Paper No: G209

18th National & 7th ISHMT-ASME
Heat and Mass Transfer Conference
January 4 - 6, 2006
IIT Guwahati, India

Experimental Investigation of Pressure Drops Across Various Components of Fuel Bundle in Two-Phase Flow

M. R. Gartia
Reactor Engineering Division
Bhabha Atomic Research Centre, Trombay
Mumbai-400 085
redths@apsara.barc.ernet.in

D. S. Pilkhwal
Reactor Engineering Division
Bhabha Atomic Research Centre, Trombay
Mumbai-400 085
pilkhwal@apsara.barc.ernet.in

P. K. Vijayan[1]
Reactor Engineering Division
Bhabha Atomic Research Centre, Trombay
Mumbai-400 085
vijayanp@apsara.barc.ernet.in

D. Saha
Reactor Engineering Division
Bhabha Atomic Research Centre, Trombay
Mumbai-400 085
dsaha@apsara.barc.ernet.in

Abstract

Single-phase (water) and two-phase (air-water) experiments were carried out for the measurement of pressure drops across various components of a prototype 54-rod fuel bundle of AHWR. From the measured values of pressure drops, the friction factor for fuel bundle and the loss coefficients for the tie plates and spacers were estimated. The single-phase experimental data were compared with different existing correlations. Correlations have been proposed based on the data generated with the air-water mixture which can be used for prediction of pressure drops across fuel channel (with 54 rod fuel bundle) of AHWR under operating conditions with appropriate correction factor for steam-water flow.

Nomenclature

General symbols

c : constant in Chi-sq distribution
C : constant in Lockhart-Martinelli correlation
D : diameter, m
f : friction factor, dimensionless
g : acceleration due to gravity, m/s^2
K : loss coefficient, dimensionless
L : length, m
n : total number of data
P : pressure, N/m^2
Re : Reynolds number, dimensionless
v : specific volume, m^3/kg
V : velocity, m/s
x : quality, dimensionless
y : data points in the sample (Here it is experimental 'f ')
Z : elevation, m
Δ : difference
μ : dynamic viscosity, N s/m^2
ρ : density, kg/m^3
σ : standard deviation
Φ^2_{LO} : two-phase friction multiplier
χ : Martinelli parameter

Subscripts

a, b : point, location
fb : fuel bundle
btp : bottom tie plate assembly
c : cold (corresponds to impulse line temperature)
cc : coolant channel
g : gas (air)
i : individual data point
l : liquid
loss : loss
LO : liquid only
m : measured
sp : spacer
tot : total
ttp : top tie plate assembly
tp : two-phase

1. Introduction

Pressure drop is an important parameter for design and analysis of many systems and components. In natural circulation systems, the mass flux and the driving heads are low compared to those of forced circulation systems. Therefore, it is necessary to determine the pressure loss components very accurately. The Advanced Heavy Water Reactor

[1] Corresponding author.

(AHWR) is a natural circulation based reactor and it uses 54-rod fuel bundles. The various components of the fuel bundle are the fuel rods, spacers (to maintain the interspacing between fuel rods), and the tie plates (to hold the fuel pins together at the ends). Due to the complex geometry of these components, experimental investigations are often necessary to determine the pressure drop under single and two-phase flow conditions. Experiments were carried out to measure the pressure drops across these components with single-phase (water) and two-phase (air-water). The data were analysed. A comparative study of the existing correlations was also done. Using Least-square non-linear regression analysis correlations have been proposed based on air-water mixture experimental data, which can be extended for steam-water flow case with appropriate correction factor.

This paper describes the experimental set up, data generated, method of analysis and the correlations developed in greater details.

2. Experimental Set-up and Instrumentation

2.1 Description of the Test Facility

Figure 1 shows a schematic diagram of the low pressure flow test facility (FTF). The FTF has the flexibility to connect any test section between the flanges of the suction and discharge headers of the pumps. Two centrifugal pumps in parallel (only one is shown in Fig. 1), with the flexibility to operate either one or both are provided to circulate the flow through the loop. The test section flow can be adjusted to the required value with the help of control valves at the inlet and outlet. Demineralised water was used as the working fluid. Because of closed loop operation, the water gets heated up due to the energy input by the pumps. A cooler was provided to maintain the loop temperature at the required value. Eight differential pressure transmitters (DPTs) were used to measure the pressure drop across the different components of the fuel bundle as shown in Fig. 2. A calibrated orifice meter was used to measure the water flow through the test section. Compressed air was injected at the bottom of the vertical test section. Three parallel rotameters of different ranges were connected to common headers in compressed line to measure the air flow rate. The air flow rate was varied with the help of valves put at the inlet or outlet of these rotameters. The maximum error in water flow rate and pressure drop measurement were $\pm 2\%$ and $\pm 1\%$ respectively. The error in air flow rate measurement was of the order of $\pm 2\%$. The locations of the pressure taps and the instruments used were decided based on the requirements of the particular test.

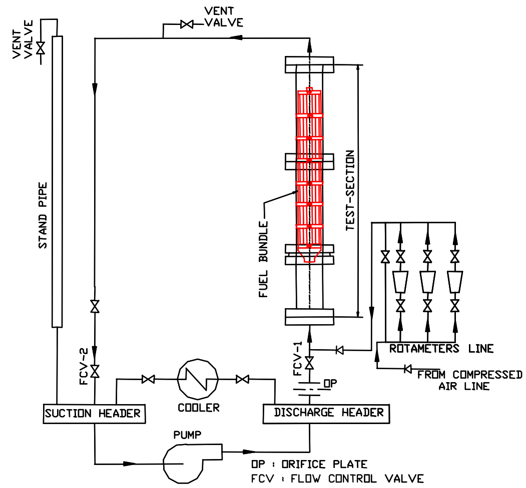

Fig. 1: Schematic of the flow test facility

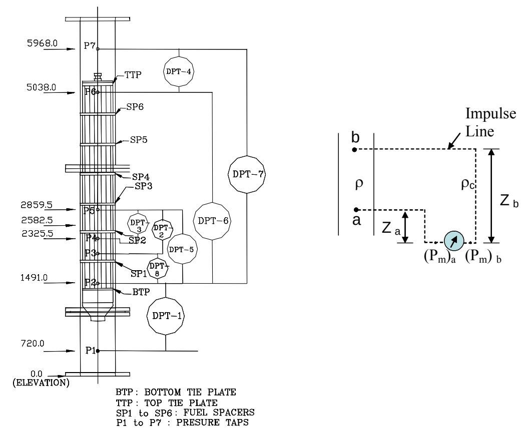

Fig. 2: Test Section and Instrumentation for Fuel Bundle Pressure Drop Experiment.

2.2 Description of the Test Bundles

The geometric detail of 54-rod bundle is shown in Table 1. Figure 3a shows the fuel assembly with cross-sectional view. The spacers in a fuel assembly and its

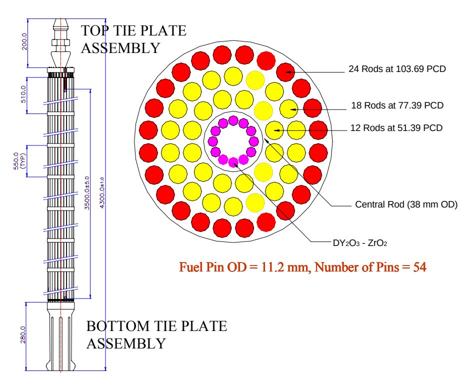

Fig. 3a: 54-rod Bundle Assembly and Cross-Sectional View

cross-sectional view are shown in Fig 3b. Figure 3c shows the bottom tie plate assembly and its cross-sectional view. The top tie plate assembly is shown in Fig. 3d.

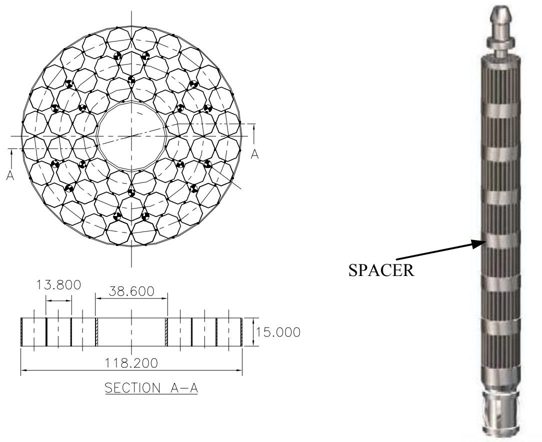

Fig. 3b: Cross-Sectional View of Spacer for 54-rod Cluster.

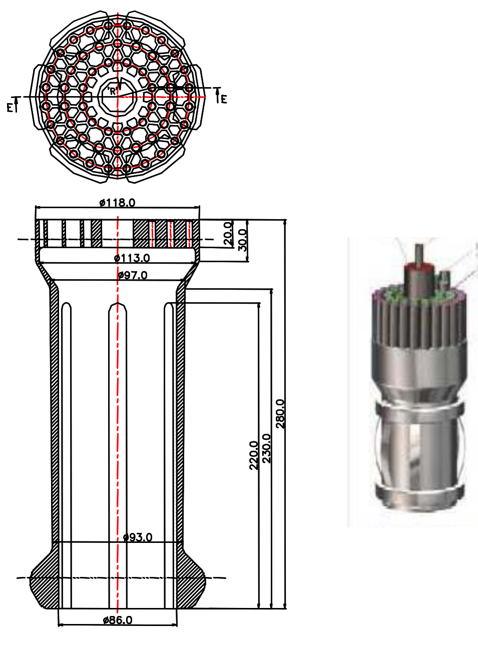

Fig. 3c: Bottom Tie Plate Assembly for 54-rod Cluster.

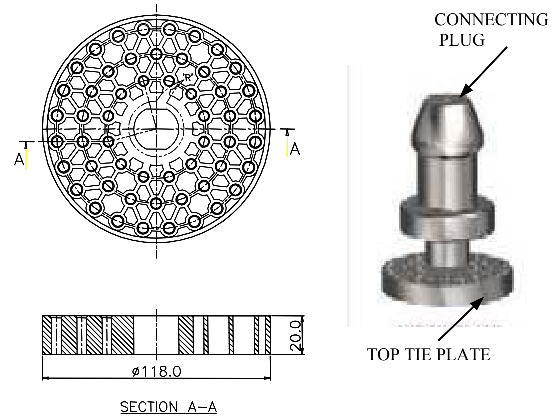

Fig. 3d: Top Tie Plate Assembly for 54-rod Cluster.

Table-1: Geometric details of 54-rod cluster.

Parameters	No./Dimensions
No. of rods	54
Rod diameter	11.2 mm
Channel I.D.	120 mm
Flow area	4855.52 mm^2
Equivalent diameter	8.105 mm
No. of spacers	6
Spacer projected area	2205.65 mm^2
% Spacer Blockage	26
Distance between two fuel spacers	540 mm
Height of Spacer	15 mm
Height of BTP assembly	280 mm
Height of TTP assembly	220 mm
Length of bundle	3.757 m

2.3 Experimental Conditions and Test Procedure

The experimental data were generated at low temperatures (35-37 ^oC) covering a air flow range of 160 lpm to 1680 lpm and water flow range of 350 lpm to 700 lpm. This corresponds to a bundle Reynolds number range of approximately 10,000 to 90,000.

Prior to conducting the experiments, the loop was filled and vented off as per standard practice at ambient temperature. The different instruments were adjusted for any zero error. The pressure drop measurements were carried out first by increasing the air flow rate from a minimum to maximum value in steps and then decreasing it back to minimum flow rate in steps and again by increasing to maximum flow rate in steps, while maintaining the water flow rate constant. The same procedure was used for the pressure drop measurements at other water flow rates.

3. Method of Analysis

Referring to Fig. 2, the pressure drop between any two points 'a' and 'b' is given by

$$P_a + \frac{\rho V_a^2}{2} + \rho g Z_a = P_b + \frac{\rho V_b^2}{2} + \rho g Z_b + \Delta P_{loss} \quad (1)$$

ΔP_{loss} is the total pressure drop. Simplifying the above equation we get;

$$P_a - P_b = \frac{\rho (V_b^2 - V_a^2)}{2} + \rho g (Z_b - Z_a) + \Delta P_{loss} \quad (2)$$

If the impulse lines are at different temperature (density, ρ_c) than that of the flowing fluid temperature then the pressure drop across 'a' and 'b' will be given by

$$P_a - P_b = \rho_c g (Z_b - Z_a) + (\Delta P_m)_{a\text{-}b} \quad (3)$$

$(\Delta P_m)_{a\text{-}b}$ is the pressure drop measured by the DPT across 'a' & 'b'. Therefore the total pressure drop across 'a' and 'b' can be given by

$$\Delta P_{loss} = (\Delta P_m)_{a\text{-}b} - (\rho - \rho_c) g (Z_b - Z_a) - \frac{\rho (V_b^2 - V_a^2)}{2} \quad (4)$$

3.1 For Free Fuel Bundle

Pressure drop across the free length of fuel bundle was measured by the difference between DPT-2 and DPT-3 using pressure taps 3, 4 & 5. The pressure loss across the fuel bundle, ΔP_{fb} can be given by;

$$\Delta P_{fb} = (\Delta P_m)_{3\text{-}4} - (\rho - \rho_c) g (Z_4 - Z_3) \quad (5)$$

The friction factor, f_{fb}, is calculated based on the fuel bundle velocity, V_{fb}, as follows;

$$f_{fb} = \frac{2D}{L} \frac{\Delta P_{fb}}{\rho V_{fb}^2} \quad (6)$$

3.2 For BTP Assembly

Pressure taps 1 & 2 were used to measure the pressure drop across the bottom tie plate assembly, with the help of DPT-1 (see Fig. 2). The pressure drop across bottom tie plate assembly, ΔP_{btp}, can be given by;

$$\Delta P_{btp} = (\Delta P_m)_{1\text{-}2} - (\rho - \rho_c) g (Z_2 - Z_1) - \frac{\rho (V_2^2 - V_1^2)}{2} - \Delta P_{cc} - (\Delta P_{fb})_{1-2} \quad (7)$$

where ΔP_{cc} is the friction pressure drop in the coolant channel portion between pressure tap 1 and to the entry to the divergent section. The ΔP_{fb} is the friction pressure drop in the fuel bundle length after the BTP to pressure tap 2.

The loss coefficient across the bottom tie plate assembly, K_{btp}, is calculated based on the fuel bundle velocity, V_{fb}, as follows;

$$K_{btp} = \frac{2.\ \Delta P_{btp}}{\rho V_{fb}^2} \quad (8)$$

3.3 For Fuel Spacer

The pressure drop across the fuel spacer, ΔP_{sp}, can be given by;

$$\Delta P_{sp} = (\Delta P_m)_{2\text{-}6} - (\rho - \rho_c) g (Z_6 - Z_2) - (\Delta P_{fb})_{2-6} \quad (9)$$

The loss coefficient across the fuel spacer, K_{sp}, is calculated as follows;

$$K_{sp} = \frac{1}{6}\left(\frac{2.\ \Delta P_{sp}}{\rho V_{fb}^2}\right) = \frac{\Delta P_{sp}}{3 \rho V_{fb}^2} \quad (10)$$

3.4 For TTP assembly

The pressure drop across the top tie plate was measured with DPT-4. The pressure drop across top tie plate assembly, ΔP_{ttp}, can be given by;

$$\Delta P_{ttp} = (\Delta P_m)_{6-7} - (\rho - \rho_c) g (z_7 - z_6) - \frac{\rho (V_7^2 - V_6^2)}{2} - \Delta P_{cc} - (\Delta P_{fb})_{6-7} \quad (11)$$

The loss coefficient across the top tie plate assembly, K_{ttp}, is calculated as follows;

$$K_{ttp} = \frac{2.\ \Delta P_{ttp}}{\rho V_{fb}^2} \quad (12)$$

3.5 For Total Pressure Drop

The total pressure drop across the fuel assembly was measured with DPT-1 and DPT-7. The total pressure drop across fuel assembly, ΔP_{tot}, can be given by;

$$\Delta P_{tot} = (\Delta P_m)_{1\text{-}7} - (\rho - \rho_c) g (Z_7 - Z_1) - \Delta P_{cc} \quad (13)$$

The total loss coefficient across the fuel assembly, K_{tot}, is calculated as follows;

$$K_{tot} = \frac{2.\Delta P_{tot}}{\rho V_{fb}^2} \quad (14)$$

3.6 Different Models Used

A list of single-phase friction factor correlations used in the present report for comparison with experimental data is given in Table 2.

4. Describing the Uncertainties in the Experimental Results

The uncertainty attributed to a measurement is an estimate of the possible residual error in that measurement, after all proposed corrections have been made. Experiments can be Single-sample or Multiple-sample. Single-sample experiments are those where each test point is run only once or at most very few times. Multiple-sample tests are those in which enough data are taken at each test point to support a sound statistical interpretation. The overall uncertainty can be described by three methods: zeroth order, first order and Nth order. The Nth order uncertainty is generally reported and hence only this is described in this paper.

The **Nth order uncertainty** is calculated as the RSS (root-sum-square) combination of the first-order uncertainty $\delta X_{i,1}$ with the root-sum-square combination of fixed errors from every source.

$$\delta X_{i,N} = \left\{ \left(\delta X_{i,1} \right)^2 + \left(RSS\, \delta X_{i,fixed} \right)^2 \right\}^{1/2} \quad (15)$$

where $\delta X_{i,1}$ is the first-order uncertainty in X_i, and $RSS\, \delta X_{i,fixed}$ is the root-sum-square of all fixed error contributions from every level of error source.

First order uncertainty of a measurement describes the scatter that would be expected in a set of observations using the given apparatus and instrumentation system, while the observed process is running. The first order uncertainty can be calculated by using the following steps:

Step-1: Choose a confidence interval Γ (95%, 99% or like)
Step-2: Determine solution 'c_1' and 'c_2' of the equations

$$F(c_1) = \frac{1}{2}(1-\Gamma)\ ;\ F(c_2) = \frac{1}{2}(1+\Gamma)$$

From the Chi-square distribution table, corresponding to $(n-1)$ degrees of freedom and $F(c_1), F(c_2)$ values, find the values of c_1 and c_2. Here n is the total number of data points.
Step-3: Compute $(n-1)s^2$ where s^2 is the variance of the sample.

$$s^2 = \frac{1}{n-1}\left[(y_1-\bar{y})^2 + (y_2-\bar{y})^2 + ... + (y_n-\bar{y})^2 \right]$$

Where $\bar{y} = \frac{1}{n}\left(y_1 + y_2 + ... + y_n \right)$

Step-4: Compute $k_1 = \dfrac{(n-1)s^2}{c_1}, \quad k_2 = \dfrac{(n-1)s^2}{c_2}$

Confidence interval is $CONF\left\{ k_2 \le \sigma^2 \le k_1 \right\}$

Step-5: $\left(\sigma^2 \right)_{\max} = k_1 - k_2$

Uncertainty is $\delta X_{i,1} = \pm 2\sigma_{\max}$ (16)

Based on the methodology given by Moffat [5] and as described above the estimated uncertainty in the calculated friction factor is $\pm$ 3.51%.

5. Development of Correlations

The friction factor and loss coefficient values obtained from the experimental data were used to develop the following correlations by the method of non-linear least square fit. A total of 107 and 208 data points were considered for 54-rod cluster with six spacers in single-phase and two-phase experiments respectively. The correlations developed based on present experimental data for single-phase and two-phase are tabulated in Table 3.

Table-2: Typical existing single-phase friction factor correlations selected for comparison

Reference	Geometry	Re	Correlation for the friction factor
Blasius (1913)	pipes	3,000~100,000	$f = 0.316\,\mathrm{Re}^{-0.25}$
Grillo and Marinelli (1970)	4 x 4 array	10,000~300,000	$f = 0.1626\,\mathrm{Re}^{-0.2}$
Pilkhwal et al. (2001)	52-rod bundle	7,900~79,000	$f = 0.5529\,\mathrm{Re}^{-0.30205}$
Rehme (1973)	7~37 rod bundle	2,000~250,000	$f = \frac{64}{\mathrm{Re}} + \frac{0.0816}{\mathrm{Re}^{0.133}}$
Rehme (Modified)	54-rod bundle	10,000~35,000	$f = \frac{64}{\mathrm{Re}} + \frac{0.0816}{\mathrm{Re}^{0.163}}$
Snoek and Ahmad (1984)	37-rod bundle	108,000~418,000	$f = 0.05052\,\mathrm{Re}^{-0.05719}$
Vijayan et al. (1999)	37-rod bundle	10,000~500,000	$f = 0.236\,\mathrm{Re}^{-0.17}$

5.1 Two-Phase Friction Multiplier (Φ_{LO}^2) Correlation developed for 54-rod bundle

The Φ_{LO}^2 obtained from experimental data were used to develop the following correlation by the method of non-linear least square fit.

$$\Phi_{LO}^2 = 2.451\left\{1+x\left(\frac{\rho_l}{\rho_g}-1\right)\right\}^{0.41568}\left\{1+x\left(\frac{\mu_l}{\mu_g}-1\right)\right\}^{1.0094} \tag{17}$$

5.2 Different Models Used for Comparing Φ_{LO}^2

5.2.1 Beattie (1973) Correlation

$$\Phi_{LO}^2 = \left\{1+x\left(\frac{\rho_l}{\rho_g}-1\right)\right\}^{0.8}\left\{1+x\left(\frac{\rho_l\mu_g}{\rho_g\mu_l}-1\right)\right\}^{0.2} \tag{18}$$

5.2.2 Sekoguchi (1970) Correlation

$$\Phi_{LO}^2 = 0.38\,\mathrm{Re}_{LO}^{0.1}\left[1+\frac{x}{1-x}\frac{v_g}{v_l}\right]^{0.95} \tag{19}$$

5.2.3 Lockhart-Martinelli (1949) Correlation

Martinelli parameter $\chi^2 = \left(\frac{dp}{dz}\right)_l \Big/ \left(\frac{dp}{dz}\right)_g$

$$\Phi_l^2 = 1 + C/\chi + 1/\chi^2 \qquad \chi^2 = \frac{\Phi_g^2}{\Phi_l^2}$$
$$\Phi_g^2 = 1 + C\,\chi + \chi^2 \tag{20}$$

where C=20 for turbulent flow of both phases
=12 for laminar liquid and turbulent gas flow
=10 for turbulent liquid and laminar gas flow
=5 for laminar flow of both phases

6. Results and Discussions

Figure 4a shows the variation of free fuel bundle friction factor with bundle Reynolds number for 54-rod cluster under single-phase condition. For comparison purpose, the predicted values of friction factors by different models are also plotted in this figure. It is seen that all the correlations are over predicting the friction factor under the present experimental condition.

The values predicted by the correlation given by Vijayan et al. [8] were developed for a 37-rod cluster of PHWR with split-wart type spacers. In case of the PHWR rod cluster, the fuel bundles are of shorter length and stacked one after another in the fuel channels having random alignments at the junctions. The friction factor predicted in this case, includes the spacers as well as the junctions, which causes to predict the higher values than the present case for bare rod bundle.

Snoek and Ahmad [1] proposed the correlation for the friction factor based on data generated in a 6-m long test section with a 37-element electrically heated bundle incorporating end plate simulation. The correlation is valid only in the range of $1.08 \times 10^5 \le \mathrm{Re} \le 4.2 \times 10^5$ which is higher than the trend of present data. The present experiment uses an unheated prototype bundle, whereas Snoek and Ahmad used a heated 6-m long bundle. Hence the over prediction may be attributed partly to the non-isothermal nature of flow and partly to the higher bundle length.

The correlation given by Pilkhwal et al. [2] is over predicting the friction factor. Pilkhwal et al. has proposed the correlation based on experimental data generated using a 52-rod cluster. The higher prediction may be due to higher flow area in a 52-rod cluster for the same Reynolds number.

Table 3: Correlations Developed for 54-rod Bundle

Components	Single-Phase♣	Two-Phase♣♣
Bundle	$f_{bl} = 3.08055\,\mathrm{Re}^{-0.50653}$	$(f_{bl})_{tp} = (f_b)_{1\phi} * 3.784\left(\frac{x}{1-x}\right)^{0.0184} * \left(\frac{\rho_l-\rho_g}{\rho_l}\right)^{800.2865} * \left(\frac{\mu_l-\mu_g}{\mu_l}\right)^{0.2}$
Spacer	$K_{sp} = 11.208\,\mathrm{Re}^{-0.14326}$	$K_{sp} = 8377.768\,\mathrm{Re}_{tp}^{-0.80179}$
BTP	$K_{btp} = 9.974\,\mathrm{Re}^{-0.13667}$	$K_{btp} = 12504.63\,\mathrm{Re}_{tp}^{-0.84075}$
TTP	$K_{ttp} = 4.758\,\mathrm{Re}^{-0.05393}$	$K_{ttp} = 147.0722\,\mathrm{Re}_{tp}^{-0.37825}$
Total loss Across Bundle	$K_{tot} = 850.75\,\mathrm{Re}^{-0.31964}$	$K_{tot} = 34334.978\,\mathrm{Re}_{tp}^{-0.66982}$

♣ for $1.2 \times 10^4 \le \mathrm{Re} \le 3.2 \times 10^4$
♣♣ for $1.0 \times 10^4 \le \mathrm{Re} \le 9.0 \times 10^4$

The prediction by Grillo and Marinelli [7] correlation is also plotted in Fig. 4a. This correlation had been developed in the range of $1.0 \times 10^4 \leq Re \leq 3.0 \times 10^5$ for a 16 rod cluster arranged in a square lattice. It is seen that the values predicted are in good agreement at low Re compared to that for higher value of Re.

The Blasius [4] correlation is over predicting the friction factor for the present experimental data. He has proposed this correlation for smooth pipes and valid in the range $3.0 \times 10^3 \leq Re \leq 1.0 \times 10^5$.

The result of the study showed that the Rehme [5] model with modification in the exponent of Reynolds number from 0.133 to 0.163 gave good agreement with experimental data in the turbulent flow regime. Figure 4b-4d show the variation of loss coefficient for spacers, TTP & BTP and the total bundle respectively for 54-rod bundle under single-phase condition.

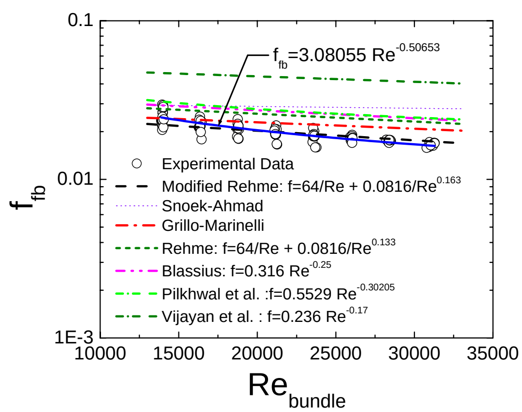

Fig. 4a: Variation of Fuel Bundle Friction Factor under Single-Phase.

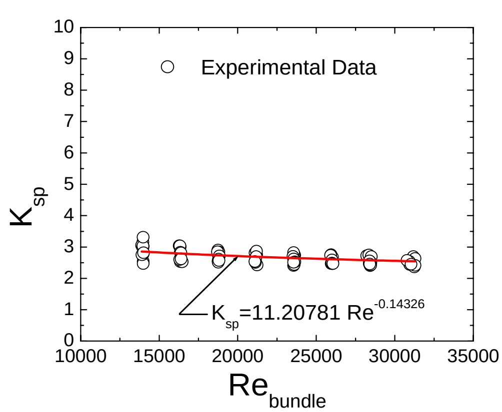

Fig. 4b: Variation of Loss Coefficient of Spacers under Single-Phase.

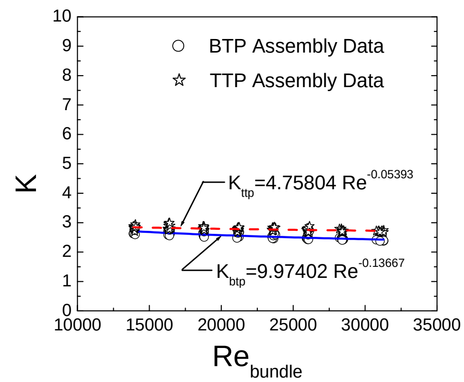

Fig. 4c: Variation of Loss Coefficient of TTP and BTP under Single-Phase.

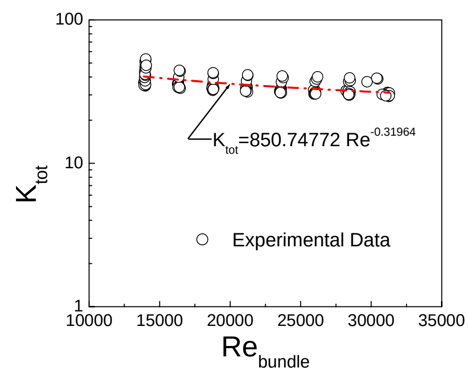

Fig. 4d: Variation of Total Loss Coefficient across Bundle under Single-Phase.

The variation of bundle friction factor with two-phase bundle Reynolds number for 54-rod cluster is shown in Fig. 5a. The two-phase Reynolds number is calculated exactly as in single-phase flow except with the use of two-phase viscosity instead of single-phase viscosity. In the present case correlation given by McAdams et al. [11] for calculating the two-phase viscosity has been used. Using regression analysis for the experimental data, a correlation has been proposed which considers the combining effect of Reynolds number, quality, densities and viscosities.

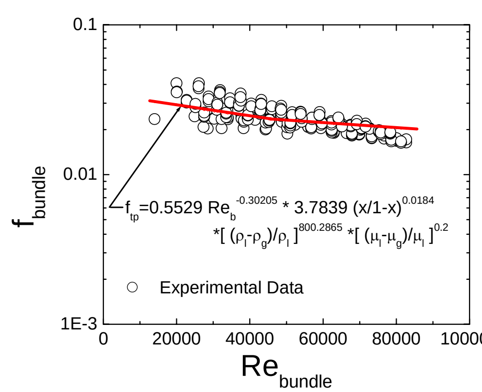

Fig. 5a: Variation of Fuel Bundle Friction Factor under Two-Phase.

This correlation can be used to predict the two-phase friction factor under steam-water condition. Figure 5b-d show the variation of loss coefficient for spacers, TTP & BTP and the total bundle respectively for 54-rod bundle under two-phase condition.

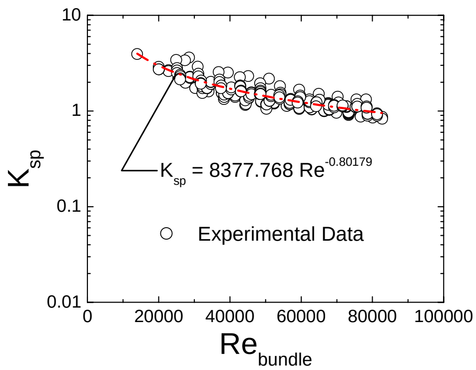

Fig. 5b: Variation of Loss Coefficient of Spacers under Two-Phase.

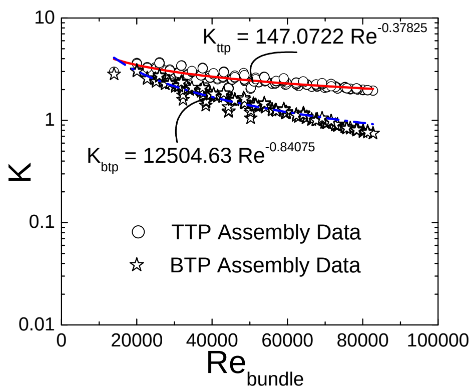

Fig. 5c: Variation of Loss Coefficient of TTP and BTP under Two-Phase.

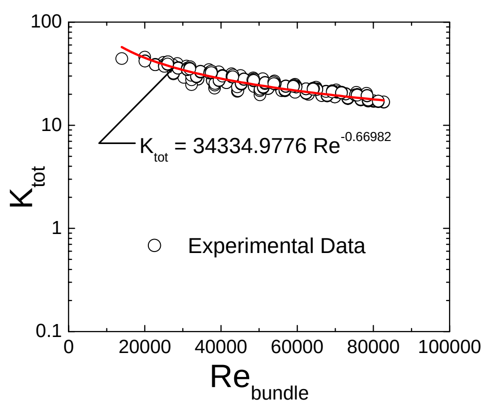

Fig. 5d: Variation of Total Loss Coefficient across Bundle under Two-Phase.

The two-phase multiplier, Φ^2_{LO} for 54-rod cluster was calculated by taking the ratio of two-phase pressure drop and single-phase pressure drop across the bundle. A correlation has been proposed [Equation (17)] using the experimental two-phase multiplier data. The present correlation was able to predict the experimental data with an error bound of $\pm$ 20%. Figure 6 shows the comparison between data predicted using present correlation and the experimental calculated data. Further a comparison study has been performed to evaluate the effectiveness of the existing two-phase multiplier correlation for air-water experimental data. Figure 7 show the comparison between existing correlation and experimental data. As shown in Fig. 7, Beattie [3] correlation was able to reproduce the data with an error bound of $\pm$35%. The error bound for Sekoguchi [6] and Lockhart-Martinelli [10] was -50% and $\pm$ 42% respectively.

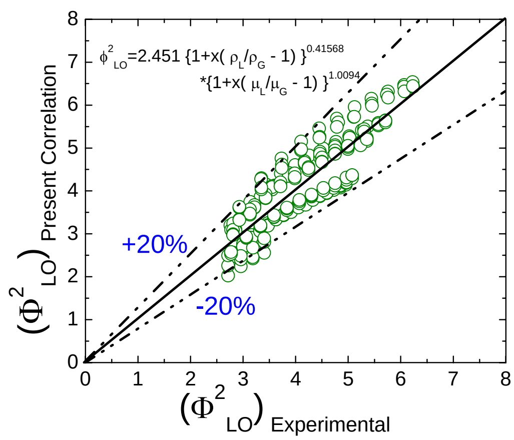

Fig. 6: Comparison of Experimental Two-Phase Friction Multiplier with the Present Correlation.

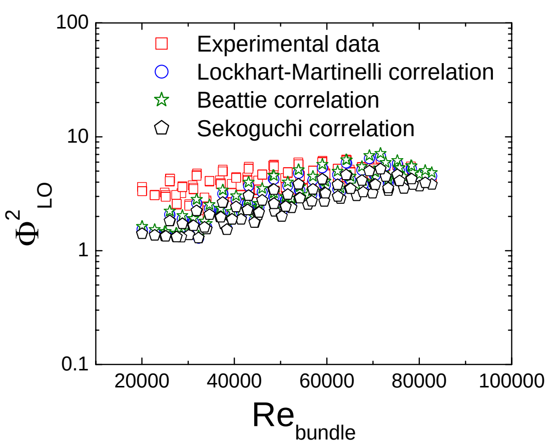

Fig. 7: Comparison of Experimental Two-Phase Friction Multiplier with three Different Correlations.

7. Conclusions

Experiments were carried out to measure the pressure drop across the various components of 54-rod cluster under single-phase and two-phase conditions. From the measured values of pressure drop, the loss coefficients for the bottom tie plate assembly, spacer and top tie plate assembly, total fuel bundle, and friction factor for free(bare) fuel bundle were derived for both single-phase as well as two-phase conditions. The single phase friction factor for bare bundle was compared with the available models. The result of the study showed that the Rehme (1973) model with modification gave good agreement with experimental data in the turbulent flow regime.

Based on the pressure drop data generated in the FTF, correlations were developed for bare fuel bundle friction factor and loss coefficients for different components of 54-rod cluster in single-phase and two-phase (air-water) region. These correlations can be used to predict the pressure drop across the fuel channel (with 54- rod cluster) under two-phase (steam-water) flow with appropriate correction multiplier. A correlation for two-phase friction multiplier has also been developed for 54-rod cluster. The present correlation was able to predict the experimental data with an error bound of $\pm$ 20%. A comparative study of three existing Φ^2_{LO} correlations, with the experimental two-phase friction multiplier obtained from experimental data has been performed. This assessment showed that the Beattie (1973) correlation is better than all the others considered in the present report for the air-water experimental data.

Acknowledgements

The authors wish to thank the Divisional Workshop, Instrumentation Section and Operational Group of Reactor Engineering Division for their technical assistance.

References

1. C.W. Snoek and S. Y. Ahmad, A Method of Predicting Pressure Profiles in Horizontal 37 element Clusters, AECL-8065, Chalk River Nuclear Laboratories, Chalk River, Ontario, 1984.

2. D.S. Pilkhwal, P.K. Vijayan, D. Saha and R.K. Sinha, Experimental Investigation of Pressure Drop across Various Components of AHWR fuel bundle, BARC/2001/I/001, 2001.

3. D.R.H. Beattie, Note on the Calculation of Two-Phase Pressure Losses, Nuclear Engineering and Design, **25,** 395-402, 1973.

4. H. Blasius, Mitt. Forsch. Geb. Ing.-Wesen, **131,** 1913.

5. K. Rehme, Pressure Drop Correlations for Fuel Element Spacers, Nuclear Technology, **17**, 15-23, 1973.

6. K. Sekoguchi, Y. Saito and T. Honda, JSME Preprint No. 700-783, 1970.

7. P.Grillo and V. Marinelli, Single and Two-Phase Pressure Drops on a 16-ROD Bundle, Nuclear Applications & Technology, **9**, 682-693, 1970.

8. P.K. Vijayan, D.S. Pilkhwal, D. Saha and V. Venkat Raj, Experimental Studies on the Pressure Drop Across the Various Components of a PHWR Fuel Channel, Experimental Thermal and Fluid Science, **20**, 34-44, 1999.

9. Robert J. Moffat, Describing the uncertainties in experimental results, Experimental Thermal and Fluid Sciences, **1**, 3-17, 1988.

10. R.W. Lockhart and R.C. Martinelli, Proposed Correlation of Data for Isothermal Two-Phase, Two Component Flow in Pipes, Chemical Engineering Progress, **45**, No.1, 39-48, 1949.

11. W.H. McAdams, W.K Woods and R.H. Heroman Jr., Vaporisation inside Horizontal Tubes.II. Benzene-Oil-Mixtures, Trans. ASME, **64**, 193, 1942.