Flow and heat transfer near a cylinders row

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Abstract. The paper aims to investigate the dependence of heat transfer classification on the Reynolds number (Re) during flow around circular heated cylinders row. The investigated range of Re number varies from $4.5 \times 10^3$ up to $42 \times 10^3$. The distance between cylinders $S$ was changed from $0.5d$ to $4d$ (where $d$ is the cylinders dia). Cylinders surface temperature was kept constant. For each Re number, the case when the cylinders were mounted one after the other was investigated. To measure heat transfer and flow parameters (velocity, heat flux and heat transfer coefficient) near and at the cylinders surface, two experimental methods were used: gradient heatmetry and PIV. Heat flux and velocity fields were obtained from gradient heatmetry and PIV results, based on which the flow mode could be determined and compared with heat transfer mode. As a result, it was found that heat transfer is influenced by both the Reynolds number and the distance between the cylinders. The observed features are associated with influence on characteristics such as separation point location, boundary layer thickness, change in flow between the cylinders and vortices formation.

1. Introduction
Experimental study of heat transfer and hydrodynamic between multiple surfaces used in heat exchangers is of both fundamental and practical importance. Flow in and behind the cylinders row is by far more complicated than that behind a single cylinder. In this configuration, in addition to the interrelationship between flow and heat transfer, described by the similarity equation $\text{Nu} = \text{Re} (\text{Nu})$, it is important to evaluate the effect of distance $S$ between cylinders ($\text{Re} = \frac{Wd}{\nu}$, where $W$ is free flow velocity, $d$ is cylinder dia, and $\nu$ is kinematic viscosity of liquid; $\text{Nu} = \frac{h d}{k}$, where $h$ is heat transfer coefficient and $k$ is heat conductivity of liquid). The flow classification in terms of Re and $S$ is crucial for understanding of heat transfer and has received considerable attention.

Lately, tubes rows and bundles of various profiles and configurations have been actively investigated. For example, Aiba and Yamazaki [1] carried out series of experiments to study flow near a tube bundle of different configurations. They investigate the flow and heat transfer characteristics. Based on the results, the authors argue that the most significant is contribution of vortex formed behind the first tube. The experiment was carried out for a narrow range of Reynolds numbers: from $10^4$ up to $5\times10^5$. In other work, Aiba and others [2] studied heat transfer in a row of 7 tubes. It was concluded that Nusselt number varies slightly in the far tubes, starting from the second.

There is a lot of numerical studies conducted to determine cross flow around isothermal circular cylinders in arrangements such as single cylinder, inline and staggered arrays. So, in the paper [3] flow over the cylinder with low Reynolds number was investigated. The authors solved two-dimensional stationary problem for a viscous incompressible fluid in a channel. The main conclusion, the authors
believe that heat transfer from a staggered array of cylinders is slightly higher than that from an inline array.

Another direction of such studies is associated with flow around cylinders of non-circular cross-section. It is known that cross-sectional shape can both improve and worsen the hydrodynamic characteristics. The study [4] esteems flow characteristics and associated instability of convective flow behind a semi-circular cylinder at incidence with a downstream circular cylinder. Unsteady computations are performed for different incidence angles and Reynolds numbers from 60 up to 160. Dependencies of coefficient of drag and lift coefficient on the angles of incidence are examined. The simulation results compared with the experimental ones [5] showed satisfactory agreement. The authors concluded that two separation points on a semicircular cylinder change its location with angles of incidence. However, flow topology behind a circular cylinder resembles flow situation behind a rotating circular cylinder. Vortex shedding frequency is nonlinear.

The work [6] aims to investigate the dependence of Reynolds number for the wake of two staggered cylinders. Hotwires were used to measure fluctuating velocities in vortex streets behind two cylinders. Power spectral density functions were obtained, based on which flow structure pattern could be determined. According to the article, there is a departure in the border between different flow modes, which is partially revealed with refined measurement grids, and hence improved resolution in determining of flow mode.

2. Experimental details
   2.1. Experimental model
   Schematic of experimental arrangement is represented at figure 1. The model consists of single (I), two (I and II) or three (I, II and III) circular cylinders, which are mounted inline one by one at distance of \( S \). The dia of all cylinders is of 66 mm, and the thickness of the cylinder wall is of 0,1 mm. Cylinders had a length of 600 mm. At the investigated cylinder (I, II or III) gradient heat flux sensor (GHFS) are mounted, and the cylinder could rotate around its axis at an angle \( \phi \) from 0 up to 180 °C. Saturated water steam at atmospheric pressure was supplied inside all cylinders. This heating scheme made it possible to maintain constant temperature at the surface of the model.

   ![Figure 1. Scheme of the model.](image-url)

   Our experimental setup made it possible to change distance \( S \) between investigated cylinders. The experimental model was installed in the working section of a subsonic wind tunnel. The wind tunnel features associated with maintaining of constant temperature of free-stream airflow, velocities range and turbulence degree are described in detail in the paper [7]. The range of modes (\( Re = 500 ... 42000 \)) is realized by change of airflow velocity in the tunnel.
2.2. Experimental methods

Two modern methods were used in the work, namely particle image velocimetry (PIV) and gradient heatmetry. The choice of methods depends on both the model used and the problem statement. Velocity measurements using PIV are described in detail in the work [7]. We used the POLIS system [8] in two-dimensional setting. The resolution of the camera used was 4MPx, and dry wood smoke was used as tracers media.

In study of heat transfer during flow around a cylinders row technique of gradient heatmetry developed in Peter the Great St. Petersburg Polytechnic University was used. Gradient heatmetry is based on use of gradient heat flux sensors. Physically, the action of these sensors is based on transverse Seebeck’ effect. It is thermal to electric energy conversion, where direction of electric field is normal to direction of heat flux. The electric field $E$ generated by transverse Seebeck’ effect is given by $E=S\nabla T$ (where $S$ is Seebeck tensor and $T$ is temperature). Moreover, the electric field $E$ and the temperature gradient $\nabla T$ are not always collinear. Unlike thermoelectric devices in which we use only the diagonal term $S$, transverse thermoelectric devices use off-diagonal term $S$ [9]. Tensor $S$ is not diagonal in two cases. Either sensor’s media is of anisotropic properties, or the main axes of media’s anisotropy must be inclined with respect to directions of thermal input and electrical output. GHFSs used in our experiments are made of single-crystal bismuth of purity 0.9999. Since this material is anisotropic, it implements transverse Seebeck’ effect described above. The GHFS is of 2×2×0.2 mm in size. Its volt-watt sensitivity was about 8 mV/W.

3. Results

Velocity fields in the vicinity of single, pair, and three cylinders row make it possible to say that the flow in the wake depends on the number of cylinders. For example, figure 1 shows the average velocity fields near cylinders for Reynolds number of $Re = 9600$.

It can be noted that for given distance of $S=d$, vortex street length depends on the number of cylinders. Average velocity fields make it possible to estimate the size as well as the average velocity distribution in the wake-zone. However, for a more complete characterization, it is necessary to analyze instantaneous velocity fields. Such analysis is given as an example in our paper [10].

In this paper, we will discuss relationship between heat transfer and system geometry in detail. Thus, figure 3 shows dependences of local Nusselt number ($Nu_\phi = h_\phi d/k$, where $h_\phi$ is local heat transfer coefficient ) on the rotation angle $\phi$ for the second and third cylinders.

Distribution of Nusselt number shows that heat transfer at the second and third cylinders is different both in nature and in magnitude. The differences are more noticeable for larger Reynolds numbers: the local Nusselt number maximums differ by about two times. However, in the $\phi$ range of 150 ... 180° there are practically no differences. The difference between surface-averaged Nusselt numbers is of 10...50%. Moreover, small differences are typical for low Reynolds numbers ($Re<5000$). As the distance between the cylinders increases, the difference in the average Nusselt number decreases.

For a visual comparison of all three cylinders, figure 4 shows distributions of heat flux per unit area. This type of presentation of results does not allow to estimate values of parameters numerically.
However, they clearly show in which part of the cylinder (I, II, or III) intensity of heat transfer is the lowest or the highest. For example, for the first and third cylinders there is a region where forced convective heat transfer is practically absent ($\varphi \approx 90^\circ$ for the first and $\varphi \approx 120^\circ$ near the third one).

**Figure 2.** Average velocity field for a, b pair of cylinders; and c for three cylinders.
Figure 3. Dependence of local Nusselt number on the angle $\phi$ for the second (II) and the third (III) cylinders ($S = d$).

Heat transfer intensity at the second cylinder is uniform. This illustration allows us to see that heat transfer in the aft part of the second and third cylinders is weakly dependent on the distance $S$. Another advantage of such figures is that in terms of heat transfer enhancement, one can immediately determine its ways and, which is most important, geometry of intensifiers.

Figure 4. Heat flux at the cylinders surface: a) for $S = d$ and b) for $S = 2d$. 
Conclusions
Simultaneously use of gradient heatmetry and PIV makes it possible to evaluate not only the qualitative, but also quantitative parameters of convective heat transfer. First of all, to derive the similarity equations for the flow around a cylinders row.

The results showed that the local heat transfer coefficient’s distribution at the surface of the second and third cylinders depends largely on the distance $S$ in the case of $Re = 500 \ldots 5000$. This is due to the action of rather large vortices that periodically descend from the first cylinder. In addition, at the second cylinder near the frontal generatrix area ($\varphi = \pm 30^\circ$) the heat transfer intensity of depends on whether the second cylinder is in the zone of developed vortices (approximately $(1.5 \ldots 3)d$ from the first cylinder) or in the stagnation zone (less than $1d$ from the first cylinder). Experiments have shown that the velocity field behind the second cylinder is practically uniform, which affects heat transfer near the third cylinder as follows: the dependence of the heat transfer coefficient on the angle $\varphi$ is qualitatively similar to the dependence for the first cylinder. There is also a displacement of the separation point to the $\varphi = 120\ldots130^\circ$. In addition, averaged heat transfer coefficient for the third and for the first cylinder are comparable.

The combined technique and the results obtained will serve as basis for study of flow and heat transfer in tube bundles and heat transfer enhancement while maintaining acceptable hydrodynamic parameters.

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