Analytical Prediction of Turbulent Friction Factor for a Subchannel Consisting of a Rod Bundle

Jun Ho Bae* and Joo-Hwan Park
Korea Atomic Energy Research Institute, P.O.Box 105, Yuseong, Daejon, 305-600, Korea
**Corresponding author: bjh@kaeri.re.kr*

1. Introduction

The pressure drop characteristics for a non-circular subchannel consisting of a fuel channel are essential for the design and reliable operation of a nuclear reactor and are important also in other engineering applications. The turbulent friction factor for a rod bundle is analytically derived by integrating the law of the wall over the cross section. In order to enhance the accuracy of prediction for the pressure drop in a rod bundle, the influences of a channel wall and the local shear stress distribution are considered in this study. The objective of this study is to examine the characteristics of geometry parameters for each subchannel consisting of a rod bundle and scrutinize the effect of the geometry parameters of each subchannel on the friction factor of each subchannel.

2. Numerical methods

For turbulent dominated wall region ($y^+ > 26$), the law of the wall has the classical form

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\frac{yu_*}{\nu} + B \tag{1}$$

Integration of the law of the wall results in

$$\left(\frac{8}{f}\right)^{1/2} = A\left[2.5\ln\left(\frac{1}{2\sqrt{8}}\mathrm{Re}\sqrt{f}\right) + 5.5\right] - G^* \tag{2}$$

where A, G^* denote turbulent geometry parameters. Figure 1 shows the typical geometry of a rod bundle which consist of a centre, corner and side subchannels.

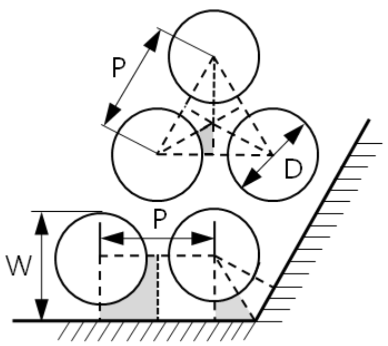

Fig.1 Geometric configuration of a fuel element

For a centre subchannel, integration of Eq. (1) over symmetric region leads to

$$\frac{\bar{u}}{u_*}F = \int_0^{\theta_s}\int_0^{P/2\sec\theta - R}\left(\frac{1}{\kappa}\ln\frac{yu_*}{\nu} + B\right)(R+y)\,dy\,d\theta \tag{3}$$

The geometry parameters A, G^* are

$$A = \frac{1}{F}\int_0^{\theta_s}\frac{Z(\theta)}{2}\left(\frac{p^2}{4}\sec^2\theta - R^2\right)d\theta \tag{4}$$

$$G^* = -\frac{2.5}{F}\int_0^{\theta_s}\{\frac{Z(\theta)}{2}\left(\frac{P^2}{4}\sec^2\theta - R^2\right)\ln\left(\frac{2Z(\theta)}{D_h}\left(\frac{P}{2}\sec\theta - R\right)\right) - \frac{Z(\theta)}{4}\left(\frac{P}{2}\sec\theta + 3R\right)\left(\frac{P}{2}\sec\theta - R\right)\}d\theta \tag{5}$$

For the side and corner subchannel, the flow area can be subdivided into three elements by the zero shear stress lines, since it can be assumed that there is no momentum transport across these lines. The law of the wall was integrated over each element of a subchannel. The law of the wall was integrated over each element of a subchannel. By applying the continuity equation in a subchannel, the friction factor equation results to have the same form with Eq.(2) except the different value of geometry parameters.

3. Results

With the information of geometry shape and the shear stress distribution, the geometry parameters for each subchannel have been calculated over the range of 1.0 < P/D < 3.0 with the increment of 0.02. Figure 2 show the geometry parameters for each subchannel. It is revealed from the figure that, for the lower rod distance ratio, the geometry parameters are largely affected by the local shear stress distribution $Z(\theta)$ which brings the steep variation of geometry parameters for P/D < 1.2. As the rod distance ratio increases, the local shear stress distribution changes to have a uniform distribution along the rod surface, which results the geometry parameter A to converge to the value of 1.0 over P/D > 1.2.

The flow area of the corner subchannel is surrounded by two wall boundaries. Hence, it has a similar shape with the angular section of circular tube flow for a large W/D. These geometrical characteristics of subchannels are reflected to the analytical value of geometry parameter. Figure 2 shows that the geometry parameter G^* of corner subchannel has the converged value of 3.97 for a large W/D, which is in accord with the Maubach's suggestion for a smooth circular tube. With different to the corner subchannel, the geometry parameters

G^* of centre and side subchannel are shown to increase with the rod distance ratio for P/D > 1.2 because of the presence of the symmetry boundary instead of a wall boundary. The increasing rate is steeper for the centre subchannel, which has a two-symmetry boundary, rather than the side subchannel having the one-symmetry and one-wall boundary. These features of geometry parameter G^* can also be interpretated by the Maubach's representation. The geometry parameter G^* of turbulent flow is represented as

$$G^* = \frac{u_{\max} - u_m}{u_*} \quad (6)$$

with the friction velocity u_*. It is noted that the wall boundary increases the friction velocity of the subchannel with the rod distance ratio, while the symmetry boundary does not affect the friction velocity of the subchannel, irrespective to the rod distance ratio. Hence, the subchannel with symmetry boundary has the increased pattern of geometry parameter with the rod distance ratio.

By substituting the geometry parameters A and G^* into Eq. (2), the friction factor for subchannels can be calculated. Figure 3 shows the friction factor for each subchannel, which is referenced by the Blasius circular tube friction factor, $f_c = 0.079 \cdot \mathrm{Re}^{-0.25}$. For P/D=1.0, the friction factor has about 60 percent of the value for a circular tube, irrespective to the subchannel shape. For lower rod distance ratio, the friction factor sharply increases and it has the value for a circular tube in the range of 1.1 < P/D < 1.3. Triangular type subchannel shows the most steep increase of friction factor and it has the value for a circular tube at P/D=1.08, which represents that the triangular type subchannel is the most sensitive structure to the shear stress distribution for lower rod distance ratio. It can be interpretated from the geometric configuration in Fig. 1 that triangular type subchannel has the lowest symmetry angle of $\pi/6$, which means the shear stress distribution varies frequently around a rod surface.

In the present study, through the derivation of the friction factor for each subchannel, it is revealed that the friction factor of each subchannel has different characteristics according to the channel shape. As disclosed in Fig. 3, for the centre subchannel, the friction factor shows a steady increase for P/D > 1.2, while, for the corner subchannel, the friction factor converges to a constant value. These features of friction factor seem to be in line with the variation of geometry parameter G^* in Fig. 2.

4. Conclusions

For each subchannel consisting of a rod bundle, the geometry parameter G^* and friction factor f sharply increases with the rod distance ratio for a lower rod distance ratio, and the effect of rod distance ratio on G^* and f is weak for higher rod distance ratio.

The analytical derivation for each subchannel reveals that the geometry parameter and friction factor are explicitly dependent on the subchannel shape.

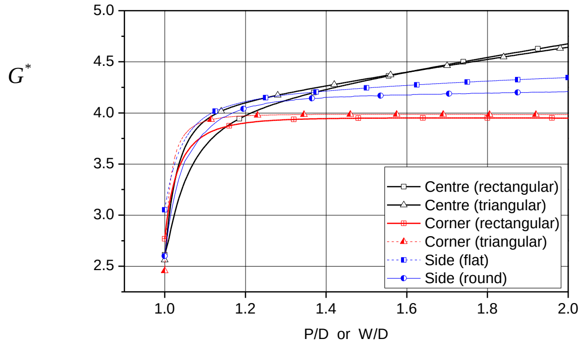

Fig.2 Turbulent geometry parameter G^*

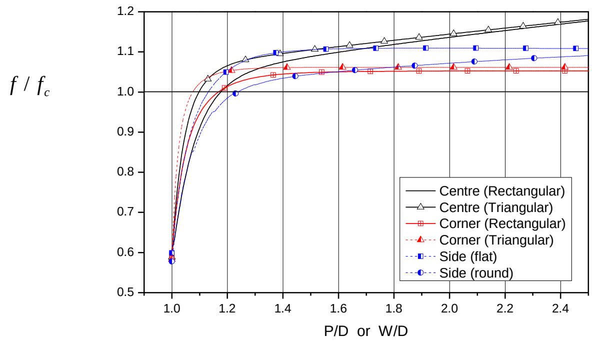

Fig.3 Turbulent friction factors for subchannels

ACKNOWLEDGMENT

This work was supported by Nuclear Research & Development Program of Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST). (grant code : M20702040005-08M0204-00510)

REFERENCES

[1] Maubach, K., Reibungsgesetze, "Turbulenter Stromungen, Chemie-Ing", Technik 42, (1970).
[2] Rehme, K., "Simple Method of Predicting Friction Factors of Turbulent Flow in Non-circular Channels, Int. J. Heat Mass Transfer", 16, 933-950, (1973).
[3] Lee, K.B., "Analytical Prediction of Subchannel Friction Factor for Infinite Bare Rod Square and Triangular Arrays of Low Pitch to Diameter Ratio in Turbulent Flow", Nuclear Eng. & Design, 157, 197-203, (1995).