Estimation of Porous Media Approach for Thermal Hydraulics of Nuclear Fuel Assembly

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1. Introduction

In many CFD studies, porous media assumption has been often used for thermal hydraulics of nuclear fuel assembly, e.g., reactor core, storage cask, spent fuel pool and etc. and it could be applied extensively as shown in Fig. 1. However, the assumption could not predict the local phenomena in a subchannel or the mixing effect between subchannels and did not consider distribution of variables.

This work validates the porous media approach in nuclear fuel assembly from two aspects, friction factor and averaged temperature and discusses about appropriate use of the porous media approach at the various fluid conditions. Commercial CFD code CFX 12.0 was used.

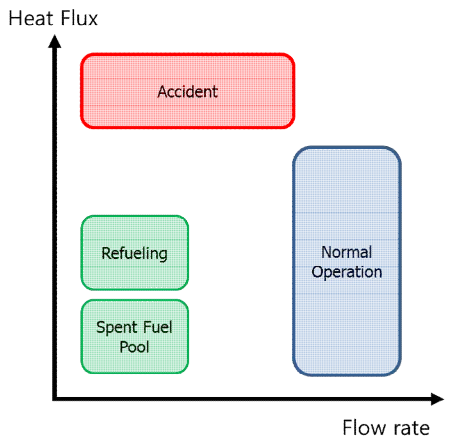

Fig. 1. Thermal hydraulic conditions of nuclear fuel assembly with operations and treatments

2. Numerical Methods

Two meshes were prepared. One is real sized nuclear fuel assembly with around quarterly length, which is bare rod bundle without any spacer grids and is shown in Fig. 2. The other is simple porous rectangle pipe. Through grid test, proper mesh size was provided into each mesh.

To accuracy of calculation, the numerical scheme and convergence was checked. When calculated in real sized nuclear fuel assembly, turbulent model was also checked. Next section shows the results of comparison of turbulent model.

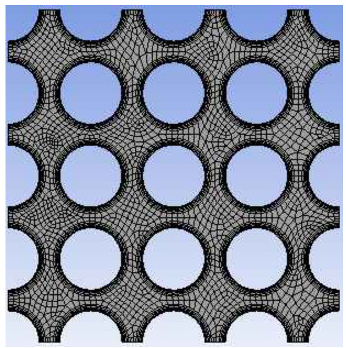

Fig. 2. Grid for bare rod bundle

2.1 Friction factor for bare rod bundle

There are many correlations to estimate the friction factor for bare rod bundle of square array and hexagonal array. In this study, the correlation proposed by Rehme [1] was considered as follows.

a. Larminar flow

$$f\,\mathrm{Re} = 40.70\left(\frac{P}{D}-1\right)^{0.435}$$

b. Turbulent flow

$$f = \frac{A_1}{4}\mathrm{Re}^{-0.25} \qquad \text{for } 10^4 \le \mathrm{Re} \le 5\times10^4$$

$$f = \frac{A_1}{4}\mathrm{Re}^{-0.2} \qquad \text{for } 5\times10^4 \le \mathrm{Re} \le 2\times10^5$$

$$A_1 = 0.181 + 0.0108\frac{P}{D} - 0.132e^{-20(P/D-1)}$$

2.2 Porous parameter

For treatment of porous media in CFX 12.0 [2], momentum source was added to governing equation as below,

$$S = -\frac{\mu}{K_{perm}}U - K_{loss}\frac{\rho}{2}|U|U$$

In his equation, K_{perm} and K_{loss} mean permeability and loss coefficient respectively. Physically, first term is by inertia force and second term is by drag force. However, typically, each term is relevant to laminar and turbulent effect.

3. Results

3.1 Turbulent Model

According to the study by J. Su et al. [3], it is hard to estimate the flow characteristics in bare rod bundle geometry completely due to complex flow phenomena. Nevertheless, RANS turbulent models are compared with each other. Table 1 shows the results. Based on Rehme's friction factor, most turbulent models were over-predicted. But the group of k-e models have a relatively good prediction especially RNG k-e model.

Table 1. Comparison of turbulent models

Rehme [1]	Standard k-e upwind	SST upwind	k-w upwind	RNG k-e upwind	RNG k-e High resol.
0.268 kPa	0.2735	0.3317	0.3416	0.2609	0.2621

3.2 Real Geometry vs. Porous Assumption

The flow condition was selected covering all conditions of nuclear fuel such as accident, normal operation, refueling and spent fuel treatment and the porous assumption was selected as a baseline conditions.

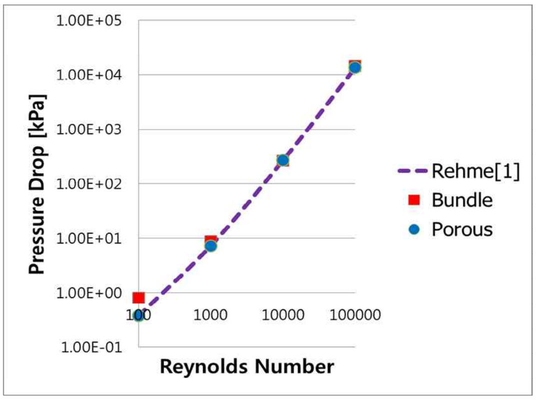

Fig. 4. Variation of pressure drop with Reynolds number

Fig. 4 shows the pressure drop (friction factor) with the Reynolds numbers. In spite of the a little over-prediction in bare rod bundle, friction factors in both geometries are generally coincident with Rehme's correlation from laminar flow regime to turbulent flow regime. But friction factor in bare rod bundle make about 200% error at very low Reynolds number. In Fig. 5, there are the trends of difference of averaged outlet temperature with wall heat flux. In this calculation, the wall heat flux was converted into volumetric heat generation in porous assumption. Averaged temperature in porous assumption is lower than that in bare rod bundle. The difference is amplified at the high heat flux due to the almost constant difference ratio. The difference ratio is defined as

$$D.R. = \frac{T_{avg,bundle} - T_{porous}}{T_{porous}} \times 100[\%]$$

In addition to prediction of averaged temperature, if ratio of maximum temperature to porous averaged temperature (Maximum Difference Ratio) was also considered, porous assumption could not be appropriate in some cases. The maximum difference ratio is defined as

$$M.D.R. = \frac{T_{\max,bundle} - T_{porous}}{T_{porous}} \times 100[\%]$$

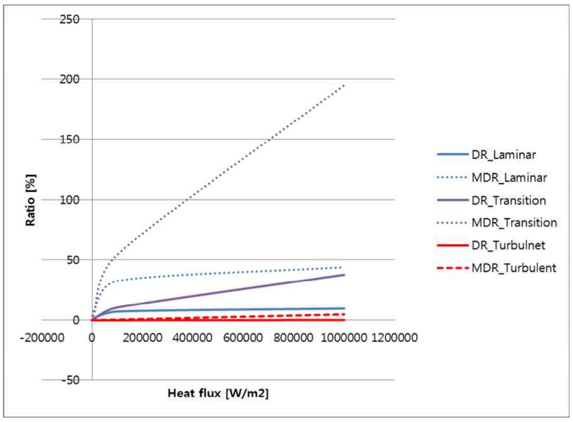

Fig. 5. Variation of the difference ratio and maximum difference ratio with heat flux

3. Conclusions

The study concludes that the prediction of friction factor is in a good agreement with experiment and porous assumption except for very low Reynolds number region. Furthermore, the study recommends that porous assumption could distort temperature calculations and if the maximum temperature is critical in any problem, porous assumption could not be appropriate. Therefore, appropriate application of porous assumption was dependent on the flow conditions.

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