PIV measurement of fluid flow through staggered tube array

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Abstract: An experimental investigation was performed on fluid flow through staggered tube arrays by varying tube spacing (center-to-center distance of cylinders) L/D = 3.0, 2.5 and 2.0. Particle image velocimetry (PIV) technique was employed to delineate the flow field at Reynolds number 2250. Proper orthogonal decomposition (POD) was employed to filter the original velocity fields to identify the underlying physics of the flow pattern.

Keywords: tube array; vortex; PIV; POD;

1. Introduction
Tube array has been widely used in industrial engineering like kettle re-boilers, feed-water heaters, steam-generators, and evaporators in power generation. An insight understanding of the flow pattern around tube array is of great significance to design. Various efforts are made to reveal the underlying physics of the flow. The visualization by Wallis [1] demonstrated that attached eddies are formed alternatively behind each of the cylinders on either side and the mean velocity across the free stream and wake regions is reduced with increasing the transverse pitch. Weaver and Abd-Rabbo [2] performed a flow visualization study of flow in inline and square arrays with a pitch-to-diameter ratio of 1.5, observing the periodic vortex shedding. By LDA measurements, Simonin and Barcouda [3, 4] observed a small recirculation zone in the wakes of tubes and the length of the recirculation zone is peaked behind the left row and then decreases in the subsequent downstream rows. A comparative study of the staggered and in-line geometries by Halim [5] determined the larger transverse mean velocities in the staggered array but the turbulence levels in both geometries are almost the same. Recently, Iwaki et al. [6] employed PIV to obtain the vortex structures behind the tube in the in-line array. Paul et al. [7] used PIV to study influence of Reynolds number on time-averaged velocity and turbulence quantities.

The particle image velocimetry (PIV) has allowed efficient quantitative measurements of the entire flow field through tube array. In combination with the sophisticated proper orthogonal decomposition (POD), the snapshots of the turbulent flow determined by PIV can be spatially decomposed to reveal the most energetic spatial modes. This means that the conjunction of PIV measurements and POD analysis would reveal characteristics of the flow pattern in terms of flow structures. In the present work, PIV was used to conduct detailed velocity measurements of turbulent flow through the staggered tube array. The measurements were performed at three cases to study the effects of tube spacing on the flow characteristics, e.g., L/D = 3.0, 2.5 and 2.0. The Reynolds number based on the inlet velocity was Re = 2250. The streamline pattern, time-averaged vorticity, swirling strength, and POD filtered flow fields were analyzed to examine the features of the flow.

2. Experimental apparatus
Figure 1 shows arrangement of the staggered tube array. The tubes were made by Fluorinated Ethylene Propylene (FEP) with the refractive index 1.338. The well-arranged refraction index matching approach ensured high-quality images of the seeded flow field. The tube is 150 mm in length and 15 mm in diameter, and arranged with different tube spacing ratio L/D of 3.0, 2.5 and 2.0. In experiment, a total of 7 rows were placed to simulate the staggered tube array. As shown in Fig.1 the rectangular region
around the central tube is chosen as the measurement region.

Experiments were performed in the recirculation open water channel shown in Fig. 2. The flow was circulated by a magnetic drive centrifugal pump (Iwaki, Japan) to avoid facility structure vibration. A settling chamber, a honeycomb, 6 screens and a contraction section were placed in sequence to ensure flow homogeneity. The dimensions of the test section were 150mm (width) × 200mm (height) × 1050mm (length). The model spanning the entire width of the test-section was placed in the water channel. The free-stream velocity was maintained at 0.15 m/s, which results in a Reynolds number Re=2250 based on the diameter of the tube. The free-stream turbulence intensity was less than 2%.

The cross-flow through the staggered tube array was measured by using planner PIV. Glass beads (ρ=1.05 kg/m³, d=10 mm) were used as tracer particles. The seeded flow field was illuminated by a 1.8-W continuous-wave semiconductor laser. A giga-pixel (4000 × 2672 pixels) CCD camera (IPX11M, USA) was used to acquire the images. Image distortion was suppressed by using an 85-mm lens (PC Micro Nikon, Japan). The laser was modulated to give 5-ms pulses and synchronized to the CCD camera with the use of a pulse delay generator. The appropriate combination of cylindrical lenses was fitted to the compact laser to produce a 1-mm-thick light sheet along the center of the tube array. As shown in Fig. 1, measurements were taken in the range of 1.7L × 1.0L for the three systems. In the measurement region, a total of 16200, 15040 and 11602 velocity fields were acquired for the systems L/D = 3.0, 2.5 and 2.0, respectively. The interrogation window size was 32 × 32 pixels with 50% overlap, which yielded a measurement grid of velocity vectors with a spacing of 0.91 mm × 0.91 mm. The standard cross-correlation algorithm, in combination with window offset, sub-pixel recognition by Gaussian fitting and sub-region distortion, was used to improve the signal-to-noise ratio.

3. Results and discussion

A preliminary view of influence of the tube spacing-to-diameter ratio on the flow pattern was obtained by plotting the time-mean streamline pattern in Fig. 2. Contours of the time-mean streamwise velocity component were superimposed to assist flow structure interpretation. As shown in Fig.2, the flow separates and forms a recirculation zone behind the cylinder. The streamlines are nearly symmetrically arranged about the center line of the bundle. Two recirculation zones are readily identified, in well agreement with the results of a single cylinder. The wake behind the cylinder is restrained by the downstream tubes. The length of the recirculation zone varies in response to the tube spacing. The length of the recirculation zone is 3.3D for the system L/D = 3.0. As the tube spacing decreases, the values are reduced to 2.71D and 2.16D for the systems L/D = 2.5 and 2.0, respectively. For the system L/D=2.0, the wake behind the center row of cylinders is somewhat asymmetric.
Fig. 2 Streamline pattern and stream wise velocity distribution of the time-averaged flow field: (a) L/D=3.0, (b) L/D=2.5 and (c) L/D=2.0

Figure 3 shows the spatial distribution of the longitudinal velocity fluctuations. A global view on the longitudinal velocity fluctuation intensity shows two shear layers from the top and bottom of the cylinder. For the system L/D = 3.0, the longitudinal velocity fluctuation of the shear layer and the area of the shear layer are obviously larger than the other two systems, which is due to the occurrence of the relatively energetic vortical structure. With decreasing tube spacing, the longitudinal velocity is reduced and energy of the vortical structure gets smaller.

Fig. 3 Contours of longitudinal velocity fluctuation intensity: (a) L/D=3.0, (b) L/D=2.5 and (c) L/D=2.0

To see influence of tube spacing on the vortex shedding, we examined the vorticity across the measurement region Fig. 4. We can see high vorticity area of the opposite value on both sides of the cylinder, and the vorticity area in the system L/D = 3.0 is longer than the other two systems. The length of area with high vorticity are 0.94D for L/D = 3.0 and 0.829D for L/D = 2.5. However, in the system L/D = 2.0, the pattern of high vorticity areas is not symmetric due to the influence of the wake behind the left row of cylinders. As the vortex shedding from the left row greatly coupled with that from the bottom of the center row, the streamwise length of the high vorticity areas is 0.863D and 0.390D for the upper and lower sides, respectively.

Fig. 4 Time-averaged vorticity fields: (a) L/D=3.0, (b) L/D=2.5 and (c) L/D=2.0

To identify and characterized the large-scale structures in the wake, we performed the proper orthogonal decomposition (POD) analysis of PIV measurements. By extracting the most energetic eigenmodes that capture most of the fluctuation energy, the POD technique was introduced to identify coherent structure in turbulent flows [8]. In order to reduce the computational effort involved in solving the eigenvalue problems, the snapshot POD method was employed.
A total of 1000 snapshot of the vector fields were decomposed by using POD. Figure 5 displays the eigenvalue of the first 10 eigenmodes, which reflects the relative contribution of each mode to the fluctuation energy of the flow field. With increasing mode number, the eigenvalue is reduced rapidly for the first several eigenmodes and the convergence speed slows down as more eigenmodes are taken into consideration. Of noted is that the first several eigenmodes have larger eigenvalues than other modes, and are probably resulted from the growing and shedding large-scale vortical structures buried in the upper and lower shear layers. As the tube spacing decreases from 3.0 to 2.0, the reduced dominance of the first two modes might be due to the weaken vortex shedding. For the system L/D = 2.5, the first two eigenvalues are very close to that of L/D = 2.0.

Figures 6, 7 and 8 show the first four eigenmodes for the systems L/D = 3.0, 2.5 and 2.0D, respectively. As shown in Fig.6, there are clear large-scale structures in the first three eigenmodes; these structures appear alternatively, representing the footprints of Karman vortices buried in the wake. The forth eigenmode is characterized by an irregular pattern; the decomposed flow field is disordered with many small-scale structures, which represents a comprehensive affect of the small-scale structures. In Figs.7 and 8, the large-scale structures are obviously identified in the first three and two eigenmodes, respectively. As the tube spacing decreases from 3.0, the spatial scale of the vortex becomes smaller. Obviously, the vortex shedding process is restrained by the downstream cylinder.

Although the large-scale structure has high energy, the flow field is interfenred by small-scale structures and turbulence dissipation. As the mode number increases, the vortex structure becomes irregular. For the system L/D = 2.0, the first two eigenmodes are regular, while the first three eigenmodes are regular for the other two systems.
In order to avoid the colored influence of the small-scale structures and background noise, we chose the first two modes to reconstruct the flow fields as shown in Fig.9. We can see that the reconstructed flow field reserves the dominant characteristic of the original flow field through comparing the streamline patterns. Due to exclusion of the interference with the small-scale structures, the spatial characteristics of the large-scale structure are easily observed in Fig.9.

Fig.9 Streamline patterns of the original and reconstructed fields: (a) L/D=2, (b) L/D=2.5 and (c) L/D=3

5. Conclusions
Influence of tube spacing of cylinders on characteristics of the flow though the staggered tube array was experimentally studied in the present work. Three cases with different tube spacing of cylinders, L/D = 3.0, 2.5, and 2.0, were chosen for comparison at the Reynolds number \( \text{Re}_D=2250 \). In experiment, high resolution PIV system was employed to measure the flow field. The spatial characteristics of the flow pattern were discussed by using POD filtered flow fields.

Reference