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A PRESSURE DROP MODEL FOR PWR GRIDS

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Abstract

A pressure drop model for the PWR grids with and without mixing device is proposed at single phase based on the fluid mechanistic approach. Total pressure loss is expressed in additive way for form and frictional losses. The general friction factor correlations and form drag coefficients available in the open literatures are used to the model. As the results, the model shows better predictions than the existing ones for the non-mixing grids, and reasonable agreements with the available experimental data for mixing grids. Therefore it is concluded that the proposed model for pressure drop can provide sufficiently good approximation for grid optimization and design calculation in advanced grid development.

1. Introduction

Spacer is an essential component in a fuel assembly primarily to keep the bundle configuration and additionally to enhance the flow mixing. But it inevitably involves the hydraulic resistance increase in the spacer region through flow obstruction and flow deflection. It means that larger capacity of a pump is needed in the reactor system to maintain a required mass flow rate. So it is expedient to reduce the pressure loss at the spacer as less as not to degrade the mechanical strength and mixing performance. On the other hand, it is generally known that the local large difference in pressures may produce an excessive crossflow, which may cause the fuel vibration and eventually fuel failure due to wear. In a new spacer development, there is usually a restriction of the pressure loss difference relative to existing spacers as a design guideline to satisfy the hydraulic compatibility. Therefore it is necessary to predict accurately the pressure drop. However, because of variation and complexity of geometry, it is hard to establish the prediction method of general validity for various spacers. A wide variety of spacer types have been used in the fuel bundles. Basically they may be classified into three categories: (i) grid-type spacers mainly encountered in PWR, (ii) spiral wire type grids for small distances between fuel element pins such as LMFBR or (iii) wart type spacers and bearing pad used in CANDU. In this study the pressure drop for the grid type spacers at single-phase flow is investigated. In the experiment, The pressure drop of a grid ΔP actually comprises the form loss term and the frictional loss term. A grid loss coefficient is defined here on the free flow area of bare rod region A_o:

$$K = \frac{\Delta P}{\frac{1}{2}\rho U_o^{\,2}} \tag{1}$$

where ρ is fluid density and U_o is average velocity of the bare rod region. Few models to predict the pressure loss coefficient for grid spacers have been reported in the open literature during the last three decades (Table 1). De Stordeur (1961) proposed a pressure drop correlation as a function of drag coefficient C_s and relative plugging $\varepsilon = A_s/A_o$. A_s is the projected area of spacer grid. C_s was presented graphically using available experimental data. A factor $1/(1-\varepsilon)^2$ is multiplied to make the definition of the loss coefficient consistent with the above since C_s was originally deduced on the fluid velocity at grid region. At high Reynolds number of $Re = 10^5$, the drag coefficient C_s of honeycomb grids was shown around 1.65. Rehme (1973) expressed the grid loss coefficient by introducing a modified drag coefficient C_V as shown in Table 1. The modified drag coefficient C_V was also given in graphical form for relatively simple grids like for FBR. Cevolani (1995) suggested the empirical correlations of C_V in Rehme model in order to conveniently use over the wide Re range for square and triangular arrays: $C_v = 5+6133\ Re^{-0.789}$ for square array, $\ln(C_v) = 7.690 - 0.942\ \ln(Re) + 0.0379\ \ln^2(Re)$ for triangular array. Kim (1993) developed a rational-based analytic model for pressure loss of a PWR-type non-mixing vaned grid. The model was successfully verified with the simple grids designed for FBR. But it was not actually examined with the measured data of PWR grids.

As the role of the grids becomes significant in standpoint of the enhancement of the safety margin, recently most of the grids have the mixing device on them. A lot of the efforts are devoted to develop the advanced grids having the excellent thermal performance in various ways by the fuel vendors. Nonetheless it seems to the authors that the prediction model for the grids with mixing devices has not been available in the open literatures. The purpose of this work is to develop a mechanistic model of the pressure drop for various grid type spacers without and with mixing devices and to compare the model with the existing ones against the measured data for PWR grids.

Table 1. Existing pressure loss coefficient models

Reference	Loss Coefficient Model	Remark
De Stordeur (1961)	$K = C_s \dfrac{\varepsilon}{(1-\varepsilon)^2}$	$C_s \sim 1.65$ for honeycomb grids for $Re > 10^5$
Rehme, K (1973)	$K = C_v \varepsilon^2$	$C_V = 6 - 7$ is recommended for $Re > 5\text{x}10^4$ for square and triangular arrays respectively
Cevolani, S (1995)	$K = C_v \varepsilon^2$	$C_v = 5+6133\ Re^{-0.789}$ for square array $\ln(C_v) = 7.690 - 0.942\ \ln(Re) + 0.0379\ \ln^2(Re)$ for triangular array
Kim, N.H. (1992)	$K = \left(C_d + C_f \dfrac{2L}{t}\right) \dfrac{\varepsilon}{(1-\varepsilon)^2}$	$C_d = 0.9$ from two-dimensional rectangular plate C_f modeled with the turbulent boundary layer with preceding laminar region

2. A Proposed Model

A new model to predict the pressure drop has been developed based on the balance of hydraulic forces acting on the grid. The drag force on the grid is divided into four parts: form drag on the grid, frictional drag on the grid, frictional drag on the rod, and form drag on the mixing device drag. So the total drag force is expressed in additive way for the individual drag terms.

$$F = F_{form}^{grid} + F_{fric}^{grid} + F_{fric}^{rod} + F_{form}^{mixing} \quad (2)$$

The grid loss coefficient in equation (1) can be described again in terms of the hydraulic force:

$$K = \frac{F}{\frac{1}{2}\rho U_o^2 A_o} \quad (3)$$

Then the total loss coefficient of a grid can be expressed using the equation (3) as:

$$K = K_{form}^{grid} + K_{fric}^{grid} + K_{fric}^{rod} + K_{form}^{mixing} \quad (4)$$

Each term in the right hand side of equation (4) is proposed by introducing the form or frictional loss coefficients of the grid elements from the open literatures:

K_{form}^{grid} : Form loss coefficient of grid

The form drag of a grid takes place in the leading and trailing edges of the strap plates, the supporting elements like dimples and springs, and the welding nuggets upstream and downstream. The form loss coefficient of a grid is formulated as:

$$K_{form}^{grid} = \sum_i C_{d,i} \left(\frac{A_{s,i}}{A_o} \right) \frac{1}{(1-\varepsilon)^2} \tag{5}$$

where $C_{c,i}$, $A_{s,i}$ is the form drag coefficient of i element and it's projected area to the axial plane, respectively. It has been observed that the leading edge shape in the plate largely affects the form loss. So considering the real edge shape, the form drag coefficient of the strap is taken from the two-dimensional thin plate. For the supporting elements, the coefficients are decided to be treated as the small body protuberances on the plates, so called surface imperfections, showing three-dimensional flow pattern. The form drags coefficient of the welding nuggets for the downstream and upstream are separately recommended. The specific values of above mentioned elements [5] are described in Table 2.

K_{fric}^{grid} : Frictional loss coefficient of grid

The frictional loss coefficient of the grid strip can be estimated using the correlation for the flow over thin flat plate, neglecting the dimples and springs. It is said that at relatively low Reynolds number the laminar boundary layer may prevail over the grid, while at high Reynolds number region the turbulent boundary layer becomes dominant. The flow scheme in the boundary layer is assumed to be changed from laminar to turbulent when Reynolds number Re_L is greater than 5×10^5. So the frictional loss coefficient of the grid for high Reynolds number is formulated to count both the laminar and turbulent friction losses by corresponding length weight:

$$K_{fric}^{grid} = \left(C_{f,lam} \frac{L_t}{L} + C_{f,tur} \frac{L-L_t}{L} \right) \left(\frac{A_f}{A_o} \right) \frac{1}{(1-\varepsilon)^2} \tag{6}$$

where L, L_t and A_f are a strap height, a distance from the leading edge to the flow transition location, and a wetted strap area, respectively. The average frictional drag coefficients of $C_{f,lam}$, $C_{f,tur}$ for the laminar and the turbulent flow [6] are determined as:

$$C_{f,lam} = \frac{1.328}{\sqrt{\mathrm{Re}_L}} \quad , \quad C_{f,tur} = \frac{0.455}{(\log \mathrm{Re}_L)^{2.58}} \tag{7,8}$$

where Re_L is the Reynolds number whose characteristic length is the grid height. If L is shorter than L_t, then the second term in right hand side of equation (6) vanishes.

K_{fric}^{rod} : Frictional loss coefficient of rod

The boundary layer on the rods may be regarded as the fully developed turbulent flow. The frictional loss coefficient of the rod in grid region may be expressed as:

$$K_{fric}^{rod} = f_r \frac{L}{D_{h,g}} \frac{1}{(1-\varepsilon)^2} \tag{9}$$

where f_r , $D_{h,g}$ are the friction factor of rod and the hydraulic diameter, respectively. The correlations of the turbulent friction factors for a rod are modeled with a smooth round tube [7] as follows:

McAdams	$f = 0.184\,Re^{-0.2}$	$3\text{x}10^4 < Re < 1\text{x}10^6$	(10)
Blasius	$f = 0.316\,Re^{-0.25}$	$Re < 3\text{x}10^4$	(11)

But it will be desirable to be implemented later with the proper correlation based on the rod bundle geometry.

K_{form}^{mixing} : Form loss coefficient of mixing device

The mixing device enhances the thermal performance by flow deflection or swirling motion. Its characteristics of the pressure drop may strongly depend on the mixing mechanism. Here the effect of the mixing device on the pressure drop is formulated in simple way as:

$$K_{form}^{mixing} = C_d \frac{A_v}{A} \tag{12}$$

where A_v, C_d are a projected area of the mixing device to the axial plane and a form drag coefficient. The form drag coefficient C_d for the mixing device is given as 1.17 as shown in Table 2. This term has to be excluded for the grid without mixing devices.

In summary, the grid loss coefficient of a spacer grid can be calculated by summing the equation (5), (6), (9) and (12).

3. Comparison Results With PWR Grid Data

The pressure drop data for five kinds of grids are selected for the evaluation of the proposed model and existing models of Cevolani and Kim. The major characteristics of the grids are described in Table 3. First two grids belong to CE types, which have the wavy strap to play a role of dimples, and have the horizontal cantilever shape springs. On the other hand, the remaining are KWU types, which possess the straight strap with oval dimples and vertical springs. Two of the KWU grids (K2 and K3) have the mixing vanes on the grids (Figure 1) as mixing devices, but they works with different mixing mechanisms. Non-split type vane in Figure 1(a) forces the coolant flow to turn chiefly toward the neighboring channels. Split type vane in Figure 1(b) induces mainly the circulation motion within a channel to utilize the centrifugal force which helps the heat transfer on the rod surface, especially in two-phase due to the significant density variation inside the heating channel in radial direction.

Figure 2 compares the measured to predicted the grid loss coefficients for three non-mixing grids. The present model shows quite a good prediction for all grids even through it slightly underestimates the grid loss coefficients. Cevolani correlation reveals the acceptable uncertainties for relatively simple CE grids in Figure 2(a), (b). But it underpredicts the grid loss coefficients by 67% for K1 grid in Figure 2(c). Kim model overestimates the thin grids as shown in Figure 2(a), (b), but underestimates the thick grid more than 50% in Figure 2(c). Kim model seems also unsuitable for the sophisticate grids.

The comparison results for mixing vane grids are presented in Figure 3. The proposed model predicts well the non-split type vane grid within 10% errors in Figure 3(a) and underpredicts a little the split type vane grid up to 15%. This increase of the uncertainty for the split type vane grid resulted from the fact that the present model for the mixing device is focused on the flow blocking effect solely neglecting the rotational effect. It is required for the model to take into account the swirl effect to improve the prediction accuracy. Anyway, it is found that even the mixing device model is formulated in simple way, the agreements of the model can be said successful, in general, considering the geometrical complexity and the variety of the grids.

4. Conclusions

A pressure drop model for the grids is proposed based on the fluid mechanistic approach. The total pressure drop across a grid is formulated as the summation of the form and frictional loss terms. The form and frictional loss coefficients of the grid elements are introduced from the available literatures. The model has been developed to cover the complicate grids like PWR types, especially including the grids with mixing devices. The model was assessed with the measured data of various PWR grids. In addition, the existing models like Cevolani and Kim were also evaluated, for the comparison purposes with the proposed one, using the same data for the non-mixing grids. From the results, the proposed model showed the reasonably accurate predictions for all kinds of grids investigated here. It yields also better predictions than others do. But some improvements are needed in the model, particularly for the swirl generation type devices. However, it is concluded that the proposed model for pressure drop can provide sufficiently good approximation for grid optimization and design calculation in advanced grid development.

References

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Nomenclature

LWR : Light Water Reactor
LMFBR : Liquid Metal Fast Breed Reactor
PWR : Pressurized Water Reactor
A_o : free flow area of bare rod region
A_s : projected area of spacer grid
A_v : projected area of mixing device
A_f : strap surface area
C_d : form drag coefficient
C_f : frictional drag coefficient
K : grid loss coefficient
L : strap height
L_t : a distance from leading edge to flow transition location
t : strap thickness
ε : relative plugging

Table 2. Form Drag Coefficients used in the model

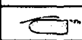
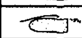
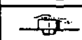
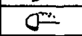
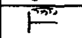
	Grid elements	shape		C_d [5]
K_{form}^{grid}	Strip	Blunt		0.9
		Stream shape		0.45
	Spring	Horizontal		0.45
		Vertical		1.2
	Dimple	Horizontal		0.45
		Oval		0.76
	Nugget	Upstream		1.17
		Downstream		0.42
K_{form}^{mixing}	Mixing Device	-		1.17

Table 3. Characteristics of the spacer grids

Parameters	CE		KWU		
	C1	C2	K1	K2	K3
Rod Dia., D [mm]	9.7	9.7	10.75	10.75	9.5
Pitch to Diameter, P/D	1.314	1.314	1.330	1.330	1.337
Relative Plugging of Flow Area, ε	0.333	0.412	0.289	0.287	0.251
Grid Height, L [mm]	35	51	48	45	40
Strip Thickness, t[mm]	0.58	0.64	0.575	0.577	0.453
Mixing Device	No		No	Yes (No- Split)	Yes (Split)

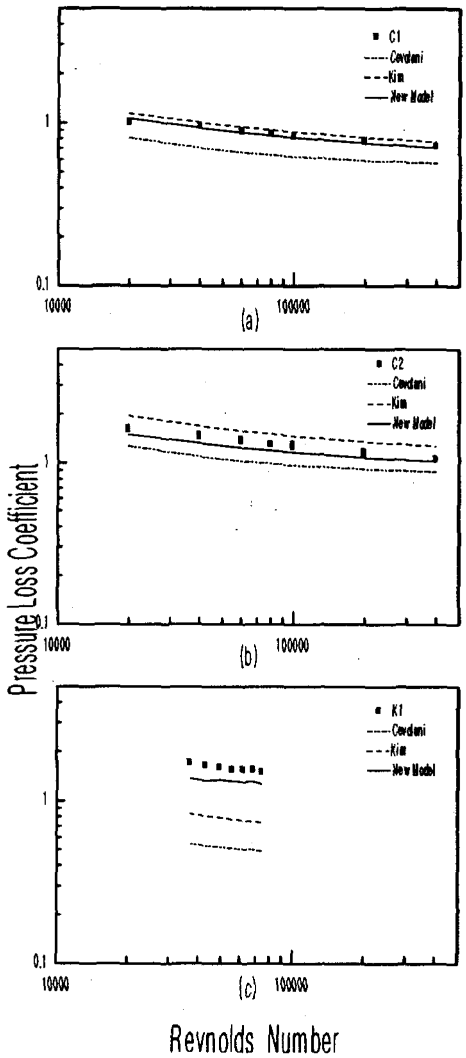


Figure 2. Comparisons of the pressure drop models against the measured data for non-mixing grids

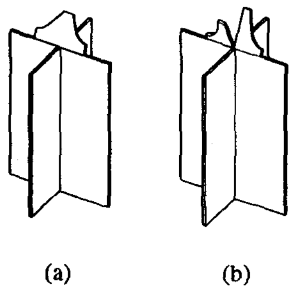


Figure 1. The mixing Devices
(a) Non-split type (b) Split type

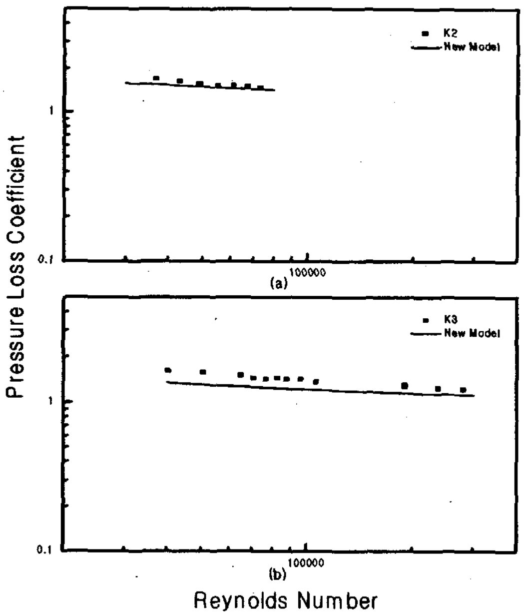


Figure 3. Evaluation of the proposed model for mixing grids