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ASSESSMENT OF THEORETICAL CORRELATIONS FOR PREDICTION OF PRESSURE DROP ACROSS SPACER

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ABSTRACT

The present paper discusses the prediction of pressure drop across spacer both by employing a set of correlations proposed by Rehme (1973) and a theoretical model. The theoretical model considers the sum of expansion, contraction and friction losses at the spacer. The results obtained by the theoretical model indicate that the pressure drop is strongly dependent on the flow area ratio and the length of the spacer as well. In addition, the pressure loss coefficient is found to decrease with the Reynolds number. It is observed that the pressure drop correlation does not take into account the length of the spacer and predicts a lower value of pressure loss coefficient compared to the theoretical model.

INTRODUCTION

In a typical nuclear reactor, the fuel pins are held in bundles and the coolant flows parallel to the rods. In general, spacers of different configurations, namely, honey comb-type, ring-type, wire-wraped-type and grid type are used to support fuel pins in a reactor core. The spacers not only guide the fuel pins but also facilitate effective cooling and prevent the bending of fuel pins due to uneven thermal expansion during cooling. At the same time significant pressure drop occurs across the spacers in a reactor core. In such a case, the knowledge of pressure drop behavior of rod bundles is very essential to assess the performance of reactor core. This has generated immense interest in studying the pressure drop behvaiour across the spacers both through experimental investigation (Rehme, 1973; Melese and Katz, 1984; DeStordeur, 1961) and theoretical investigations (Okubo et al., 2000). Some of the important studies are elaborated below.

NOMENCLATURE

A	Cross sectional area, *m*^{2}
C_V	Drag coefficient
A_2/A_1	Flow area ratio
De, De_2	Equivalent hydraulic diameter, *m*
f	Friction loss coefficient
K_{eq}	Pressure loss coefficient
L	length of the test section, m
ΔP	Pressure loss, *N/m*^{2}
ΔP_{FB}	Pressure loss at fuel assembly
ΔP_{SP}	Pressure loss at spacer, *N/m*^{2}
ΔP_C	Pressure loss due to contraction, *N/m*^{2}
ΔP_E	Pressure loss due to expansion, *N/m*^{2}
ΔP_F	Friction pressure loss across spacer, *N/m*^{2}
V	Coolant velocity, *m/sec*
Re	Reynolds number

Greek Symbols

1, 2	Before and at the spacer location, respectively
ε	Relative plugging, defined in Eq. 6
ρ	Density of the fluid, Kg/m^3
μ	Dynamic viscosity, N-s/m^2
ζ_C	Coefficient of the pressure loss due to the contraction
ζ_E	Coefficient of the pressure loss due to the expansion

Subscripts & Abbreviations

SP	Spacer

PHWR	Pressurized heavy water reactor
BWR	Boling water reactor

Over the years, several correlations have been proposed by different authors in order to predict the pressure drop of grid spacers in fuel rod bundle (Rehme, 1973; Melese and Katz, 1984; DeStordeur, 1961). Rehme (1973) carried out experiments to evaluate the pressure loss across various spacers in the rod cluster. It was observed that pressure loss coefficient for the grid type spacer and wire wrapped fuel bundle depends on the relative plugging of the flow cross section and lead of the wire wraps, respectively. Okubo et al. (2000) reported that the spacer loss coefficient depends on the length of the grid spacer. Rehme & Trippe (1985) reported the correlations for the evaluation of the pressure loss due to spacer grids and compared with the test data. It was observed that various parameters, namely, ratio of pitch to diameter of rods (*P/D*), the ratio of distance of the fuel rod from the wall to the diameter of rod (*W/D*) influences the pressure drop in a rod bundle (Rehme, 1973; Grover and Venkat Raj, 1980). Vijayan et al. (1999) carried out experiments to measure the pressure drop across various components of a pressurised heavy water reactor (PHWR) fuel channel under single-phase flow conditions. The authors reported various empirical correlations to predict the pressure drop for various components of the fuel channel such as: rod bundles, end fittings, fuel locator and refuelling tools. In addition, both experimental and theoretical studies have been carried out to study the effect of geometry of the spacer for the local pressure drop in vertical circular geometry (Yano et al., 2001). It was observed that the spacer affects the flow of coolant in the fuel pins; subsequently influences the thermal hydraulics behaviour of reactor core. Feldhaus et al. (2002) performed experiments to study various parameters, namely, the pressure drop and the rate of coolant flow on the fuel channel with and without spacer grids. The authors reported the applicability of existing friction factor correlations for varying range of coolant conditions. The aim of the present study is to evaluate the pressure drop at spacer by employing a theoretical model and a set of pressure drop correlations proposed by Rehme (1973). The results obtained by the theoretical model have been compared with that obtained by the pressure drop correlations. The general applicability of such methods to evaluate spacer loss coefficients has been discussed.

THEORTICAL ANALYSIS

The total pressure drop in the fuel bundle assembly includes the pressure drop across various components such as: inlet, outlet, orifice, support grid, flow friction and across the spacer. Mathematically, one can write:

$$\Delta P_{FB} = \Delta P_{in} + \Delta P_{out} + \Delta P_{orf} + \Delta P_{sg} + \Delta P_{fri} + \Delta P_{sp} \quad (1)$$

Subsequently, the pressure loss can be expressed by the pressure loss coefficients and Eq. (1) can be expressed as:

$$\Delta P_{FB} = 0.5 K_1 \rho V_1^2 + 0.5 K_2 \rho V_1^2 + 0.5 K_{eq} \rho V_1^2 \quad (2)$$

Where,

$$K_1 = K_{in} + K_{out} + K_{orf} + K_{sg}, \; K_2 = fL / D_e \quad (3)$$

K_1 represents to the sum of pressure loss coefficients due to various components such as: inlet, outlet, orifice and support grid, K_2 represents the pressure loss coefficient due to flow friction along a smooth pipe and K_{eq} represents the pressure loss coefficient across spacer. It may be noted that the value of K_1 can be determined from the test data and K_2 can be evaluated by using the geometrical parameters of the test section such as, length of test section and equivalent hydraulic diameter and the flow friction factor. On the contrary, the value of K_{eq} can be evaluated either by using a pressure drop correlation or through the theoretical model. In the present study, the focus is made to discuss theoretical models and correlations to predict K_{eq} and is summarized below.

Pressure drop across spacer: Theoretical model

Figure 1 depicts the schematic of a spacer in an annular geometry. The loss of pressure at spacer 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 (Okubo et al., 2000):

$$\Delta P_{SP} = \Delta P_C + \Delta P_F + \Delta P_E \quad (4)$$

From the basic fluid mechanics (Appendix-1), one can write the pressure loss at spacer as a function of spacer loss coefficient (K_{eq}) and velocity of the gas as:

$$\Delta P_{SP} = 0.5 \left(K_{eq} \right)_{theoritical} \rho V_1^2 \quad (5)$$

Rearranging Eq. 5, one can write:

$$\left(K_{eq} \right)_{therotical} = \left(2 \Delta P_{SP} / \rho V_1^2 \right) \quad (6)$$

Where,

$$\left(K_{eq} \right)_{therotical} = \left(\zeta_C + f \left(L_{Sp} / De_2 \right) + \zeta_E \right) \left(A_2 / A_1 \right)^{-2} \quad (7)$$

The subscript 1 and 2 denotes the normal flow section and the flow section at the spacer, respectively. L_{SP}, De_2, f, ζ_C and ζ_E represents the length of a spacer, the hydraulic diameter, the friction loss coefficient, the coefficient of the pressure loss due to the contraction and the coefficient of the pressure loss due to the expansion, respectively.

Following, Idelchik (1986), the contraction & expansion loss coefficient in a single phase flow condition are defined as follows:

$$\zeta_C = 0.5 \left[1 - \left(A_2 / A_1 \right) \right]^{0.75}, \; \zeta_E = \left[1 - \left(A_2 / A_1 \right) \right]^2 \quad (8)$$

Using Equation (8), Eq. (7) can be expressed as:

$$\left(K_{eq} \right)_{therotical} = \left[0.5 \left[1 - \left(A_2 / A_1 \right) \right]^{0.75} + f \left(L_{Sp} / D_2 \right) + \left[1 - \left(A_2 / A_1 \right) \right]^2 \right] \left(A_2 / A_1 \right)^{-2} \quad (9)$$

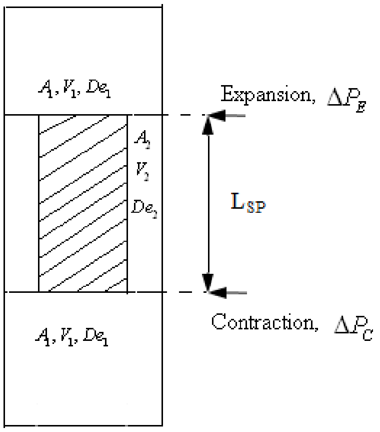

Figure 1 Schematic of pressure loss at spacer

A generalized expression for the pressure loss coefficient at spacer has been derived based on the flow area ratio and expressed in Eq. 9. This reveals that the pressure loss coefficient at spacer depends on ratio of flow area, length of the spacer and friction loss coefficient. At this juncture, one needs to use the value of friction loss coefficient for evaluating the loss of pressure at spacer. For a steady state and fully developed flow inside the annulus, various friction pressure drop correlations have been proposed by several authors and are summarized in Table 1. Here, *Re* represents Reynolds number of the flow channel and is calculated as: $\mathrm{Re} = \rho V De_2 / \mu$. The proposed correlation shows that friction loss coefficient *f is* a strong function of *Re*. Using Eq. 9 and the values of f (Table 1), the values of spacer loss coefficient has been evaluated for a varied range of area ratio, length of the spacer and Reynolds number.

Table 1: Various friction factor correlations

SOURCE	VALUE OF FRICTION FACTOR	RANGE OF REYNOLDS NUMBER
BLASIUS (1913)	$f = 0.316\,\mathrm{Re}^{-0.25}$	$3000 \le \mathrm{Re} \le 10^5$
BLASIUS (1913)	$f = 0.184\,\mathrm{Re}^{-0.2}$	$3000 \le \mathrm{Re} \le 10^6$
DREW ET AL. (1932)	$f = 0.0056 + 0.5\,\mathrm{Re}^{-0.32}$	$3000 \le \mathrm{Re} \le 10^6$
FILONENO (1948)	$f = \left[1.82\log(\mathrm{Re}) - 1.64\right]^{-2}$	$3000 \le \mathrm{Re} \le 10^6$

Pressure drop across spacers: Correlations

Earlier, Rehme (1973) carried out the experimental investigation to predict the pressure drop on both pressurised water reactors (*PWR*) and boiling water reactors (*BWR*) involving grid spacers. Based on the test data, the author has recommended the correlation to evaluate the loss of pressure on grid spacers and is expressed as:

$$\Delta \mathrm{P}_{\mathrm{SP}} = 0.5 C_V \varepsilon^2 \rho V_1^2 \qquad (10)$$

Where, C_V is the modified drag coefficient and ε is the relative plugging; defined by $\varepsilon = A_{Sp}/A_f$; A_{Sp} and A_f denotes the area of grid spacer and flow area, respectively. With reference to Fig.1, relative plugging can be defined as:

$$\varepsilon = 1 - \left(A_2/A_1\right) \qquad (11)$$

Using, Eq. (11), Eq. 10 can be written as:

$$\left(K_{eq}\right)_{Correlation} = \left(2\Delta \mathrm{P}_{\mathrm{SP}} / \rho V_1^2\right) \qquad (12)$$

Where,

$$\left(K_{eq}\right)_{Correlation} = C_V \left[1 - \left(A_2/A_1\right)\right]^2 \qquad (13)$$

Using Eq. 13, one can evaluate the spacer loss coefficient for a given value of area ratio and C_V. The value of C_V is recommended by several researchers and is summarized in Table 2.

Table 2: Various correlations for drag coefficient

SOURCE	VALUE OF C_V
REHME (1973)	$C_V = 6 - 7 \quad \left(\mathrm{Re} \ge 0.5 \times 10^5\right)$
GROVER AND VENKAT RAJ (1980)	$C_V = \begin{cases} 9.5 - 11.5 & for\ L_{Sp} = 25mm \\ 7.3 - 13.9 & for\ L_{Sp} = 20mm \\ 10.8 - 14.8 & for\ L_{Sp} = 15mm \\ 1.7 - 2.2 & for\ full\ grid\ spacer \end{cases}$ $0.25 \times 10^5 \le \mathrm{Re} \le 0.75 \times 10^5$
CIGARINI AND DALLE DONNE (1988)	$C_V = \min\left\|3.5 + \left(73.14/\mathrm{Re}^{0.264}\right) + \left[(2.79) \times 10^{10}/\mathrm{Re}^{2.79}\right],\ 2/\varepsilon^2\right\|$

RESULTS AND DISCUSSION

It has been observed that the value of K_{eq} is used in order to predict the drop of pressure at spacer and subsquently the total pressure drop is evaluated in the entire fuel assembly. In the present study, both the theoretical model and a set of pressure drop correlations have been used to evaluate the pressure loss coefficient at spacer. Initially, a theoretical model that considers the sum of expansion, contraction and friction losses has been used to evaluate the pressure drop across spacer. Later on, the correlation proposed by Rehme (1973) has been used to predict the pressure loss coefficient across the grid spacer. Several correlations for friction loss coefficient (Table 1) and various correlations for drag coefficient (Table 2) have been used in the analysis.

The variation of spacer loss coefficient as a function of flow area ratio has been evaluated by using Eq. 9 and is depicted in Fig. 2. The Reynold number *Re* is 20,000 and the hydrulic diameter at the spacer is considered as 2.0 mm. The coefficient of the friction loss is evaluated by using several correlations proposed by various authors (Blasius,1913; Drew et al., 1932; Filoneko, 1948). The results exhibits the strong dependecy of K_{eq} on A_2/A_1. The pressure loss coefficient decreases with the increase in flow area ratio and attains a minimum value for a unit flow area ratio. A unit flow area ratio essentailly represents the situation with no spacer and hence the pressure loss is minimum. Earlier, similar trend was observed by previous researchers as well (Rehme,1973; Rehme and Trippe, 1980).

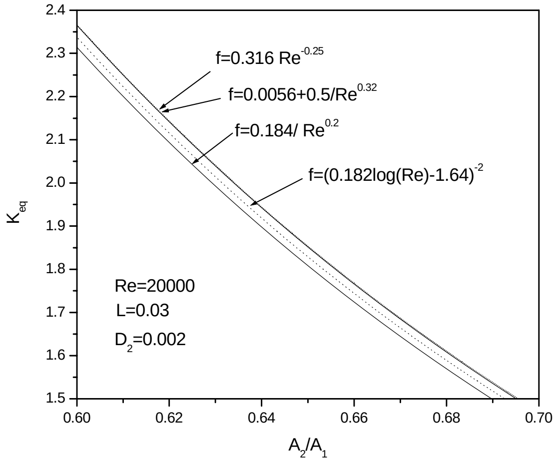

Figure 2 Spacer loss coefficient vs area ratio for different value of f

The variation of pressure loss coefficient for various values of spacer length is shown in Fig. 3. It is observed that for a given value of Reynold number and area ratio, the pressure loss coefficient decreases with the spacer length. This may be explained by the fact that the spacers usually act as obstacles in the flow path leading to significant pressure drop across the spacer. In general, the loss of pressure is caused because of the skin friction drag and the profile drag as well. Skin friction drag essentially increases with the increase of surface area in contact with the flowing fluid. On the contrary, the profile drag depends on the shape of the obstacle, i.e, the ratio of the thickness perpendicular to the flow path and the length along the flow path. Very often, this is termed as slenderness ratio. With decreasing the slenderness ratio, the profile drag decreases (Vijayan et al., 1999). The combined effect is the net decrease in the pressure loss coefficient with the increase in the length of the spacer. This may be the reason that the slenderness ratio plays a significant role in determing the pressure drop across the spacer. This trend is observed by previous authors as well.

The variation of f with Re and the variation of $\left(K_{eq}\right)_{therotical}$ with Re is depicted in Figs. 4 and 5, respectively. Different correlations proposed by several researchers (Table 1) have been used to evaluate the friction loss coefficient. In all the cases, f is found to decrease with the increase in the Reynolds number. Subsquently, the pressure loss coefficient $\left(K_{eq}\right)_{therotical}$ is evaluated and is found to decrease with the increase in Reynolds number. Alternatively, the pressure loss coefficient across spacer can be evaluated by utilizing the value of C_V and relative plugging of the grid spacer ε.

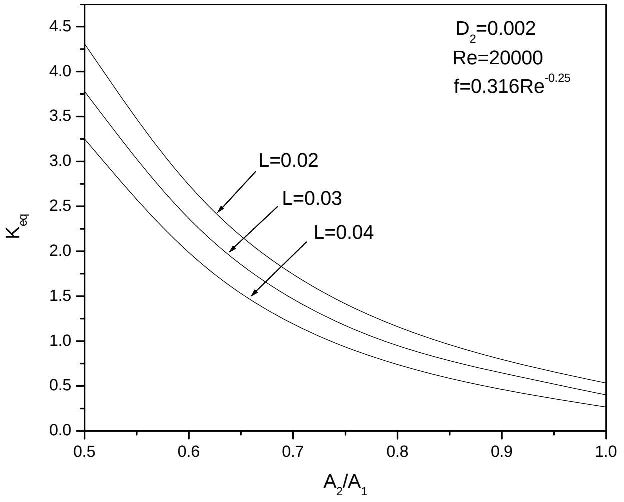

Figure 3 Spacer loss coefficient vs area ratio

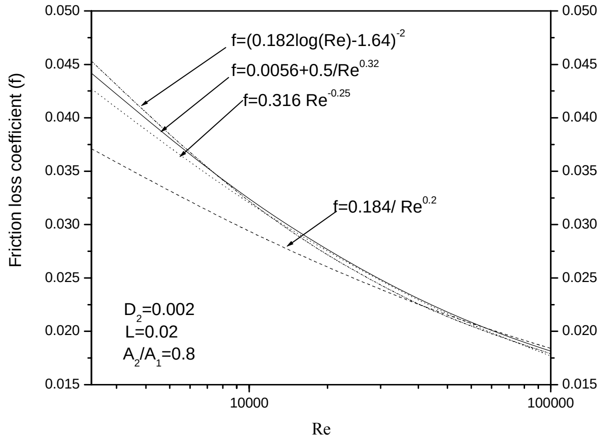

Figure 4 Friction loss coefficient vs Re

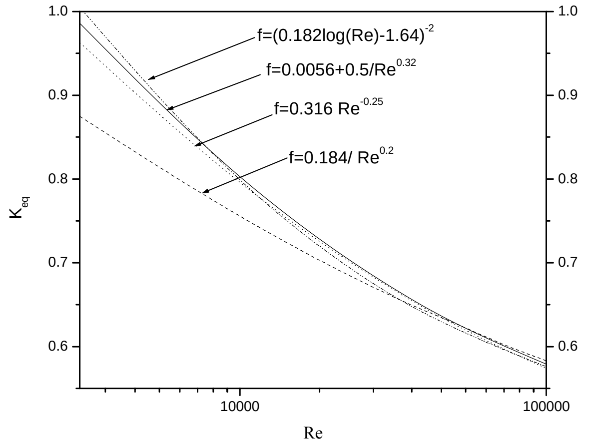

Figure 5 Spacer loss coefficient vs Re

Eq. 10 has been used to evaluate the pressure loss coefficient $\left(K_{eq}\right)_{\text{Correlation}}$ across the spacer for various values of *Re* and is shown in figs. 6 (a) and 6(b). The value of C_V has been proposed by several authors and is shown in Table 2. With the use of modified Rehme/Dalle donne correlation a higher value of $\left(K_{eq}\right)_{\text{Correlation}}$ is obtained compared to Rehme (1973) correlation and is depicted in Fig. 6(a).

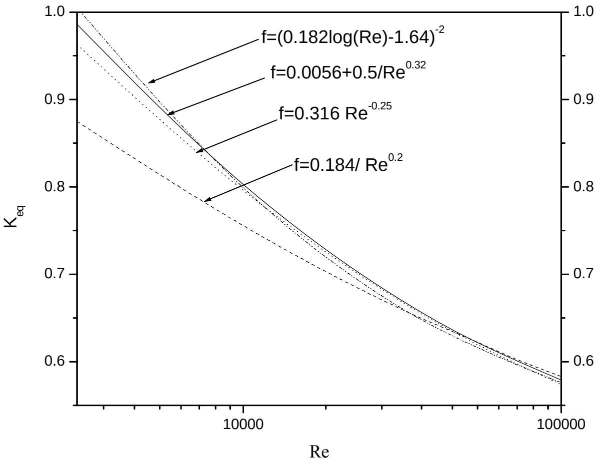

Figure 6 (a) Spacer loss coefficient vs *Re* (C_V=6)

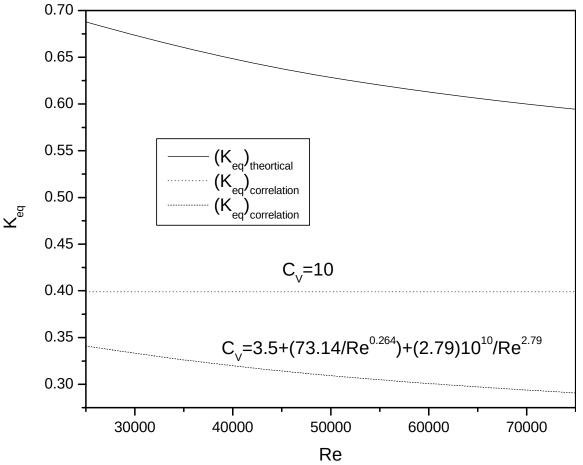

Figure 6 (b) Spacer loss coefficient vs *Re* (C_V =10)

CONCLUSIONS

A theoretical model and a set of pressure drop correlations have been used separately to evaluate the pressure drop across the spacer. The results obtained from the theoretical model indicate that the spacer loss coefficient strongly depends on the length of the spacer and the area ratio.

Furthermore, the pressure loss coefficient is found to decrease with the Reynolds number. The results obtained by a set of pressure drop correlations proposed by Rehme (1973), modified Reheme/Dalle donne and modified Rehme/Venkat Raj is compared with that of the theortical model. In all the cases, the theortical model predicts a higher value compared to that obtained by employing pressure drop correlations. It has been observed that the pressure drop correlations proposed by Reheme (1973) and modified Reheme/Dalle donne donot take into the account of the length of the spacer, this is a significant parameter and should be considered for the analysis.

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Appendix 1

$$\Delta PSP = K\frac{1}{2}\rho V1^2 \tag{1}$$

$$\Delta PC = \zeta c\frac{1}{2}\rho V2^2 = \zeta c\left(\frac{A2}{A1}\right)^{-2}\frac{1}{2}\rho V1^2 \tag{2}$$

$$\Delta PF = f\frac{1}{2}\rho V2^2\frac{L}{D2} = f\left(\frac{A2}{A1}\right)^{-2}\frac{L}{D2}\frac{1}{2}\rho V1^2 \tag{3}$$

$$\Delta PE = \zeta E\frac{1}{2}\rho V2^2 = \zeta E\left(\frac{A2}{A1}\right)^{-2}\frac{1}{2}\rho V1^2 \tag{4}$$