Numerical Simulation of Turbulent Cross-flow Over an In-line Tube Bundle

Youngmin Bae [a*], Han-Ok Kang [a], Young-In Kim [a]
[a] *Korea Atomic Energy Research Institute, 1045 Daedeok-Daero 989-111, Yuseong-gu, Daejeon, 305-353, Korea*
[*] *Corresponding author: ybae@kaeri.re.kr*

1. Introduction

A turbulent flow in tube bundles has received much attention in a variety of heat transfer applications. It is characterized by a three-dimensional, unsteady motion of separated shear layers, anisotropic vortices over a wide range of length scales and their interactions, and a high-level turbulence intensity [1]. All of these complexities often make numerical simulations of tube bundle flows a challenging task [2,3]. In this paper, we numerically investigate a turbulent cross-flow in an in-line tube bundle using a large eddy simulation (LES) approach.

2. Methods and Results

2.1 Computational Setup

Under the assumption of a single-phase constant-property Newtonian fluid, the filtered Navier–Stokes equations are expressed as

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_i \partial x_i} - \frac{\partial \tau_{ij}}{\partial x_i} \qquad (2)$$

where the overbar denotes the spatial filtering operation. In the present LES, a segregated and double precision solver in Fluent 12.0 [4] is utilized with a SIMPLE algorithm for pressure-velocity coupling, second-order central differencing method for discretization, and second-order implicit method for time advancement. For the subgrid-scale (SGS) stresses τ_{ij} in equation (2), we employ the classical Smagorinsky model, based on the fact that the influence of a subgrid-scale model is insignificant for a tube bundle flow [5].

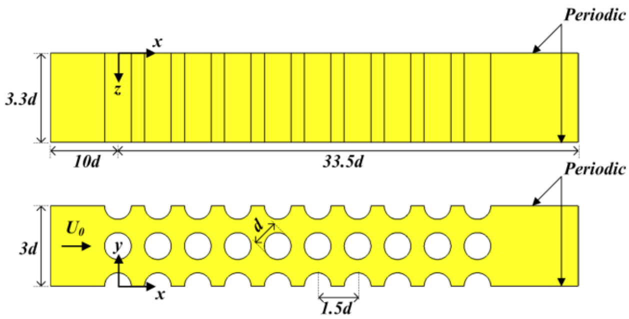

Fig. 1. Schematic of turbulent flow in an in-line tube bundle: *x-z* (top) and *x-y* (bottom) planes

Figure 1 illustrates the computational domain and corresponding boundary conditions used in the LES. The in-line tube bundle is composed of 10 rows of tubes arranged with a pitch-to-diameter ratio of 1.5. In the transverse direction, there is one full rod and two half-rods of diameter *d* and span width 3.3*d*. For the boundary conditions, uniform velocity is prescribed at the inlet, while the outflow boundary condition is imposed at the outlet. The flow periodicity is assumed in both the *y*- and *z*-directions. The tube surfaces are treated as stationary no-slip smooth walls.

2.2 Flow Characteristics

Figure 2 shows the instantaneous flow structures at a Reynolds number of 27000 based on the inlet velocity and tube diameter. It is observed that the complex flow phenomena such as the interaction of separated shear layer with a downstream row, three-dimensional vortical structures over a wide range of length scales, and a high velocity jet behind the last row changing its direction intermittently are effectively resolved in the LES. Moreover, the vortex pattern in the wake region is found to be nearly 180° out of phase with those in the neighboring rows except for the first row. This result is consistent with the previous observation [6], indicating that the present LES provides reliable predictions of a turbulent flow across the tube bundles.

2.3 Comparison with Experiment

Figure 3 compares the time-averaged streamwise velocity distributions behind the second row at several locations downstream from the tube center. It is seen that the mean velocity profiles agree favorably with measurement of Iwaki et al. [6], in both the inter-tube

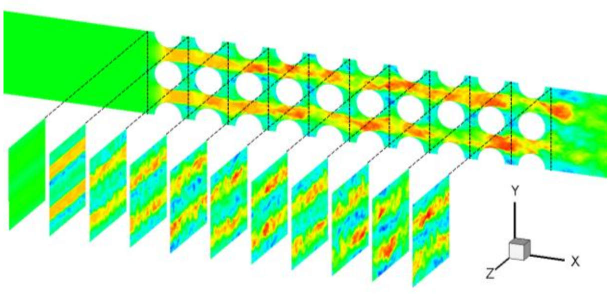

Fig. 2. Instantaneous streamwise velocity distributions u/U_0 (31 levels between -2 and 4)

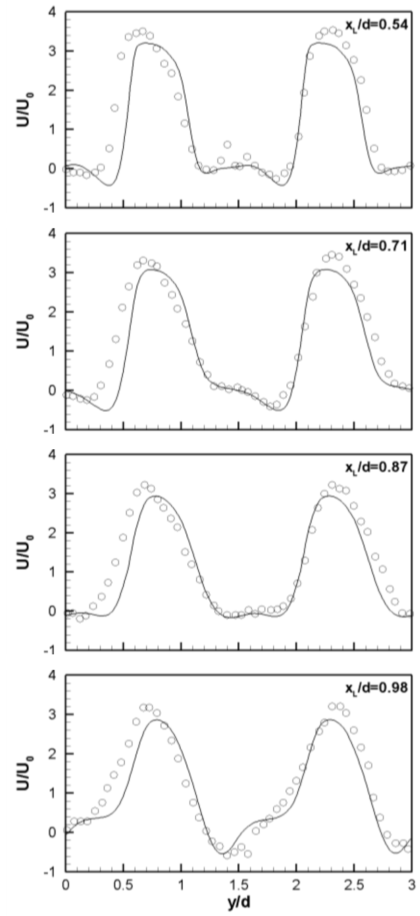

Fig. 3. Comparison of streamwise velocity development U/U_0 behind the tubes at the second row: — present solution, ○ measurement

region and recirculation region. The development of streamwise velocity with the distance downstream (e.g. increase of non-uniformity) is also found to be well predicted in the present LES.

Figure 4 gives a comparison of the separation points on the tubes, which are defined by the angle from the front stagnation point of each tube. The overall agreement between the present LES and the measured data is also shown to be reasonably good, in particular, downstream of the second row where the separation angle does not change significantly. In the experiment of Iwaki et al. [6], it was reported that wake structure behind the first row is much different from the others, leading to an increased width of the recirculation region and an upward movement of the separation point at the first row. In our simulation, the separation point of the first row is about 90°, while the separation points at other rows are in the range of 100~120°.

3. Conclusions

We numerically investigate the turbulent cross-flow in an in-line tube bundle consisting of 10 rows of rods arranged with a pitch-to-diameter ratio of 1.5. With the

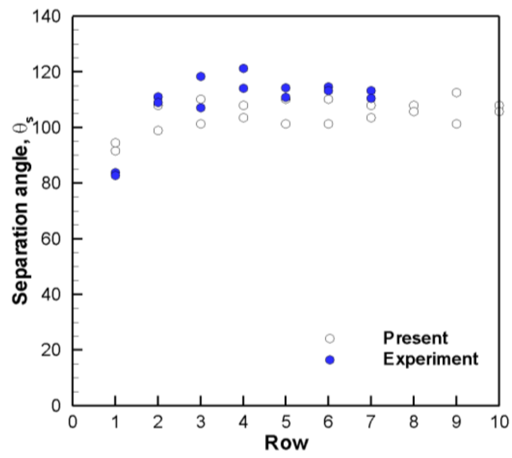

Fig. 4. Comparison of separation angle with the experimental data: ○ present solution, ● measurement of Iwaki et al. [6]

aid of Fluent 12.0, a large eddy simulation is performed at a Reynolds number of 27000 based on the inlet velocity and tube diameter. By comparing the time-averaged streamwise velocity distributions behind the tubes and separation points with the experimental data, it is shown that LES provides reliable predictions of a turbulent flow across an in-line tube bundle, and thus more in-depth investigations will be pursued in a future study.

Acknowledgement

This study has been performed under a contract with the Korean Ministry of Educational Science and Technology. The authors would like to acknowledge the support from KISTI super-computing center through the strategic support program for the supercomputing application research [No. KSC-2012-C1-03].

REFERENCES

[1] Y. A. Hassan and H. R. Barsamian, Tube Bundle Flows with the Large Eddy Simulation technique in Curvilinear Coordinates, International Journal of Heat and Mass Transfer, Vol. 47, p. 3057-3071, 2004.
[2] S. S. Paul, S. J. Ormiston and M. F. Tachie, Experimental and Numerical Investigation of Turbulent Cross-flow in a Staggered Tube Bundle, International Journal of Heat and Fluid Flow, Vol. 29, 387-414, 2008.
[3] S. Benhamadouche and D. Laurence, LES, Coarse LES, and Transient RANS Comparisons on the Flow across a Tube Bundle, International Journal of Heat and Fluid Flow, Vol. 24, 470-479, 2003.
[4] ANSYS Inc., Fluent 12.0 Manual, 2009.
[5] P. Rollet-Miet, D. Laurence, and J. Ferziger, LES and RANS of Turbulent Flow in Tube Bundles, International Journal of Heat and Fluid Flow, Vol. 20, p. 241-254, 1999.
[6] C. Iwaki, K. H. Cheong, H. Monji, and G. Matsui, PIV Measurement of the Vertical Cross-flow Structure over Tube Bundles, Experiments in Fluids, Vol. 37, p. 350-363, 2004.