Single-Phase Bundle Flows Including Macroscopic Turbulence Model

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1. Introduction

Analysis for bundle flows is the main subject of thermal hydraulics in nuclear systems, of which reactor cores or steam generators can be the representatives. For the analysis of the bundle flows, subchannel analysis codes [1, 2] have been validated faithfully and used widely in designing the components in bundle geometries.

We focus on developing a multi-dimensional thermal hydraulics analysis methodology for bundle geometries covering accidental conditions. To deal with various thermal hydraulic phenomena due to rapid change of fluid properties when an accident happens, securing mechanistic approaches as much as possible may reduce the uncertainty arising from improper applications of the experimental models.

In this study, the turbulence mixing model, which is well defined in the subchannel analysis code such as VIPRE, COBRA, and MATRA by experiments, is replaced by a macroscopic k-e turbulence model, which represents the aspect of mathematical derivation. The performance of CUPID [3] with macroscopic turbulence model is validated against several bundle experiments: CNEN 4x4 and PNL 7x7 rod bundle tests.

2. Turbulence Mixing

2.1 k-ε Turbulence Model in Porous Medium

The dispersion effect in momentum equation, which is derived mathematically when porous approach is used, can be passed down from fluctuation equations of momentum conservation to the k-e turbulence equation. Even though the dispersion is modelled into $\overline{R}$, it remains still in the turbulence equations in a form of fluctuation sources. For physical understanding, the dispersion effect in turbulence conditions should be added in the turbulence transport equations, because there is no sources of turbulence (e.g. wall) generation due to porous media concept.

Eqs. (1)-(2) show the double decomposed time- and volume-averaged k-e turbulence equation for porous medium [4, 5].

$$\begin{aligned}&\rho\frac{\partial}{\partial t}\left(\phi\langle k\rangle^{i}\right)+\nabla\cdot\left\{\overline{u}_{D}\langle k\rangle^{i}\right\}\\&=\nabla\cdot\left[\left(\mu+\frac{\mu_{T}}{\sigma_{k}}\right)\nabla\left(\phi\langle k\rangle^{i}\right)\right]\\&+\langle u'u'\rangle^{i}:\nabla\overline{u}_{D}+\phi P_{k}-\rho\phi\langle\varepsilon\rangle^{i}\end{aligned}\quad, \tag{1}$$

$$\begin{aligned}&\rho\frac{\partial}{\partial t}\left(\phi\langle\varepsilon\rangle^{i}\right)+\nabla\cdot\left\{\overline{u}_{D}\langle\varepsilon\rangle^{i}\right\}\\&=\nabla\cdot\left[\left(\mu+\frac{\mu_{T}}{\sigma_{\varepsilon}}\right)\nabla\left(\phi\langle\varepsilon\rangle^{i}\right)\right]\\&+\phi\left\{2c_{1}\left(\mu_{T}\langle s_{ij}\rangle^{i}\langle s_{ij}\rangle^{i}\right)-c_{2}\langle\varepsilon\rangle^{i}\right\}\frac{\langle\varepsilon\rangle^{i}}{\langle k\rangle^{i}}\\&+\phi S_{\varepsilon}\end{aligned}\quad, \tag{2}$$

where P_k and S_ε are modelled for porous medium and it makes Eqs. (1)-(2) the macroscopic k-e turbulence equation. P_k (or S_ε) includes both the turbulence kinetic (or the dissipation rate) energy source and turbulence dispersion source.

2.2 Modelings

The friction and foam loss in momentum conservation equation are modelled on the basis of Darcy-Forchheimer equation.

$$-\frac{1}{2}\rho\left(\frac{K}{L}\langle\overline{u}\rangle_{f}+\frac{C_{f}}{D_{h}}\langle\overline{u}\rangle_{f}\right)\langle\overline{u}\rangle_{f}\ , \tag{3}$$

where K is the foam loss factor determined by experiments and adopts models of typical subchannel analysis codes. C_f means the friction coefficients as follow [2]:

$$C_{f}=\begin{cases}64\,\mathrm{Re}^{-1} & ,\mathrm{Re}<2300\\0.316\,\mathrm{Re}^{-0.25} & ,2300<\mathrm{Re}<30000\\0.084\,\mathrm{Re}^{-0.2} & ,3\cdot10^{4}<\mathrm{Re}<10^{6}\end{cases}\cdot \tag{4}$$

The turbulence sources [4] are as follow:

$$S_k = \frac{0.1582}{\left(\frac{\langle \bar{u}\rangle^f d}{\nu}\right)^{1/4}} \frac{\left(\langle \bar{u}\rangle^f \langle \bar{u}\rangle^f\right)^{3/2}}{d^2}, \qquad (5)$$

$$S_\varepsilon = 0.18984 c_2 \left(\frac{\langle \bar{u}\rangle^f d}{\nu}\right)^{-1/4} \frac{\left(\langle \bar{u}\rangle^f \langle \bar{u}\rangle^f\right)^2}{d^2}. \qquad (6)$$

Eqs. (5)-(6) is only for channel and pipe flows.

3. Validation of Macroscopic Turbulence Model

The macroscopic k-e turbulence model is tested against CNEN 4X4 [6] and PNL 7X7 (90% blockage) [7]. CNEN 4X4 problem is chosen as a representative of straight rod bundle flow problems and PNL 7X7 problem represents strong axial flows effect.

Fig. 1 shows the CNEN 4X4 rod bundle configuration. The corner is modelled as a rectangular area but revised the flow area, porosity and hydraulic diameter.

Fig. 2 shows the PNL 7X7 rod bundle configuration. The solid black lines over the rod geometry are the mesh for the analysis using the CUPID code. The blockage is located in the middle of the total height. Although 70% and 90% blockage tests were done in experiment, in this study, only 90% blockage was consider.

All the other details can be found in [6-7].

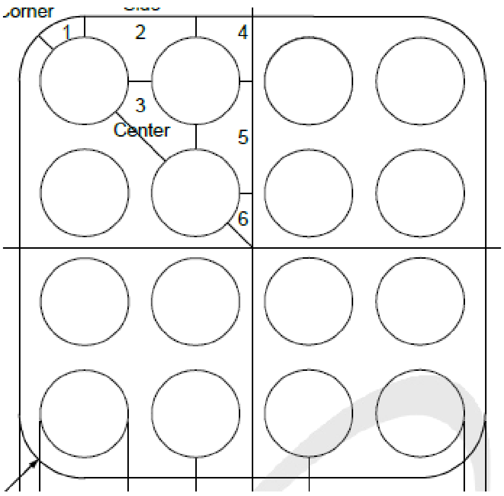

Fig. 1. CNEN 4X4 rob bundle configuration [2].

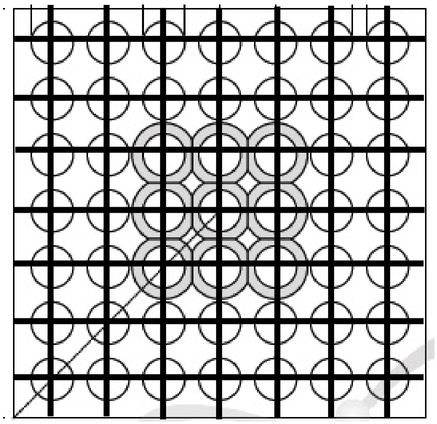

Fig. 2. PNL 7X7 rob bundle Configuration with blockage [2].

CNEN 4X4 rod bundle tests were done for 5 different inlet velocities as shown in Fig. 3. Fig. 3 shows that without the turbulent mixing term velocity at corner cells is under-predicted. When k-e turbulence model is applied, mass and momentum exchange across the subchannels is increased. Furthermore, macroscopic model improves the results of the standard model up to the experiments.

A PNL 7X7 rod bundle with 90% blockage was tested. Due to the blockage, the axial flow was disturbed and strong cross flows appear. Fig. 4 shows all models in CUPID predict well the jetting flow inside the blockage. After the blockage area, the recovery region is affected by turbulence mixing. The standard k-e turbulence model tends to over-predict, while the macroscopic model under-predicts. Since there is no proper model for those curved flows in porous medium, the accuracy of the macroscopic model cannot be guaranteed in this case.

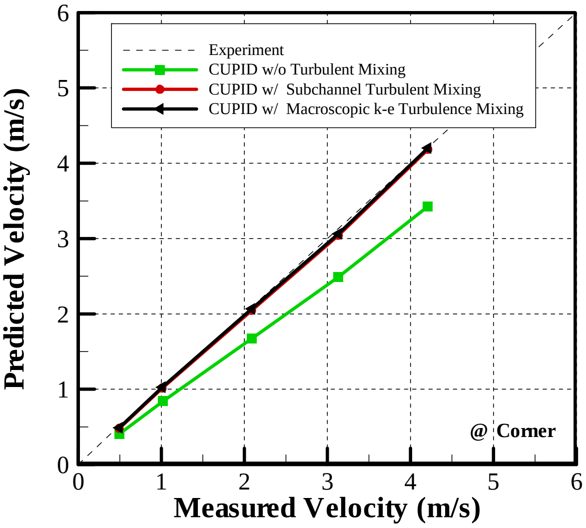

Fig. 3. CNEN 4X4 rod bundle analysis result.

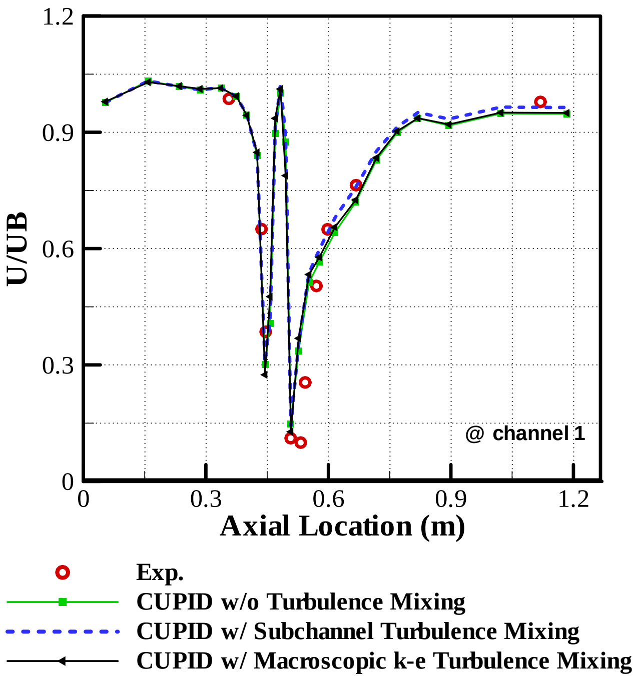

Fig. 4. PNL 7Ｘ7 rob bundle (90% blockage) analysis result.

4. Conclusions

In this study, the macroscopic k-e model has been validated for the application to subchannel analysis. It has been implemented in the CUPID code and validated against CNEN 4x4 and PNL 7x7 rod bundle tests. The results showed that the macroscopic k-e turbulence model can estimate the experiments properly. Especially when the major flow direction is longitudinal to the rod bundle, the macroscopic turbulence model was the same with the subchannel turbulence mixing model. For the flows across the blockage, the strong dispersion around the blockage can may affect the deviation of velocity. For the future work, the macroscopic k-e turbulence model will be modified to include the dispersion effect.

ACKNOWLEGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1305011) and Nuclear Research and Development Program (2012M2A8A4025647).

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