Assessment of Turbulence Models and Its Application to Pebble Bed Reactor

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1. Introduction

In this study, some Reynolds-averaged Navier-Stokes (RANS) models were evaluated using a commercial computational fluid dynamics (CFD) code, CFX 5.7 [1]. Results of numerical analysis are introduced and compared with those of experiment to determine the most applicable model that is to be applied to a three-dimensional sample pebble geometry. Though, in experiment, a cylindrical heating element was installed as an obstacle while pebbles are in spherical shape, the characteristics of flows which are dependent on Reynolds number such as flow separation, vortex generation, drag forces, etc show physically similar trends for both flows around a cylinder and a sphere [2].

For pebble bed simulation, a numerical analysis result was recently reported by Yesilyurt et al.[3] in which a body-centered cubic (BCC) pebble assembly was used while a face-centered cubic (FCC) was considered in this study.

2. Experiment

The experimental facility is 2.7m-high vertical open channel using air which flows down by suction with a turbofan blower. The dimension of test section is 0.2m × 0.5m × 0.023m. One cylindrical heating elements (d = 0.04m) was installed at the center of test section.

Mean velocities, temperatures and pressure drop are measured. Inlet velocity of the air flow was set to 10m/s. Hot-wire was used for velocity measurements at inlet and outlet of test section and at surroundings of heating element. Pressure drop between inlet and outlet of test section was measured by a DP transmitter.

3. Turbulence model assessment

3.1 Turbulence models

Turbulence models considered in current study are models based on RANS equations. RANS models seek to solve a modified set of transport equations by introducing averaged and fluctuating components. In this study, Reynolds stress models and eddy viscosity models which consist of the standard k-ε model, the RNG k-ω model and the standard k- ω model were used.

3.2 Results of model assessment

Figure 1 shows the comparison result of streamwise velocity profiles between experiment and calculation. Velocity magnitude divided by average inlet velocity U_{IN} was depicted. The velocities were obtained along the centerline of the test section. The x-axis shows distance from the center of obstacle normalized by outer diameter of the obstacle. In front of the cylinder where the flow is basically inviscid, all results show no difference, while there are large differences in the wake region. The negative velocity just after the cylinder implies the recirculation region and the negative value of experiment was determined by visualization using tufts. Standard k-ε model and standard k-ω model considerably overestimate the length of the separation zone. Especially the results by k-ω model are most far from experimental results.

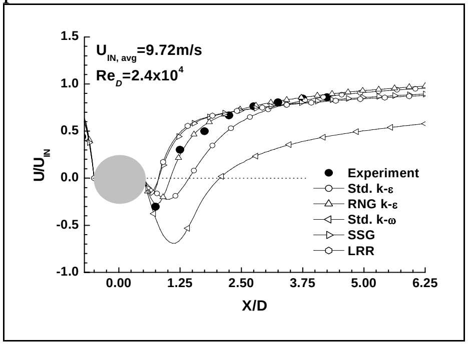


Figure 1. Streamwise Velocity Profiles at Centerline

RNG k-ε model gives the best agreement with the measurement. This model shows a better result than the results of Reynolds stress models which yield too short separation region and considerably too small negative velocities for both LRR and SSG models. The length of separation region and the recovery behavior of RNG k-ε model can be seen in Figure 2.

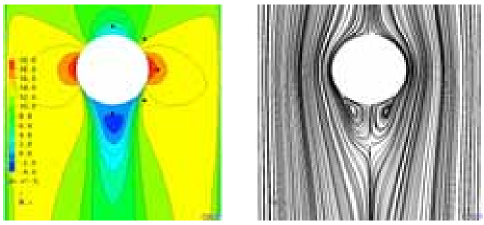


Figure 2. Streamwise Velocity Contours and Streamlines

4. Pebble bed simulations

4.1 Geometries and Assumptions

Based on the results of the turbulence model assessment, flow and temperature fields in three-dimensional pebble bed were investigated. One of the objectives of these simulations is to peep at flow fields in a pebble bed reactor (PBR) core using a RANS model mentioned above. Another objective is to investigate the turbulence induced non-uniform heat transfer at fuel surfaces. An FCC-closed-packed bed was taken into consideration as illustrated in Figure 3. It consists of 53 parts of pebbles which corresponds to 24 spheres. Total number of node and elements used in the simulation are 107,147 and 497,420, respectively. Several assumptions were made:

- Packed bed consists of fuels only;
- Each pebble has constant uniform heat flux;
- Packed bed is located where the main coolant temperature is 700 °C;
- Pebbles are stationary.

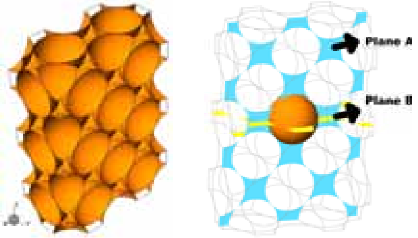


Figure 3. Model Geometry

4.2 Initial & boundary conditions

Initial and boundary conditions of calculation were decided by referring to the Pebble Bed Modular Reactor (PBMR) 250 MW_{th} and estimated inlet mass flow rate is:

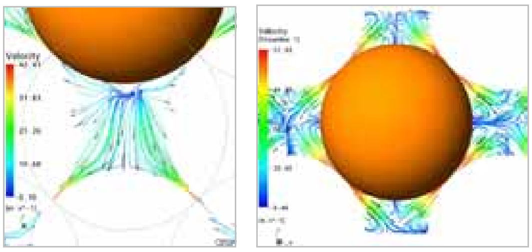
$$\dot{m}_{sim} = A_{sim}\left(\dot{m}/A\right)_{PBMR} = 0.3506 kg/s$$

Outlet boundary condition was set for the average static pressure to be zero for both cases. Surface heat flux of a fuel sphere was approximated by using the reactor thermal power (250 MW_{th}) divided by total surface area of fuels loaded in the reactor to give a value of 58.194kW/m^2 per a pebble. Side walls of packed bed were set to symmetry boundaries.

4.3 Results of pebble bed simulations

Figure 4 shows pressure streamlines and flow directions on Plane A. Pressure drop evaluated at inlet and outlet was 23.6kPa. Flows passing the FCC geometry experience very complicated narrow flow path and irregular flow separations occur. As shown in Figure 4(a), at just the lower positions under each pebble there exist recirculation zones and especially the negative streamwise velocity becomes the maximum near the contacted points between two pebbles which are diagonal to each other. However it is interesting that the streamwise velocity profiles on a horizontal plane show the maximum near the contacted points where the pebbles are on the same vertical level as illustrated in Figure 4(b).

Existence of recirculation flows in pebble bed influences on the heat transfer between fuels and coolant. Since there are stagnation region and recirculation region at the upper region and the lower region of a pebble, respectively, heat transfer at such regions decreases and it results in relatively higher fuel surface temperatures in those regions. These turbulence induced local heat transfer phenomena may consequently generate local hot spots on the surface of pebbles as illustrated in Figure 5. In the figure, local hot spots on the fuel surfaces can be seen mainly around the stagnation and recirculation regions of the flow field.



(a) Plane A (b) Plane B

Figure 4. Streamline and Flow Direction

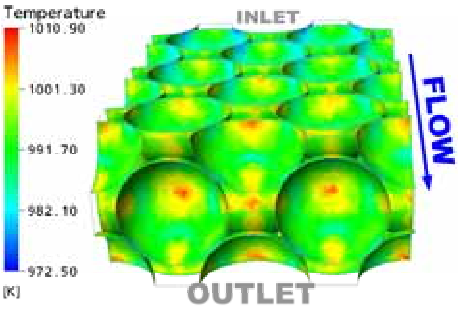


Figure 5. Pebble Surface Temperatures

5. Conclusion

In this study turbulence models based on RANS equations were evaluated with experimental validation. The RNG k-ε model showed the best agreement with experimental data and the model was applied to a model geometry representing a part of pebble bed core. Non-uniform turbulent flows and heat transfer could be found and they affect the hot spot generation on the pebble surfaces, especially in stagnation and recirculation regions in the pebble bed core. Moreover such phenomena might cause a serious safety problem in the outlet region of the core where the fluid temperature is relatively high.

REFERENCES

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[3] Yesilyurt, G and Hassan, Y.A., LES Simulation in Pebble Bed Modular Reactor Core through Randomly Distributed Fuel Elements, Proceedings of GENES4/ANP2003: International Conference on Global Environment and Advanced Nuclear Power Plants, September, Kyoto, Japan, 2003.