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Flow structure between the tubes and heat transfer of a tube bundle in pulsating flow

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Abstract. Experimental results on the flow structure and heat transfer of the pulsating cross-flow past the in-line and staggered tube bundles have been obtained. The effect of forced flow pulsations on the statistical characteristics of flow in the gap between the inner-row tubes was analyzed for different pitch values. Average heat transfer in steady and pulsating flow past the bundle has been measured. Correlation between heat transfer and the variation of flow pattern in the gap between the tubes has been determined. The opportunity to enhance heat transfer in the tube bundle by forced freestream pulsations has been shown.

1. Introduction
Shell-and-tube heat exchangers have been used in various industries for years. Most often the design of such heat exchangers includes a tube bundle with a cross flow around it. The flow and heat transfer of tube bundle in a steady external flow are well studied. Empirical correlations have been derived for prediction of heat transfer from a tube bundle depending on the bundle configuration, pitch of the tube bundle and the Reynolds number [1 - 4]. Generally, the in-line and staggered tube arrangements in the bundle are considered. Data on the distribution of pressure, velocity and its root-mean-square fluctuations along the surface of the cylinder depending on the location of tubes in the bundle and the pitch between them have been obtained. Over the last decades, more attention has been paid to the flow structure in the gap between the tubes. Flow visualization [5, 6] as well as PIV measurements of instantaneous flow velocity fields [7] were performed. Nevertheless, the problem of heat transfer enhancement in the tube bundle remains very relevant. To date, the main approaches to its solution are passive methods that involve modification of the external tube surface (ribs, roughness, cross-section shape, etc.) [8, 9]. Attempts to find a solution to this problem by actively forcing the flow with pulsations are extremely rare. Thus, in [10], the possibility of heat transfer enhancement in the tube bundle by means of low-frequency asymmetric flow pulsations is shown. However, it is rather difficult to generalize and use the obtained results in practice due to the particularities of the experimental tuning. The effect of forced flow pulsations on the flow pattern in a tube bundle was studied in a series of studies [11-13]. The in-line, staggered and semi-staggered tube arrangements in the bundle were considered. The amplitude of flow pulsations in experiments varied from 5 to 13\%, however, a separate effect of the amplitude on the flow structure in the bundle was not examined. It was shown...
that at a certain ratio of forced unsteadiness parameters the vortex formation locked on to the forced pulsations in the inner rows of tubes accompanied by the increase in flow fluctuations (turbulence intensity). This increase is supposed to lead to heat transfer enhancement [11-13] but the authors did not study the heat transfer. The lack of such information impedes the creation of compact heat exchangers with active control of heat transfer by the forced flow unsteadiness.

The results of experimental studies of the flow structure in the gap between tubes (cylinders) in a bundle and heat transfer in pulsating cross-flow past a tube bundle are presented here. Flow velocity profiles, velocity fluctuations and Reynolds stresses were measured in the wake of the third-row cylinders of in-line or staggered arrangement with varying tube pitch but constant frequency and amplitude of flow pulsations. Data on the heat transfer in tube bundle are obtained and the opportunity to enhance heat transfer by forced freestream pulsations is shown.

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 I 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 module 3 of the pulsator provided the adjustment of mean velocity while the module 2 was used for variation of the frequency and amplitude of forced velocity pulsations. Air flow rate through the setup was provided by a turbocharger 8 operating in a suction mode and maintained constant by a set of critical nozzles mounted on the sealed baffle of the receiver 7.

The diameter of each cylinder in bundle was \( d = 38 \) mm. 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. In-line (figure 2,a) and staggered (figure 2,b) cylinder arrangements were considered. The distance between the cylinders’ axes, \( t \), in streamwise and spanwise directions was the same. To provide correct flow conditions, the cylinders located closest to the wall were replaced by semicylinders (figure 2). When the tube pitch was changed, so was the channel width, \( H_1 \). A special insert was used for this purpose. The experiments were carried out at two values of the pitch: \( t/d = 1.8 \) and 1.2.

In all experiments, the flow velocity in the gap between the tubes was \( U_1 = 1 \) m/s, which corresponded to the Reynolds number \( \text{Re} = U_1 d/\nu = 2800 \). The frequency of forced flow pulsations and the relative amplitude of pulsations was \( f = 11 \) Hz and \( \beta = A_U/U_0 = 0.6 \), respectively. Here, \( A_U \) is the amplitude of flow velocity; \( \nu \) is the kinematic viscosity of air, \( <U_0> \) is the freestream velocity. The flow pattern in the wake of the third-row cylinder located at the channel axis was studied. The flow velocity components, their root-mean-square fluctuations and Reynolds stresses in the gap between the tubes were measured using the SIV technique (Smoke Image Velocimetry) [14]. In addition, the averaged heat transfer from the third-row tube was measured. For this, a cylinder of a special design was used. The coefficient of heat transfer from the cylinder surface was determined from the heat balance equation according to the cooling rate of the preheated cylinder.
3. Results and discussion

The analysis of the instantaneous velocity vector field measurements in the gap between the cylinders revealed the following. Forced pulsations cause almost no effect on the distribution of the streamwise velocity component in the bundle at two values of the relative pitch, both for the in-line and staggered tube bundles. Distribution of the transverse flow velocity was unaffected by pulsations only in the case of staggered arrangement. In the in-line array, there is some increase in the transverse velocity component in the gap between the cylinders at $t/d = 1.8$, and decrease at $t/d = 1.2$.

The level of turbulent fluctuations of the streamwise $u'$ and transverse $v'$ components of the flow velocity in the in-line bundle under the forced pulsations increases substantially at $t/d = 1.8$ (figure 3). In a closer packed cylinder array ($t/d = 1.2$), this increase is insignificant for the streamwise velocity component (figure 4,a) and somewhat more pronounced for the transverse one (figure 5). In the staggered bundle, $u'$ and $v'$ also increase slightly at $t/d = 1.8$ (figure 5), but this is less substantial than in the in-line arrangement. In the staggered array, the fluctuations of streamwise and transverse velocity components slightly decrease at $t/d = 1.2$ (figure 6).

Under forced flow pulsations, at $t/d = 1.8$, the increase in Reynolds stresses $u'v'$ in the gap between the in-line cylinders is far more substantial than in the staggered array. In the closer packed ($t/d = 1.2$) bundle, the Reynolds stresses increase slightly for the in-line arrangement, while the staggered one exhibits a pronounced decreasing trend.

**Figure 2.** In-line (a) and staggered (b) tube arrangement.

**Figure 3.** The profiles of fluctuations of streamwise (a) and transverse (b) velocity components in the in-line bundle at $f = 11$ Hz ($t/d = 1.8$). Tube arrangement is illustrated in figure 2,a.
Heat transfer studies included test experiments, as well as measurements of the average heat transfer in a pulsating flow past a tube bundle. Test experiments showed that the difference in the measured average Nusselt numbers, Nu, from those calculated by the known empirical relations [2] does not exceed 11%, which is quite acceptable for heat transfer experiments.

The effect caused by forced flow pulsations on heat transfer of the in-line tube bundle is more pronounced: the largest increase in heat transfer as compared to the steady flow equaled to 30% and was observed at \( t/d = 1.8 \). At the same tube pitch for the staggered bundle, the forced pulsations led to an increase in the heat transfer coefficient by 13%. In a closer packed cylinder array (\( t/d = 1.2 \)) of staggered arrangement in the pulsating flow, the heat transfer coefficient decreased.

The revealed features of the effect caused by forced flow pulsations on the heat transfer from the cylinder are largely due to the level of velocity component fluctuations in the gap between the cylinders. Thus, the increasing fluctuations of velocity components promote the heat transfer, while the decrease in fluctuation level impedes the latter. In addition, maximum heat transfer enhancement was obtained in regimes with a pair of almost symmetric vortices formed behind the cylinder over the period of forced pulsations [15]. Maximum heat transfer augmentation was also observed in the identical regime of pulsating cross-flow past a single cylinder [16].
Figure 6. Profiles of fluctuations of streamwise (a) and transverse (b) velocity components in the staggered tube bundle at $f = 11$ Hz ($t/d = 1.2$). Tube arrangement is illustrated in figure 2,b.

4. Conclusions
The effect of forced flow pulsations on the profiles of streamwise and transverse velocity components, their RMS fluctuations and Reynolds stresses in the gap between the cylinders in the in-line and staggered bundles at $t/d = 1.8$ and 1.2 has been revealed from the instantaneous velocity field measurements. For the case of $t/d = 1.8$, the fluctuations were promoted significantly in the in-line bundle, while the staggered arrangement exhibited less pronounced increase in velocity fluctuations. Fluctuations of streamwise and transverse velocity components in the staggered array decreased at $t/d = 1.2$. The opportunity to enhance heat transfer in a tube bundle by forced unsteadiness has been demonstrated. The maximum increase in the average heat transfer coefficient of a tube in a bundle was 30% for the in-line array at $t/d = 1.8$. The correlation between the variation of heat transfer from the bundle in forced unsteady flow and the flow structure in the gap between the tubes has been shown.

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