COMPUTATION OF TURBULENT CROSS-FLOW OVER AN IN-LINE TUBE BUNDLE

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ABSTRACT

In this study, we numerically investigate the turbulent cross-flow over an in-line tube bundle consisting of 10 rows of rods arranged with a transverse pitch-to-diameter ratio of 1.5. A three-dimensional incompressible turbulent flow is computed using a large eddy simulation approach at a Reynolds number of 6300 based on the inlet velocity and tube diameter. The validity of the numerical results is first assessed by comparing the time-averaged streamwise velocity distributions behind the tubes and separation points with experimental data. The impact of longitudinal pitch-to-diameter ratio is then analyzed with a discussion of pressure drop and spatio-temporal characteristics of wall pressure fluctuations.

INTRODUCTION

A turbulent cross-flow over a tube bundle has received much attention in a variety of heat transfer applications. Specifically, it continues to be one of the major concerns in the design of steam generators for nuclear power plants. A great deal of experimental and numerical studies have been conducted in order to clarify the detailed features of the tube bunle flow (Barsamian and Hassan, 1997; Paul et al., 2008) and to predict the pressure drop as well as the heat transfer coefficient (Gaddis and Gnielinski, 1985; Zhukauskas and Ulinskas, 1987). Extensive investigations of velocity and turbulence distributions in the near-wake region have also been made for decades (Balabani et al., 1994; Barsamian and Hassan, 1997; Benhamadouche and Laurence, 2003; Hassan and Barsamian, 2004; Iwaki et al., 2004; Bae et al., 2012).

The tube bundle flow is typically characterized by the three-dimensional, unsteady motion of separated shear layers, anisotropic vortices over a wide range of length scales and their interactions, and a high level of turbulence intensity (Hassan and Barsamian, 2004; Iwaki et al., 2004), which are strongly dependent on the tube arrangement and flow condition. These complexities often make numerical simulations of the tube bundle flow a challenging task. For instance, a Reynolds averaged Navier-Stokes (RANS) approach has been widely used for the prediction of turbulent flows in many industrial applications. However, it was reported that RANS models severely underestimate the turbulence level and may not be appropriate for the computation of the tube bundle flow (Paul et al., 2008). On the other hand, large eddy simulation (LES) technique has the potential to provide more accurate predictions of turbulent statistics, and is considered a promising tool for studying the tube bundle flow (Barsamian and Hassan, 1997; Benhamadouche and Laurence, 2003; Hassan and Barsamian, 2004).

The primary objective of this study is to investigate the turbulent cross-flow over an in-line tube bundle, with a particular focus on the effect of longitudinal pitch-to-diameter ratio. To this end, an incompressible LES is first carried out for a square array of tubes, and the obtained results such as mean velocity profiles behind the tubes and separation angles are compared with experimental data. The influence of tube spacing is then scrutinized in terms of pressure drop and spatio-temporal characteristics of wall pressure fluctuation.

COMPUTATIONAL SET-UP

Assuming a single-phase incompressible flow of a constant-property Newtonian fluid, the filtered Navier-Stokes equations read as

$$\frac{\partial \overline{U}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{U}_i}{\partial t} + \frac{\partial \overline{U}_i \overline{U}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + \nu \frac{\partial^2 \overline{U}_i}{\partial x_i \partial x_i} - \frac{\partial \tau_{ij}}{\partial x_i} \tag{2}$$

where the overbar denotes the spatial filtering operation, ρ and ν represent the density and kinematic viscosity of the fluid, respectively. For the subgrid-scale (SGS) stresses, the classical Smagorinsky model is employed here, based on the fact that the influence of subgrid-scale model is insignificant in the tube bundle flow (Rollet-Miet et al., 1999). The deviatory part of τ_{ij} in Eq. (2) is then given by

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2C_s\overline{\Delta}^2\left|\overline{S}\right|\overline{S}_{ij} \tag{3}$$

in which δ_{ij} denotes the Kronecker delta, C_s=0.065 is the Smagorinsky constant, and Δ is the filter width. The strain rate for the resolved scale S_{ij} is

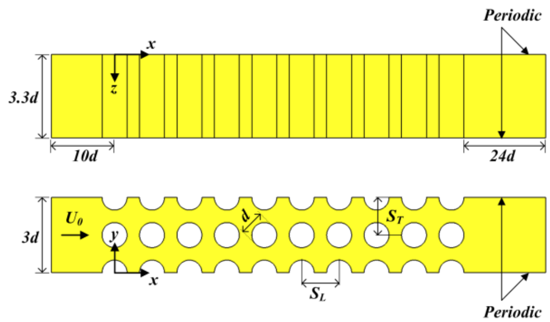

Figure 1. Schematic of flow over an in-line tube bundle.

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right) \quad (4)$$

$$\left|\bar{S}\right| = \left(2\bar{S}_{ij}\bar{S}_{ij}\right)^{1/2} \quad (5)$$

The governing equations are solved using a commercial code, Fluent 12.0 with SIMPLE algorithm for pressure-velocity linkage, a 2nd-order central differencing method for discretization, and a 2nd-order implicit method for time advancement (Ansys Inc., 2009).

Figure 1 illustrates the computational domain and boundary conditions used in the LES. The in-line tube bundle is composed of 10 rows of rods with a transverse pitch-to-diameter ratio of S_T/d=1.5 and longitudinal pitch-to-diameter ratios of S_L/d=1.5, 1.75, 2, 2.25, and 2.5. In the transverse direction, there is one full rod and two half-rods of diameter d and span width 3.3d. For the boundary conditions, a uniform velocity U_0 is prescribed at the inlet; a pressure outlet condition is imposed at the downstream end; a flow periodicity is assumed in both the spanwise and transverse directions; and the tube surfaces are treated as stationary no-slip smooth walls. The Reynolds number based on the inlet velocity U_0 and tube diameter is 6300.

The simulations are performed on a body-fitted grid system consisting of approximately 5 million hexahedral cells clustering around the tube surface, where 160 and 40 grid points are distributed uniformly in the circumferential and the spanwise directions, respectively. The first grid spacing normal to the wall is set to be Δy=0.0008d, and this correponds to the nondimensional wall distance of y^+=1.5.

RESULTS AND DISCUSSION

Flow Features (S_L/d=1.5)

Figures 2 and 3 show the instantaneous iso-surface of the second invariant of the velocity gradient (Q=372) and streamwise velocity distributions in case of a square array of tubes, respectively. As expected, it is shown that the complex flow phenomena such as the interaction of separated shear layer with the downstream row, vortical structures over a wide range of length scales, and the high velocity jet behind the last row changing its direction intermittently are effectively resolved in the LES. Two distinctive flow regions can be clearly seen in Fig. 3: the high velocity region in the narrow passage between adjacent tubes and the recirculation region behind the tubes. It is also noteworthy that similar to the previous observation (Iwaki et al., 2004), the recirculation flows differ from row to row, i.e., an asymmetric vortex pattern of a large vortex accompanied by a smaller one is most frequently observed behind the tubes, while a symmetric pair of vortices or a single large vortex seldom forms. Moreover, the vortex pattern in the wake region appears to be nearly 180° out of phase with those in the neighbouring rows except the first row, which is consistent with the experiment (Iwaki et al., 2004).

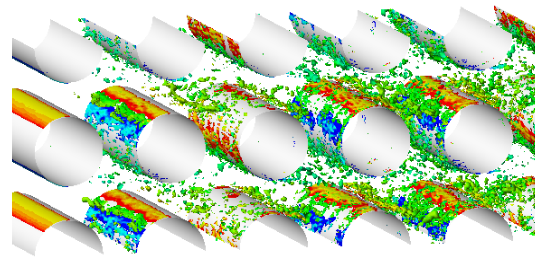

Figure 2. Instantaneous vortical structures around the first five rows for S_L/d=1.5 (coloured with spanwise vorticity ω_z).

Comparison with Experiment (S_L/d=1.5)

Figure 4 compares the mean streamwise velocity (normalized by U_0) profiles behind the first three rows for S_L/d = 1.5, at several locations downstream from each tube centre. It is shown that mean velocity profiles agree fairly well with the measurement of Iwaki et al. (2004) in both the inter-tube and recirculation regions. The development of the streamwise velocity with distance downstream (e.g. increment of non-uniformity) is also well predicted in the LES.

Figure 5 next provides a comparison of the separation angle, which is measured from the front stagnation point of each tube. The overall agreement between the present

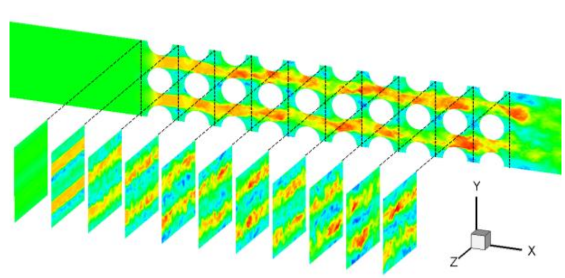

Figure 3. Instantaneous streamwise velocity contours

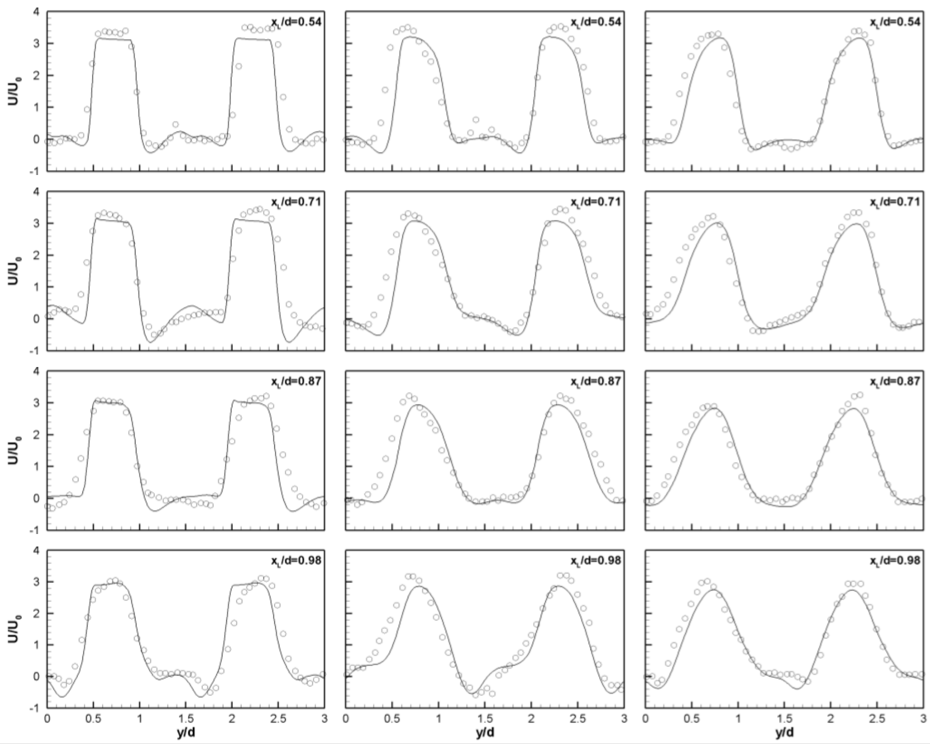

Figure 4. Mean streamwise velocity profiles behind the tubes at the first (left), second (middle), and third row (right) for S_L/d=1.5: ― present LES, ○ measurement of Iwaki et al. (2004).

LES and measurement is reasonably good, in particular downstream of the second row where the separation angle does not change significantly. In the experiment of Iwaki et al. (2004), it was reported that wake structure behind the first row is much different from others, leading to an increase in width of the recirculation region and upward movement of the separation point at the first row. In our simulation, the separation angle is estimated about 90° at the first row, while it is in the range of 100°–120° at other rows. Together with the streamwise velocity distributions shown in Fig. 4, these results suggest that the LES may provide a reliable prediction of the tube bundle flow.

Effect of Longitudinal Pitch

Figure 6 shows the influence of longitudinal pitch-to-diameter ratio on the mean pressure drop (normalized by $0.5\rho U_0^2$) across the tube bundle. One may recognize that with increasing longitudinal tube spacing, the interaction between the neighbouring rods in the streamwise direction becomes weak and the irreversible pressure drop increases, except the case of S_L/d=1.5. It can be also seen in Fig. 6 that the predicted pressure drops are in good agreement with those obtained from the existing correlation (Gaddis and Gnielinski, 1985). This supports again the validity of the present LES.

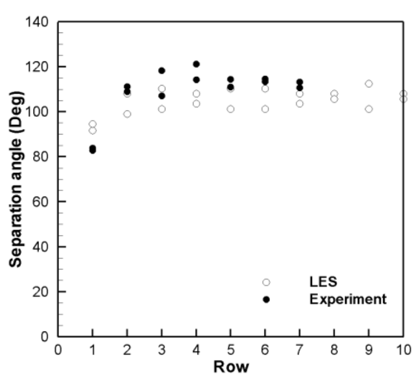

Figure 5. Comparison of separation angle: ○ present LES, ● measurement of Iwaki et al. (2004).

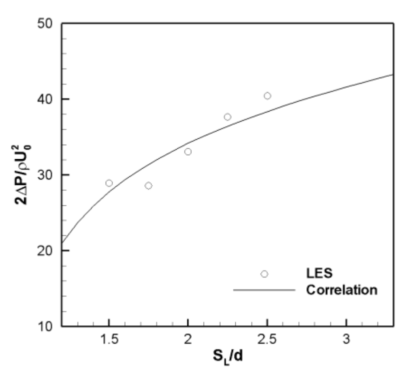

Figure 6. Variation of pressure drop across the bundle with longitudinal pitch-to-diameter ratio: ○ present LES, ― correlation of Gaddis and Gnielinski (1985).

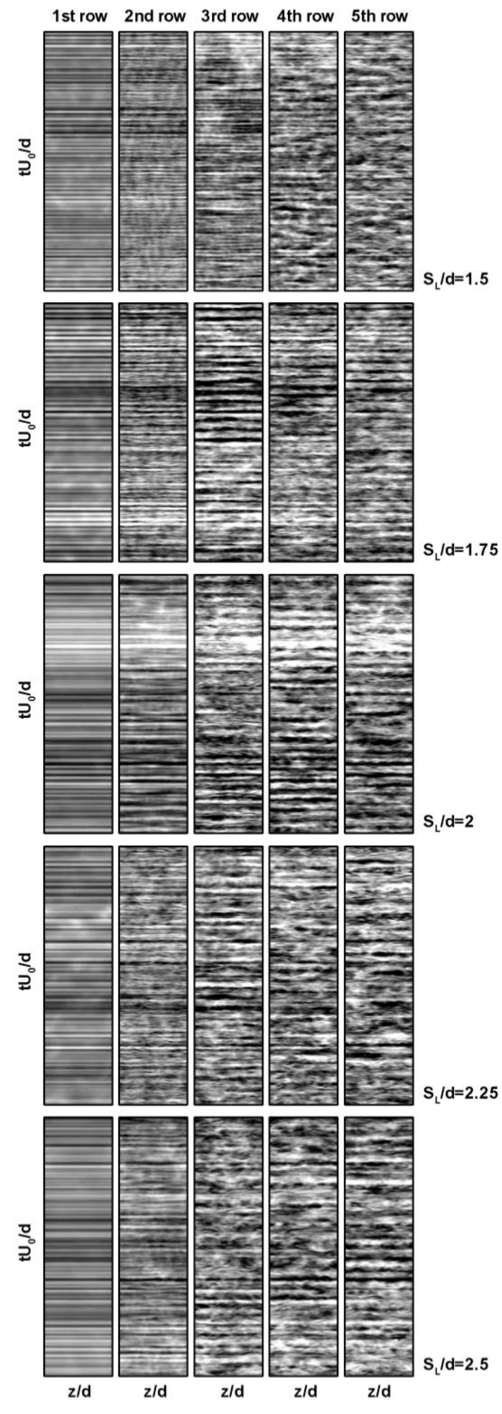

Figure 7. Temporal variation of spanwise wall pressure fluctuation distribution on the top of the tubes for various longitudinal pitch-to-diameter ratios.

Figures 7 and 8 present the spatio-temporal variation of the wall pressure fluctuation at the top of the circular cross-section of the tube (up to the fifth row) and the corresponding spanwise correlation, respectively. At the

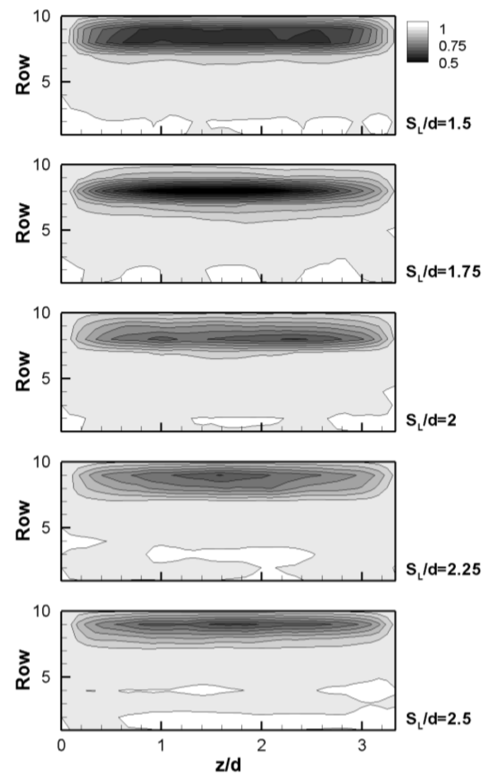

Figure 8. Spanwise correlation of pressure fluctuation on the top of the tubes for various longitudinal pitch-to-diameter ratios.

first row, one can see the quasi-periodic (in time) and uniformly distributed (in the spanwise direction) pressure fluctuation. Towards downstream, the pressure fluctuation exhibits a chaotic distribution and its intensity becomes larger until a fully developed state is reached. Moreover, it can be seen in Fig. 8 that for all the longitudinal pitch-to-diameter ratios tested here, the spatially coherent pressure fluctuations in the spanwise direction are presented at the upstream tubes up to the sixth row. Further downstream, the spanwise correlation of the wall pressure fluctuation appears to be reduced and to reach its lowest value near the eighth row. As regards the longitudinal pitch effect at the downstream rows, it is also interesting to note that the minimum spanwise correlation occurs at S_L/d=1.75, which is similar to the pressure drop across the bundle (Fig. 6).

Figure 9 depicts the power spectral density (PSD) of the wall pressure fluctuation at a mid-span point located on the top of the tube for various longitudinal pitch-to-diameter ratios. It is shown that at the upstream rows, the pressure fluctuation at a typical vortex shedding frequency of $St=fd/U_0$=0.3−0.5 for in-line tube bundles (Ziada and Oengören, 1992; Ziada, 2006) is indiscernible. Instead, the pressure fluctuation at around St=1−2, which seems to be associated with the shear layer instability, is found to be significant at the upstream rows. However, in cases of small longitudinal pitch-to-diameter ratios (e.g., S_L/d=1.5), this peak diminishes at the downstream rows in which the vortex shedding peak at St=0.3−0.5 becomes pronounced,

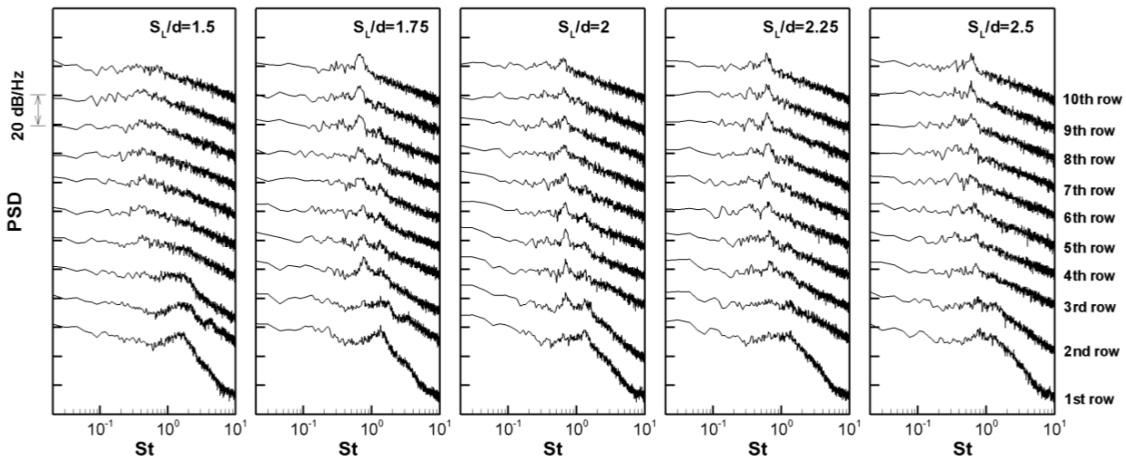

Figure 9. Power spectral density of wall pressure fluctuation at a mid-span point located on the top of the tube for various longitudinal pitch-to-diameter ratios.

whereas it tends to be maintained further downstream with an increase in the longitudinal tube spacing.

SUMMARY AND CONCLUSION

In the present study, we numerically investigate the incompressible turbulent flow over an in-line tube bundle consisting of 10 rows of rods arranged with a transverse pitch-to-diameter ratio of 1.5. Large eddy simulations are performed for several longitudinal pitch-to-diameter ratios at a Reynolds number of 6300 based on the inlet velocity and tube diameter. The validity of the numerical results is demonstrated through comparisons of streamwise velocity profiles behind the tubes and the separation angles with experimental data. The spatio-temporal characteristics of the wall pressure fluctuation have been also investigated with a brief discussion of the longitudinal pitch effect. The obtained results show that the spatially coherent pressure fluctuations in the spanwise direction are presented at the upstream tubes up to the sixth row, while the spanwise correlation is minimized near the eighth row when the longitudinal pitch-to-diameter ratio is 1.75. It is also found that the pressure fluctuation at a Strouhal number of 1−2 is prominent at the upstream tubes, but this peak appears to weaken in the downstream rows for a small longitudinal pitch-to-diameter ratio. More in-depth investigations will be pursued in the future.

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