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Pressure Drop Correlation for a PWR Fuel Assembly with Mixing Vane

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Abstract

A pressure drop correlation is developed to estimate the pressure drop across a PWR fuel grid spacer with the mixing vane using a simplified computational fluid dynamics (CFD) analysis. The pressure loss at the mixing-vane spacer was assessed to largely depend on the relative plugging of the flow cross section by the fuel support elements and the mixing vane and the flow acceleration. The correlation coefficients were determined from the experimental data and the increase of fluid velocity from the CFD analysis. The CFD analysis simulated the spacer and mixing vanes as infinite thin surfaces, and neglected the fuel support elements. The measured loss coefficient for the split-vane spacer was reproduced by new correlation well and showed good agreement with the estimated one from the CFD calculation. The correlation loss coefficients for other mixing-vane spacers are also in good agreement with those that are directly estimated from the predicted pressure drops.

1. Introduction

The pressurized water reactor (PWR) fuel assembly is the rod bundle whose rod-to-rod clearance is maintained by the grid spacer. The coolant moves axially through the subchannels formed between neighboring fuel rods and between the peripheral fuel rods and the flow tube. The fuel spacer affects the coolant flow distribution in a fuel rod bundle, and so spacer geometry has a strong influence on a bundle's thermal-hydraulic characteristics, such as critical heat flux and pressure drop. Attempts have been made to increase departure from nucleate boiling (DNB) performance by providing the support grid structures employed to contain the members of the fuel assembly with integral flow mixing vanes. These vanes can improve performance by increasing coolant mixing and rod heat transfer ability downstream of the spacer. These attempts to improve performance have been met with varying success depending on the vane design and the design of other grid components, which can impact the effectiveness of vanes.

The amount of pressure drop at the vane-grid spacer is an important factor of the vane design because it greatly influences the hydraulic compatibility with the existing fuel assembly as well as the capacity of reactor coolant pump. The pressure drop at the vane-grid spacer would increase due to the flow blockage and the acceleration by the mixing vane. The excessive pressure loss at a vane-grid assembly would produce a locally large crossflow that may cause the fuel vibration. The large pressure drop also requires the high capacity of reactor coolant pump to maintain the coolant flow rate. Hence, an accurate prediction of the pressure drop at the vane grid-spacer is necessary for the reactor design calculation but also for the vane-grid development. There are no reliable correlations for the pressure drop caused by the PWR fuel spacer with mixing vane. De Stordeur[1] proposed pressure drop correlations for the fuel spacers with helical pins or the spacers used in gas cooled breeder reactors. Since they were developed based on the small number of experimental data, the correlations given by de Stordeur are bound to be an approximation. Rehme[2] developed more precise correlations based on numerous experimental data for various fuel-spacer configurations without the mixing vane. He assumed that the relative plugging by the fuel spacer straps and elements constitutes the main factor influencing the pressure loss. Kim et al.[3] developed an analytic pressure drop model for a PWR grid spacer without the mixing vane, which was not verified against the experimental data. Oh et al.[4] also proposed a mechanistic model for the pressure drop at various grid-type spacers with mixing vane, which is based on the hydraulic drag forces acting on the grid. The pressure drop by the mixing vane is simply modeled by the plugging area and the form drag coefficient for a simple shape. This model underpredicted a pressure loss coefficient for the split-vane spacer by 15%.

The objective of this paper is to develop a pressure drop correlation for a PWR fuel spacer with mixing vane, which accounts for flow acceleration as well as plugging of the flow cross section by the mixing vane. A computational fluid dynamics (CFD) analysis for the fuel bundle with mixing vane was performed to obtain the increase of the fluid velocity.

2. Correlation Setup

The pressure drop at the grid spacer is related to the fluid velocity U_B in the rod bundle:

$$\Delta P_A = C_B \frac{r U_B^2}{2}, \qquad (1)$$

where C_B is the loss coefficient of the grid spacer and r the fluid density. Assuming that the pressure drop largely depends on the relative plugging (e) of the flow cross section, C_B is written as (Rehme[2])

$$C_B = C_V e^2, \qquad (2)$$

where C_V is the modified loss coefficient. The modified loss coefficients C_V fitted for rod bundles in hexagonal and square arrays showed good agreement and dependence on the Reynolds number Re_B. The Reynolds number Re_B of the flow in the rod bundle is defined as

$$\mathrm{Re}_B = \frac{U_B D_h}{n}, \qquad (3)$$

with n the kinematic viscosity and D_h the hydraulic diameter. It was recommended to use C_V = 6 – 7 for Reynolds numbers in the rod bundle $Re_B > 5 \times 10^4$.

Yang and Chung[5] carried out hydraulic experiment for a 5 x 5 rod bundle with the FOCUS grid spacer. The fuel assembly with optimized cladding and upgraded structure (FOCUS) developed by Siemens is a square array rod bundle with the split vane on the grid spacer. They presented the experimental data of pressure drop at the grid spacer with split vane for various Reynolds number. Figure 1 shows the loss coefficients of the grid spacer for honeycomb-type spacer in square array without mixing vane (Rehme[2]) and for the FOCUS spacer with the split vane (Yang and Chung[5]). The comparison of the loss coefficients in Fig. 1 explicitly illustrates additional pressure drop due to the mixing vane.

Taking into account additional pressure drops by mixing vane, the total loss coefficient for the grid spacer with mixing vane can be expressed as

$$C_B = C_V e^2 + C_{mv} e_{mv}^2 + C_a b^2 . \tag{4}$$

The second term in the right hand side of eq. (4) represents a loss coefficient for the flow blockage with C_{mv} the vane dependent coefficient and $e_{mv} = A_{mv} / A_o$ the relative plugging area by the mixing vane, where A_{mv} is the projected vane area on the flow cross section and A_o is the undisturbed flow section. The third term represents a loss coefficient for the flow acceleration by the mixing vane with C_a the acceleration coefficient and b the relative increase of fluid velocity:

$$b = \frac{U_{\max}}{U_B} , \tag{5}$$

where U_{max} is the local maximum axial velocity at the top of the spacer. The fluid velocity distribution can be obtained from the CFD analysis for the rod bundle with mixing vane.

3. Evaluation of Correlation

3.1 Correlation Coefficients

The experiment with the FOCUS spacer by Yang and Chung[5] provides the measured pressure data at the grid-type spacer with the mixing vane that are only available to the authors. The coefficients in the proposed correlation (eq. 4) were determined using the measured loss coefficients and the predicted velocity distribution. It is noted that the relative plugging of the flow cross section is e =0.254 for the honeycomb-type spacer (no mixing vane) and e_{mv} =0.22 for the split vane, respectively. Figure 2 is the contour plot of the calculated axial velocity at the top of the FOCUS spacer. It shows a peak velocity at the unplugged quadrants of the subchannel. The vane dependent coefficient (C_{mv}) for the split vane is assumed to be equal to the modified loss coefficient (C_V) for the fuel support elements because they are both configured to cause an abrupt plugging. The flow acceleration coefficient (C_a) in eq. 4 was then determined using the measured loss coefficient.

Figure 3 shows the relative increase of fluid velocity (b) and the flow acceleration coefficient (C_a) as a function of the Reynolds number. Both the increase of fluid velocity and the flow acceleration coefficient tend to decrease as the Reynolds number increases. The flow acceleration coefficient can be well fitted with the following polynomial form,

$$C_a = 4.5668 - 1.7382\log(\mathrm{Re}) + 0.1704\log^2(\mathrm{Re})\,. \tag{6}$$

3.2 Loss Coefficients for the FCOUS Spacer

A CFD analysis was performed to predict the axial variations of velocity and pressure. A single subchannel of one grid span is modeled using flow symmetry by a CFD code, CFX[6]. Body-fitted and non-staggered grid systems were used to deal with complex geometries. The spacer and mixing vanes are treated as infinite thin surfaces. The other fuel spacer elements such as the spring and arches are neglected for simplicity because their effect on the flow field is judged to be minimal only inside and near the spacer. The numerical simulation starts 40 mm upstream and 500 mm downstream of the top of the grid spacer. Figure 4 shows the axial variation of predicted pressure for the FOCUS spacer. It can be noted in Fig. 4 that a large pressure drop occurs across the spacer. The amount of pressure drop appears to decrease as the Reynolds number increases. This is consistent with the exponential decay of the measured loss coefficient in Fig. 1.

The measured loss coefficient for the FOCUS spacer is compared with the calculated loss coefficient by the CFD analysis in Fig. 5. It is noted that the loss coefficient due to the fuel support elements is added to the calculated loss coefficient from the CFD analysis. This is because the fuel support elements were neglected in this CFD simulation. Although the calculated loss coefficient is slightly higher than the measured one, the comparison shows an excellent agreement within the error of 4%. Hence, it is reasonable to estimate the loss coefficient across the spacer with the mixing device by a simplified CFD analysis.

3.3 Loss Coefficients for Other Mixing-Vane Spacers

The new pressure drop correlation was applied to the advanced PWR fuel spacers with the Westinghouse split vane (with vane cutout) and the ABB-CE side-supported vane. The CFD analyses were also performed to obtain the distributions of velocity and pressure. The split-vane angle(q), defined as the angle bent from the axial direction, was assumed to be 30^o in this study because it is not known. The side-supported vane is bent inward along its side by 90^o. The relative plugging of the flow cross section by the mixing vane is 0.243 for the W split vane and 0.195 for the CE side-supported vane. Figure 6 shows the axial velocity distribution in the flow cross section at the top of each grid spacer. The maximum velocity is observed at the unplugged quadrants of the subchannel for both vanes. The split-vane case shows a relatively higher velocity at the center of the gap in the plugged quadrants of the subchannel. Figure 7 shows the increase of fluid velocity for the Westinghouse split vane and the ABB-CE side-supported vane. The increase of fluid velocity slightly decreases as the Reynolds number increases. The velocity increase appears to stay at an asymptotic value for the Reynolds number higher than approximately 40000. The Westinghouse split vane is predicted to cause higher increase of fluid velocity than the ABB-CE side-supported vane.

Figure 8 shows the comparisons of pressure loss coefficients for the Westinghouse split vane and the ABB-CE side-supported vane. Since the experimental results for these mixing vanes are not available to date, the loss coefficients by new correlation model (eq. (4)) were compared with those of the CFD calculations. It is noted that the correlation coefficients for the FOCUS spacer were used in this estimation. The comparison for the

Westinghouse split vane shows excellent agreement between the correlation and the calculation within the maximum difference of 4%. This agreement is largely due to the similarity of the Westinghouse split vane (vane cutout) and the FCOUS split vane (no vane cutout). The correlated loss coefficient for the ABB-CE side-supported vane also agrees well with the estimated loss coefficient from the CFD result. The maximum difference is less than 12% at low Reynolds number. The somewhat large difference for the side-supported vane is believed to result from the vane dependent correlation coefficient whose value was assumed for the split-type vane. For a more accurate pressure drop correlation, it is necessary to optimize the vane dependent coefficient for the side-supported vane if the experimental data is available in the future.

4. Conclusion

This study investigated the pressure drop across a PWR fuel grid spacer with the mixing vane and developed a loss coefficient correlation. Experimental data illustrated that the pressure loss at the mixing-vane spacer is largely depend on the relative plugging of the flow cross section by the fuel support elements and the mixing vane, and the flow acceleration. A new correlation was established to predict the pressure loss coefficient for the fuel spacer with the mixing vane. The correlation coefficients were determined from the experimental data and the CFD analysis for the FOCUS split-vane spacer. The correlated loss coefficient reproduced the measured one for the FOCUS split-vane spacer well, and showed good agreement with the estimated one from the CFD calculation within an error of 4%. The correlation loss coefficients for the Westinghouse split vane and the ABB-CE side-supported vane are also in good agreement with those that are directly estimated from the CFD pressure drops. It is however necessary for more accurate pressure drop correlation to validate the correlation with experimental data for various mixing-vane spacers in the future.

Acknowledgements

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References

[1] A. N. de Stordeur, "Drag Coefficients for Fuel Element Spacers," *Nucleonics*, Vol. 19, No. 6, 74 (1961).

[2] K. Rehme, "Pressure Drop Correlations for Fuel Element Spacers," *Nuclear Technology*, Vol. 17, 15 – 23 (1973).

[3] N. H. Kim, S. K. Lee and K. S. Moon, "Elementary Model to Predict the Pressure Loss across a Spacer Grid without a Mixing Vane," *Nuclear Technology*, Vol. 98, 349 – 353 (1992).

[4] D. S. Oh, W. K. In, J. G. Bang, Y. H. Jung and T. H. Chun, "A Pressure Drop Model for PWR Grids," *Proc. of the KNS Spring Meeting*, Seoul, Korea, May, 483 - 488 (1998).

[5] S. K. Yang and M. K. Chung, "Spacer Grid Effects on Turbulent Flow in Rod Bundles," *J. of the Korean Nuclear Society*, Vol. 28, No. 1, 56 – 71 (1996).

[6] CFX International, CFX-4.2: Solver, AEA Technology, Oxfordshire, UK (1997).

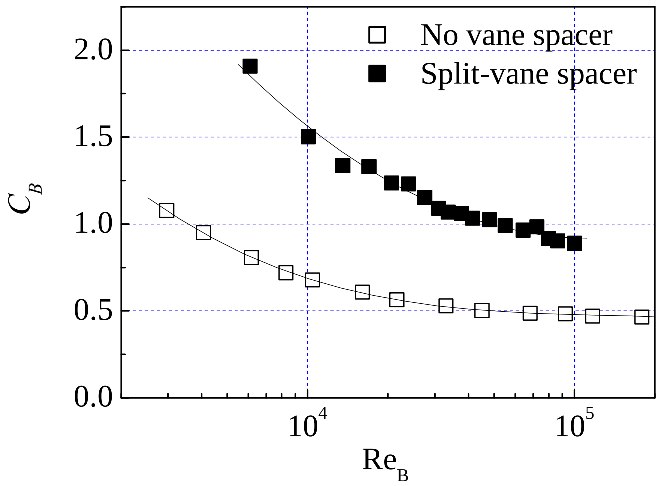

Fig. 1 Pressure loss coefficients for the square array spacers without mixing vane (Rehme[2]) and with the split vane (Yang and Chung[5])

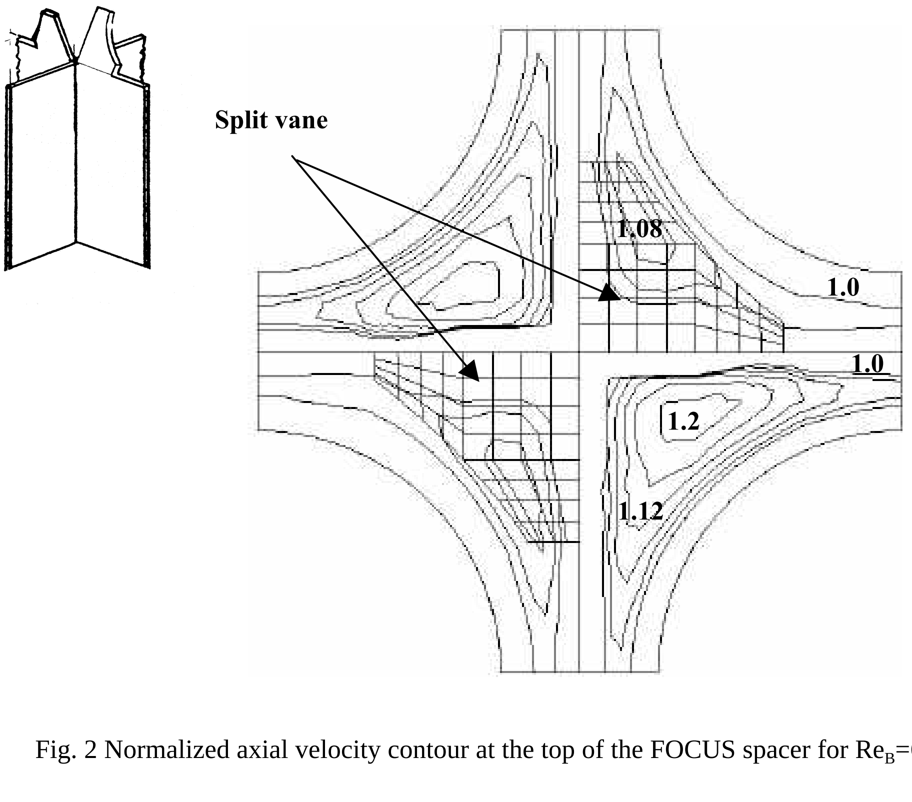

Fig. 2 Normalized axial velocity contour at the top of the FOCUS spacer for Re_B=62500

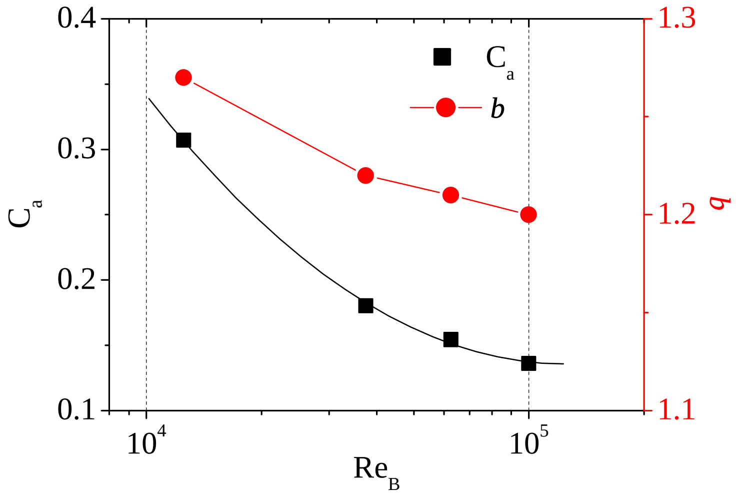

Fig. 3 Flow acceleration coefficient (C_a) and relative increase of fluid velocity (b) for the FOCUS spacer

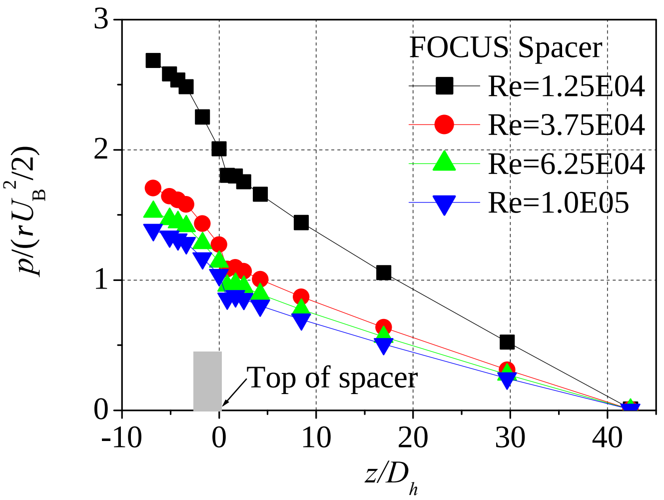

Fig. 4 Calculated pressure distributions for the FOCUS spacer

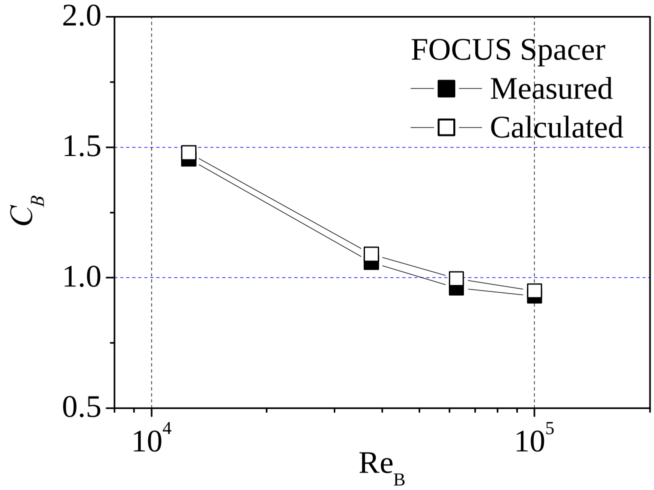

Fig. 5 Comparison of the pressure loss coefficients for the FOCUS spacer

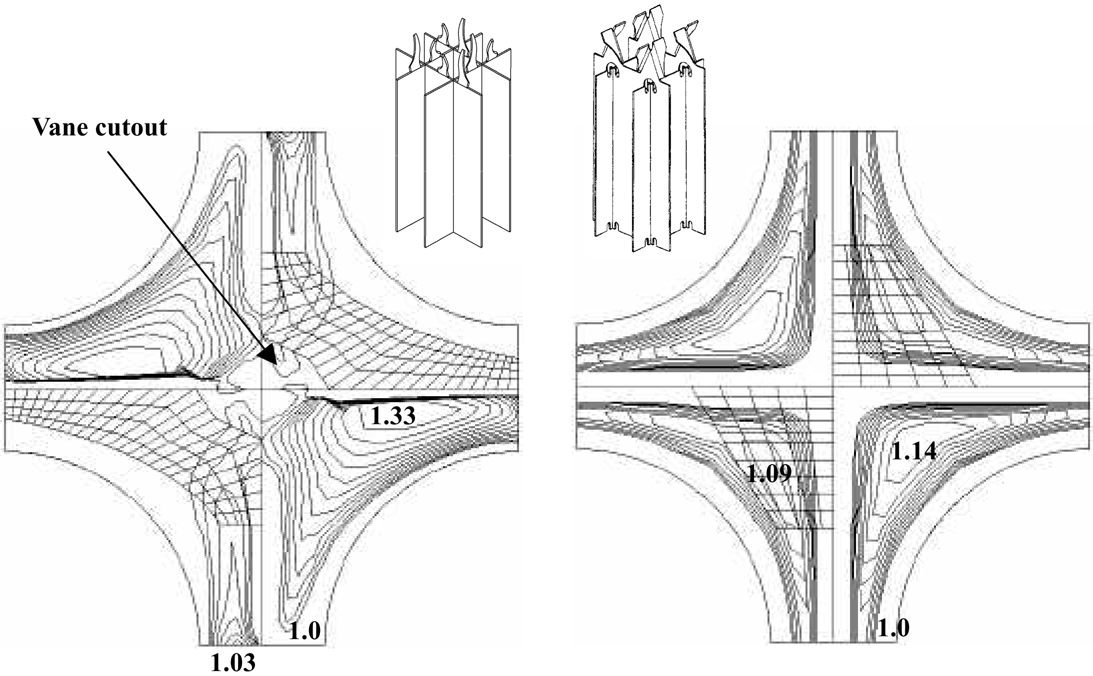

Fig. 6 Normalized axial velocity contour at the top of the spacer for Re_B=85000; (left) Westinghouse split vane with vane cutout, (right) ABB-CE side-supported vane

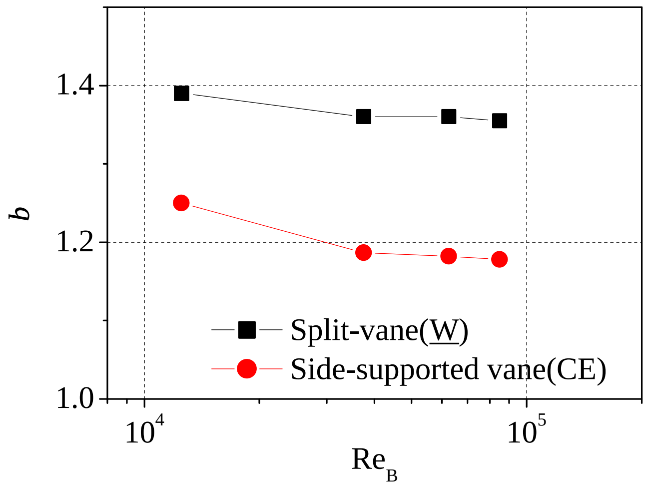

Fig. 7 Calculated increase of fluid velocity for the Westinghouse split vane and the ABB-CE side-supported vane

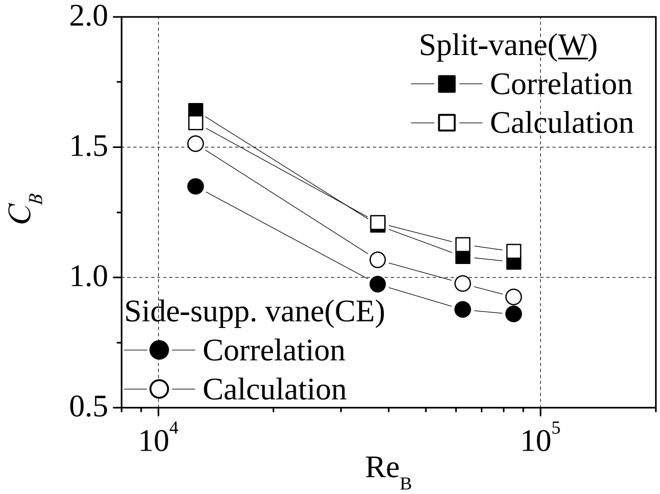

Figure 8 Comparisons of the pressure loss coefficients for the Westinghouse split vane and the ABB-CE side-supported vane