Computation of Pressure Drop in Cross-flow through an In-line Tube Bundle

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1. Introduction

Over the past decades, flow in tube bundles has received much attention from researchers because of its practical importance in the design of heat exchanger, steam generators, evaporators, etc. In particular, pressure drop performance of rod bundles has been of great interest to the design of nuclear reactors, so numerous studies have been made to understand the underlying physics of such flows [1,2] and to develop correlations for the pressure drop [3,4]. This paper numerically investigates the turbulent cross-flow over an in-line tube bundle, with an emphasis on the effects of longitudinal pitch-to-diameter ratio and Reynolds number.

2. Methods and Results

2.1 Computational Setup

Under an assumption that the flow of constant-property Newtonian fluid is steady, incompressible, isothermal and turbulent, the following Reynolds–Averaged Navier–Stokes (RANS) equations are solved using a commercial CFD code, Fluent 12.0 [5].

$$\frac{\partial\langle u_i\rangle}{\partial x_i}=0 \qquad (1)$$

$$\rho\frac{\partial\langle u_i\rangle\langle u_j\rangle}{\partial x_j}=-\frac{\partial\langle p\rangle}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial\langle u_i\rangle}{\partial x_j}+\frac{\partial\langle u_j\rangle}{\partial x_i}\right)-\rho\langle u_i'u_j'\rangle\right] \qquad (2)$$

The computations are performed using a segregated solver, SIMPLE algorithm for pressure-velocity coupling, and second order upwind method for discretization. For the Reynolds stresses in Eq. (2), the realizable *k*-*ε* turbulence model is used with enhanced wall treatment.

Table 1. Summary of grid dependency test

Case	Number of grid	Pressure loss coefficient ($\zeta=2\Delta P/\rho U_b^2$)	Deviation w.r.t case M4 (%)
M1	409,600	12.876	3.44
M2	1,446,000	12.488	0.32
M3	3,837,200	12.452	0.03
M4	6,280,400	12.448	-

Figure 1 shows the computational domain, a subset of in-line tube bundles tested here, and corresponding boundary conditions. The tube bundle consists of 40 rows of rods arranged with a transverse pitch-to-diameter ratio of S_T/d=1.32. The tube diameter is d=10 mm and length is L=300 mm. The simulations are conducted for various longitudinal pitch-to-diameter ratios (S_L/d=1.08, 1.18, 1.28, 1.38, and 1.48) and Reynolds numbers (*Re*=3,185 to 25,484) based on the tube diameter and bulk velocity U_b through the gap between the tubes.

2.2 Grid sensitivity study

For the grid dependency test, 3D simulations are firstly conducted for the flow at *Re*=25,484 on several meshes with different levels of refinement. The computational grid is clustered at the wall, at which the maximum y^+ value is kept less than unity. Table 1 summarizes the details of the four meshes M1, M2, M3 and M4, and the results of mesh convergence study. The difference of pressure drop between the coarse (M1) and very fine meshes (M4) is found to be less than 4%. It is also observed that a further grid refinement beyond M2 has insignificant influence on the pressure drop. Therefore, M2 is chosen for the following computations.

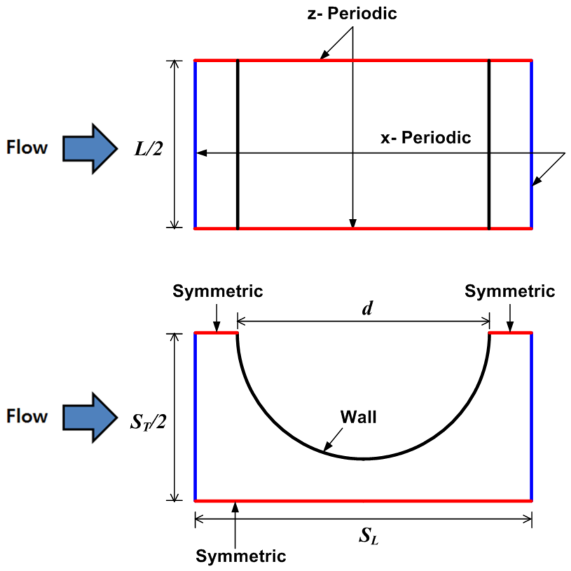

Fig. 1. Schematic of computational domain and boundary condition

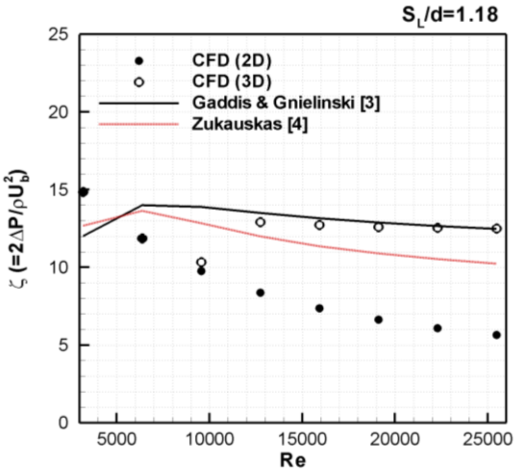

Fig. 2. Comparison of pressure drop for an in-line tube bundle at S_L/d=1.18

2.3 Comparison with empirical correlation

Figure 2 compares the pressure drop for an in-line tube bundle at S_L/d=1.18 as a function of Reynolds number. Overall, 3D simulation provides a favorably good agreement with the empirical correlations [3,4], except for some discrepancies at Reynolds numbers less than 10,000. On the other hand, 2D simulation underestimates the pressure drop and it gives less accurate prediction than 3D, particularly at Re>10,000. This is believed to be mainly due to the lack of 3D effect, implying that 3D simulation might be essential for better prediction of the pressure drop at high Reynolds number. So, in the rest of paper, we have conducted 3D simulations only.

2.4 Effect of longitudinal pitch and Reynolds number

Figure 3 shows the impact of longitudinal pitch and Reynolds number on the pressure drop performance of in-line tube bundles at Re=3,185 to 25,484 and S_L/d=1.08 to 1.48. It is observed that the larger the longitudinal pitch, the greater the pressure drop. This is because the interaction effect between the rods becomes weak by the increase in longitudinal pitch at a given Reynolds number. It is therefore conjectured that the interaction between the rods in the streamwise direction might be beneficial to the pressure drop performance of in-line tube bundles. It is also seen in Fig. 3 that the pressure loss coefficient is less likely to be affected by the change of Reynolds number at Re=13,000~25,484. These results are consistent with the previous observations of Zukauskas and Ulinskas [4], thus supporting the validity of the present computation.

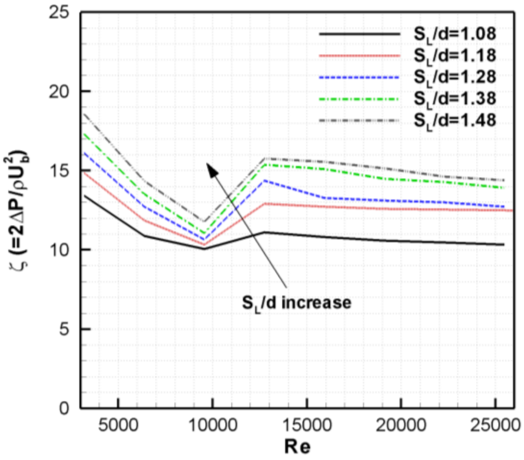

Fig. 3. Pressure loss coefficient *vs.* Reynolds number relationships for various longitudinal pitch-to-diameter ratios

3. Conclusions

In this paper, we numerically investigate the flow through an in-line tube bundle consisting of 40 rows of rods arranged with a transverse pitch-to-diameter ratio of S_T/d=1.32. The steady, incompressible and turbulent flow are predicted by the commercial CFD code, Fluent 12.0 with different mesh resolutions, longitudinal pitch-to-diameter ratios and Reynolds numbers. It is observed that at the relatively high Reynolds number, 3D simulation provides better prediction of the pressure drop than 2D. The computed result also shows that the larger the longitudinal pitch, the greater the pressure drop. This confirms that the pressure drop performance of an in-line tube bundle is strongly influenced by the tube arrangement, so more extensive investigation will be pursued in the future study.

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