta P_{bp} + \Delta P_{button} \tag{2}$$

Therefore, the total pressure drop for one channel can be

$$\Delta P_{channel} = \left(f\frac{L}{D_e} + K_{app} + 11K_{jun}\right)\frac{\rho v^2}{2} \tag{3}$$

where $K_{app} = 12K_{sp} + 24K_{bp} + 24K_{button}$. K represents the form loss coefficients for each appendage obtained from the experiments[3]. Two types of the CANFLEX bundles tested in this work have the same dimensions and geometries except the existence of buttons, that is, K_{button}.

The friction factor for heated rods is calculated to get friction factor for isothermal conditions by using the Kays and Crawford's correction factor[4]. Since the fuel channel of CANDU reactor consists of the heated fuel elements and unheated pressure tube, the friction factor is required a correction for the unheated wall. The friction factor, f_o, for the isothermal condition is obtained and correlated by using single phase pressure drop data for a CANFLEX bundle:

$$f_o = 0.140 Re^{-0.165} \tag{4}$$

where $Re = \frac{\rho v D_e}{\mu}$, D_e = hydraulic diameter of a bundle

Figure 1 shows the comparison of the predicted friction factor with experimental data for CANFLEX bundle without button planes, and the RMS discrepancy between them is 5.7 %. It is found that the friction factor for the CANFLEX bundle is about 20 % higher than that of Blasius equation for a smooth circular pipe.

The comparison of the predicted channel pressure drop with the experimental one is was shown in Figure 2 and the RMS discrepancy between them for unbuttoned and buttoned CANFLEX bundles are 1.8 % and 1.7 %, respectively.

3.2 Two-Phase Frictional Multiplier and Pressure Drop

Two-phase pressure drop can be calculated by following equation:

$$\Delta P_{2\phi} = \phi^2 \Delta P_{1\phi,fric} + \Delta P_{2\phi,app} + \Delta P_{2\phi,junction} \tag{5}$$

where $\Delta P_{1\phi,fric}$ is the frictional pressure drop under single phase flow condition, $\Delta P_{2\phi,app}$ is obtained by using the form loss coefficients for the appendages such as spacer planes, bearing-pads and button planes and $\Delta P_{2\phi,junction}$ is obtained by using the loss coefficient for the bundle-to-bundle junction. Therefore, two-phase frictional multiplier, ϕ^2 is

$$\phi^2 = \frac{\Delta P_{2\phi} - \Delta P_{2\phi,app} - \Delta P_{2\phi,junction}}{\Delta P_{1\phi,fric}} \tag{6}$$

Two-phase frictional multiplier, ϕ^2 may be expressed by fluid density ratio in case of homogeneous two-phase flow and ϕ^2 versus density ratio (ρ_f/ρ) from experiments are plotted in the Figure 3. While experimental ϕ^2's are increasing as increase of density ratio, those are different from the flow conditions as shown in Figure 3.

In general, two-phase frictional multiplier, ϕ^2 is known to be a function of local quality and void fraction as well as density ratio [5,6,7]. Otherwise, ϕ^2 may be modelled with two-phase viscosity, which has large uncertainties. Baroczy[8] or Chisholm[9] recommended two-phase frictional multiplier by introducing the influence of mass velocity on ϕ^2. The method proposed by Baroczy[8] was tested against data from a wide range of system including both liquid metals and refrigerants, in which the calculated values are well agreed with the measured values. These results represents that two-phase frictional multiplier may be functions of mass velocity as well as of local quality and void fraction. Since these correlations have been developed with basis of the circular tubes, it is difficult to apply to a bundle geometry without correction. With the experimental data for the CANFLEX bundle, hence, we performed the sensitivity study for the influence of flow parameters on the two-phase frictional multiplier. It results that the most dominant parameters are density ratio, local quality, void fraction and dimensionless superficial liquid velocity. Finally, we found ϕ^2 as follows:

$$\phi^2 = a_1\left(\frac{\rho_f}{\rho}\right)^{a_2}\frac{(1-x)^{a_3}}{(1-\alpha)^{a_4}}j_f^{*a_5} \qquad (7)$$

where ρ_f=saturated density, ρ=local density, x=flow quality, α=void fraction, j_f^*= dimensionless superficial liquid velocity and a_1, a_2, a_3, a_4, and a_5 are coefficients which were obtained from regression analysis.

Generally, superficial momentum flux of liquid, $\rho_f j_f^2$ and superficial momentum flux of vapor, $\rho_g j_g^2$ are different each other according to the flow patterns. Regardless of flow direction, the flow may have a transition from bubbly or slug/churn flow to annular flow according to changing of $\rho_g j_g^2$ and $\rho_f j_f^2$[10]. The fact that the above equation (7), ϕ^2 is influenced by j_f^* represents indirectly the existence of flow transition from bubbly or slug/churn flow to annular flow in a channel with CANFLEX bundle in the experiments. It indicates that two-phase frictional multiplier for the flow conditions of CANDU reactor should be modelled in consideration of two-phase flow pattern such as slug/churn or annular flow regimes at the CHF occurrence. It can be also seen in Figure 3 in which the influence of mass velocity on ϕ^2 is strong for high mass velocity, but weak for low mass velocity.

In order to find ϕ^2 by the equation (7), flow quality and void fraction were calculated by Levy's subcooled void fraction model[11] and homogeneous model, respectively. Two-phase frictional multiplier, ϕ^2 is found from experimental data for several flow conditions. The channel pressure drops were calculated for unbuttoned CANFLEX bundle by using the present ϕ^2 model and, as shown in Figure 4, compared to pressure drop calculated by the homogeneous ϕ^2 model(ρ_f/ρ). It shows that homogeneous ϕ^2 model over-predicted with respect to the measurement two-phase pressure drop. But, all the single and two-phase pressure drop data predicted by present model for buttoned CANFLEX bundle as well as for un-buttoned CANFLEX bundle are agreed well with the measured pressure drops and the range of their discrepancy is within ±5 % as shown in Figure 5 and the RMS discrepancy between them for buttoned and unbuttoned CANFLEX bundle are 4.5 % and 3.3 %, respectively.

6. CONCLUSION

Friction factor and two-phase frictional multiplier are modelled by using R-134a experimental data for the single and two-phase pressure drops in the range of Reynolds number, $5.5\times10^4 \sim 3.0\times10^5$. From the present study with comparison of the present models with experimental data, some conclusions are as follows:

- The single phase friction factor modelled for a CANFLEX bundle is 20 % higher than that of Blasius. The isothermal friction factor for CANFLEX bundle is found as $f_o = 0.140Re^{-0.165}$
- The single phase pressure drops for a channel were predicted by using the present model. The results show that the RMS discrepancy between them for buttoned and unbuttoned CANFLEX bundles under the single-phase flow conditions are 1.7 % and 1.8 %, respectively.

- The two-phase frictional multiplier, ϕ^2 was modelled by using two-phase pressure drop data for a CANFLEX bundle. It was found that ϕ^2 is strongly depended on dimensionless superficial liquid velocity as well as density ratio, flow quality and void fraction.
- The two-phase pressure drop predicted by using the generalized ϕ^2 model is compared with experimental data for the CANFLEX bundles in a CANDU-6 channel. The discrepancy between them is 4.5 % for unbuttoned CANFLEX bundle and 3.4 % for buttoned CANFLEX bundle.

REFERENCES

[1] C.H. Song, et al., Study on the Characteristics of Pressure Drop and Subchannel Velocity Distribution for the Wolsong-type Fuel Bundle, Proceedings of the KSME Spring Meeting, July 1987.

[2] J.H. Park, et al., The Button Effect of CANFLEX Bundle on the Critical Heat Flux and Critical Channel Power, Proceeding of the KNS Autumn Mtg. Taegu, Korea Oct. 1997, pp. 528-533.

[3] A. Hameed, Single-phase Pressure Drop Measurements on CANFLEX-Mk.4 Bundles in Freon; Phase II and III Misaligned Bundles in Uncrept and Crept Channels, FFC-FCT-061/CANFLEX-109, AECL/KAERI, Dec. 1997.

[4] W.M. Kays and M.E. Crawford, Convective Heat and Mass Transfer, 2nd Ed. McGraw-Hill, New York, 1980, Ch. 14, p. 280.

[5] S.Y. Armand, Axial Distribution of Bulk Temperature and Void Fraction in a Heated Channel with Inlet Subcooling, J. of Heat Transfer, pp. 595-609, Nov. 1970.

[6] W.A. Messena, Steam-Water Pressure Drop and Critical Discharge Flow - A Digital Computer Program, HW-65706, Hanford Atomic Products Operation, Richland, Washington, June, 1960.

[7] R.C. Lockhart and R.C. Martinelli, Proposed Correlation of Data for Isothermal Two-phase Two-component Flow in Pipes, Chem. Eng. Prog., Vol. 45, No. 39, 1949.

[8] C.J. Baroczy, A Systematic Correlation for Two-phase Pressure Drop, AIChE reprint 37 presented at 8th Nat'l Heat Transfer Conference, Los Angeles, Aug., 1965.

[9] D. Chishlom, The Influence of Mass Velocity on Friction Pressure Gradients During Stream-Water Flow, Paper 35 presented at 1968 Thermodynamics and Fluid Mechanics Convention, Institute of Mechanical Engineers (Bristol), March, 1968.

[10] J.G. Collier, Convective Boiling and Condensation, McGraw-Hill International Book Company, Second Ed., 1972.

[11] S. Levy, Forced Convection Subcooled Boiling-Prediction of Vapor Volumetric Fraction, GEAP-5157, General Electric Co., Atomic Power Equipment Dept., San Jose, California, April 1966.

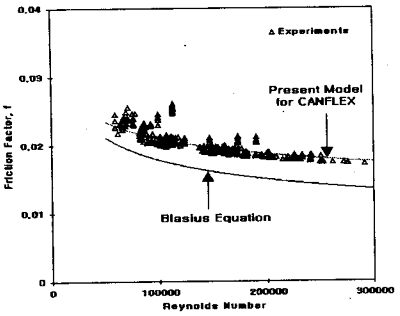

Fig. 1. Comparison of Friction Factors for CANFLEX bundle and Blasius Equation

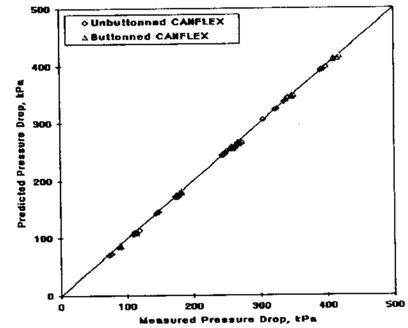

Fig. 2. Comparison of Measured and Predicted Channel Pressure Drops Under Single Phase Flow Condition

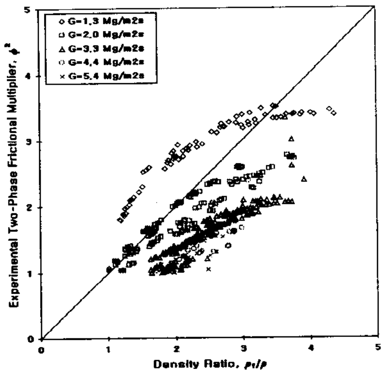

Fig. 3. Experimental Two-Phase Multipliers for Several Mass Flux Conditions According to Density Ratio Change

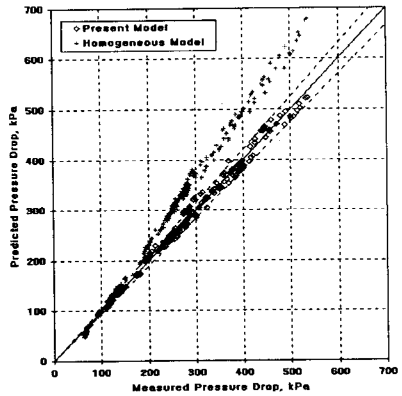

Fig. 4. Comparison of Channel Pressure Drops of unbuttonned CANFLEX Predicted by Homogeneous and Present Two-phase Multiplier Models

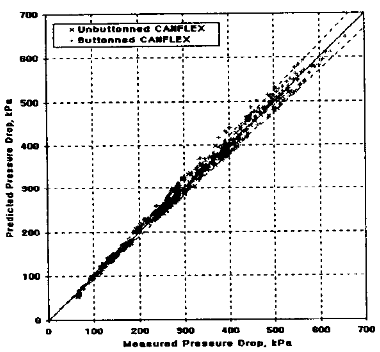

Fig. 5. Comparison of Measured and Predicted Channel Pressure Drop for Buttoned and Un-buttoned CANFLEX Bundle