Pulsating flow past a tube bundle

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Abstract. Visualization of the pulsating cross-flow past the in-line and staggered tube bundles has been performed. The frequency and amplitude of forced flow pulsations and the tube pitch in the bundle varied in the experiments. The main attention was focused on the flow pattern in the near wake of the third-row tube. The most indicative regimes of flow past a tube in a bundle have been revealed depending on forced flow unsteadiness parameters. The obtained data have been generalized in the flow maps in the space of dimensionless frequency (Strouhal number, St) and relative pulsation amplitude, $\beta$, individually for the in-line and staggered tube arrangement. Three most indicative regimes of pulsating flow past the tubes in a bundle have been singled out in each flow map.

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1. Introduction
Shell-and-tube heat exchangers are the most commonly used ones in process industry and power engineering. The design of such heat exchangers includes a tube bundle with a cross flow around it (hereinafter the terms “tube bundle” and “cylinder array” are used interchangeably). The heat is transferred between the fluid running inside the tubes and the fluid running past the tubes in transverse direction. One of the issues with the enhancement of thermal-hydraulic performance of shell-and-tube heat exchangers to be handled is heat transfer augmentation in the cross-flow past a tube bundle. The level of heat transfer is determined here by the flow pattern, which is rather complex. The flow pattern in the gap between the tubes is governed by the boundary layer separation from the tube surface and interaction of vortex wakes behind the tubes. The analysis of steady cross-flow past a tube bundle has been performed in multiple papers (e.g. [1-4]). It showed that the pattern of flow past a tube bundle is extremely sensitive to the upstream intensity of turbulent fluctuations, the blockage ratio of the flow cross section and aspect ratio of the tube, tube roughness, tube vibration, acoustic resonance, etc. The number of tubes in a row is also among the parameters determining the flow pattern in the tube bundle [5]. Considerable progress in understanding of the flow structure in the gap between the tubes was made owing to flow visualization [6-8]. Heat transfer in the steady flow past a tube bundle has been studied in detail. The results have been generalized in books, textbooks and reviews [1, 9, 10]. A number of empirical correlations have been derived for prediction of averaged heat transfer from the tubes in the bundle depending on the bundle configuration, tube pitch, row number and Reynolds number.

Multiple scientific and design studies dealt with heat transfer enhancement in shell-and-tube heat exchangers [11, 12]. A number of passive methods to enhance heat transfer have been proposed so
far that involve modification of the external tube surface (ribs, roughness, cross-section shape, etc.). Far less information is available on active methods: tube oscillation or freestream pulsations [13 - 15]. Meanwhile, experimental and theoretical results prove these methods to be efficient in heat transfer enhancement in cross-flow past a single circular cylinder (tube) [16 –19]. The studies of possible heat transfer enhancement in a tube bundle by freestream pulsations should obviously start from the detailed examination and generalization of the effect of forced flow pulsations on the flow pattern in the gap between the tubes under variable tube arrangement and flow unsteadiness parameters.

The results of visual examination of pulsating cross-flow past a tube bundle are presented here. In-line and staggered tube arrangement in the bundle were considered. Tube pitch and forced unsteadiness parameters varied in the experiments. Typical flow patterns were revealed from the flow visualization analysis along with the flow maps constructed in the space of governing dimensionless numbers.

2. Experimental setup and procedure

An experimental setup shown in figure 1 was used for the experiments. The test section 4 with a smooth inlet had a square cross section of 0.38×0.38 m and the length of 2.73 m. The test section wall 1 was made of glass allowing observation and video recording of the flow pattern. The adjacent wall had a groove closed with the glass. It served for generation of a light sheet for flow visualization. Forced periodic velocity pulsations in the test section were generated by a special device (pulsator) 6. The flow rate component 3 of the pulsator provided the adjustment of mean velocity, and the component 2 was used for variation of the frequency and amplitude of forced velocity pulsations. Air flow rate through the setup was provided by a suction fan 8 and measured by a special ultrasonic flowmeter 5 mounted between the test section and the pulsator. The receiver 7 damped the flow pulsations at the fan inlet.

![Figure 1. Schematic of the experimental setup](image)

The cylinder array (tube bundle) was mounted in the test section in such a way as to place the axis of the first row of cylinders at the distance of 1.1 m downstream of the test section inlet. The cylinder array consisted of five rows in the freestream direction. The number of cylinders in a row was four or five depending on their pitch. Two types of cylinder arrangement in the array were considered: in-line and staggered ones. These are schematically shown in figure 2. The cylinders were arranged in the array in such a way as to provide identical spacing, t, in streamwise and spanwise directions. This spacing was characterized by the pitch, t/d, which was the distance between the cylinders’ axes normalized by the cylinder diameter, d. Three values of cylinder spacing were considered in the experiments: t = 100; 80 and 70 mm (t/d = 2.0; 1.6 and 1.4, respectively).

The mean freestream velocity of undisturbed flow in the test section and the amplitude of its pulsations were measured by a special ultrasonic flow meter of IRVIS product line. The flow meter was calibrated on a Gas Flow Standard UPG10.

Air flow rate in the test section was 170 m³/hour (at t/d = 2) and 260 m³/hour (at t/d = 1.6 and 1.4). The corresponding Reynolds number based on the mean freestream velocity, <U₀>, and the cylinder diameter, d, was Re = <U₀>d/ν = 1130 and 1725. The frequency of forced pulsations and
the relative amplitude of pulsations varied in the experiments: \( f = 1.0 - 12.8 \text{ Hz} \) and \( \beta = \frac{A_U}{<U_0>} = 0.1 - 0.6 \), respectively. Here, \( A_U \) is the amplitude of flow velocity; \( \nu \) is the kinematic viscosity of air. For the steady flow case it is well-known that the flow structure and the averaged heat transfer from the tubes remain almost constant starting from approximately the third row. For this reason, the flow pattern in the wake of the third row cylinder located at the channel axis was studied in the pulsating flow case. The measurement area is shown with a rectangular in figure 2.

Due to the flow blockage, the velocity of flow past the cylinders in the array is higher than the freestream velocity. Owing to this, the Reynolds and Strouhal numbers were based on the bulk velocity, \( <U_1> \), in the minimal gap between the cylinders [1, 4]. Allowing for this condition, the Reynolds number in experiments was \( \text{Re}_{1} = \frac{<U_1> d}{\nu} = 1865 \) and 5040, and the Strouhal number varied in the range of \( \text{St} = \frac{f d}{<U_1>} = 0.02 - 0.44 \).

The outside diameter of cylinders was \( d = 50 \text{ mm} \), cylinder wall thickness was \( \delta = 1.0 \text{ mm} \). Cylinder walls were made of transparent polycarbonate enabling to record the cylinder wake structure.

The flow pattern around the cylinders in the array was studied using flow visualization data. The flow was seeded with special tracer particles – small glycerol particles with the diameter of no more than 5 \( \mu \text{m} \). The tracers were generated by an aerosol generator FOG 2010 Plus. Flow patterns were recorded using a monochrome Fastec HiSpec high-speed camera at the frame rate of 500 fps with full frame resolution of 1280×1024 pix. The light sheet for flow illumination was generated by a continuous laser KLM-532/5000.

3. Results and discussion
The analysis of the tube bundle flow visualization data showed the following. There are three main flow patterns around the third-row cylinder in a bundle. Pattern I corresponds to the jet flow in the gap between the cylinders, which is accompanied by generation of small-scale vortices at the jet boundary and formation of stagnation zone between the cylinders (figure 3 a). Pattern II is characterized by alternation of the jet flow and intermittent vortex shedding from opposite sides of the cylinder (resembling Karman vortex street in the confined flow). Pattern III shows two symmetric vortices formed simultaneously on opposite sides of the cylinder over the period of forced pulsations (figure 3 b). This pattern is close to the pattern IV of the pulsating cross-flow past a single cylinder [19], but the vortices in pair are usually non-symmetric, and the flow pattern repeatability over the subsequent periods of forced pulsations is less pronounced if compared with the flow past a single cylinder.
Three main flow patterns past the cylinder can be distinguished in the staggered array. Alternating vortex formation on the opposite sides of the cylinder is observed in pattern I (figure 4 a) (resembling Karman vortex street in confined flow). In this case, the vortex formation period is not a multiple of forced flow pulsation period. The pattern II is intermediate. In this pattern, Karman vortex street alternates with simultaneous formation of symmetric vortices on opposite sides of the cylinder. In the pattern III (figure 4 b), similarly to the in-line array, a pair of symmetric vortices is formed behind the cylinder over one period of forced pulsations.

Flow visualization results are summarized in flow maps in the space of governing dimensionless numbers: dimensionless frequency of pulsations, St1, and relative amplitude of pulsations, β. Flow maps were constructed separately for the in-line (figure 5) and staggered (figure 6) tube bundles. Symbols in the figures denote three different characteristic flow patterns past tube bundles. In the considered ranges of cylinder pitch \( t/d = 1.4 - 2.0 \) and forced unsteadiness parameters, the flow patterns can be clearly distinguished in the flow map.

The flow maps show that under identical Strouhal numbers and depending on the pulsation amplitude there can be two or three different flow patterns around a cylinder. The amplitude effect on the flow pattern in the in-line tube bundle is more pronounced: the inclination angle of the pattern boundaries is smaller in almost the whole range of St1 (figure 5).

It should be noted that the pulsating flow pattern past a closer packed cylinder array (\( t/d < 1.4 \)) needs further examination.
Figure 5. Flow map for the in-line tube bundle: 1 – pattern I; 2 – II; 3 – III

Figure 6. Flow map for the staggered tube bundle: 1 – pattern I; 2 – II; 3 – III

Conclusions
The structure of pulsating flow past the in-line and staggered tube bundles has been studied experimentally. It has been established that vortex shedding from the tube in a bundle is governed by the parameters of forced flow unsteadiness. In the considered range of tube pitch $t/d = 1.4 – 2.0$ the experimental results have been generalized in flow maps in the space of the governing dimensionless numbers: dimensionless frequency, $St_1$, and relative amplitude of forced pulsations, $\beta$. Separate flow maps have been built for the in-line and staggered arrangements of tubes. Each flow map contains three indicative flow patterns past a tube in a bundle. The flow pattern exhibiting two symmetrical vortices simultaneously formed on opposite sides of the tube over one period of forced pulsations was observed for both bundle arrangements at $\beta \geq 0.4$.

Alteration of flow pattern in a tube bundle due to forced flow unsteadiness must influence heat transfer from the tubes in the bundle. This effect should be further investigated.

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