Features of vortex formation and heat transfer during cross flow around two cylinders

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Abstract. The creation of all heat exchangers supposes the establishment of a quantitative and qualitative relationship between the flow and heat flux distribution at heat transfer surfaces. The paper presents the study’s results of the vortex flow’s structure and heat transfer near two circular cylinders. The distance between the cylinders ranged from 0.5\textit{d} to 4\textit{d} during the experiments (here \textit{d} is the diameter of the cylinders). The vortex flow’s patterns in hydro- and wind tunnels in the Reynolds numbers’ range from 4000 to 40,000 are compared. To study heat transfer near the cylinders, gradient heat flux measurement was used. In aerodynamic experiments, both cylinders were heated with saturated steam, ensuring a constant surface temperature of the cylinder. The results showed an agreement of the flow patterns. The effect of distance and flow velocity on the flow around the second cylinder is revealed: there may be cases when the second cylinder is at rest, in other cases it fluctuates. Gradient heatmetry revealed a decrease in the level of fluctuations near the second cylinder. However, the average Nusselt number for the second cylinder is expectedly lower than for the first.

1. Introduction

Flow near tubes of various shapes and configurations is one of the main problems of hydrodynamics and heat transfer \cite{1-3}. The widespread use of tubes as the basic elements in the vast majority of recuperative heat exchangers makes studying the interaction’s characteristics of the working fluid and the heat exchange surface relevant. In addition, improving the quality and efficiency with a simultaneous decrease in mass-dimensional parameters and the cost of manufacturing technical devices poses a new task - the heat transfer enhancement with a simultaneous increase in aerodynamic efficiency \cite{3-5}. Despite almost a hundred-year history of studying the issue, research on this topic does not stop.

With a cross-flow around a single cylinder, a wake-off zone with a return flow and a swirl wake zone are formed in the wake. This phenomenon has been studied both over the past century and in recent years in leading laboratories and research centres in our country and abroad. Figure 1 shows a picture of the flow around a single cylinder, on which the flow’s separation zone and the vortex wake obtained in a vertical water tunnel (VWT) is clearly visible.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{flow_vortex.png}
\caption{Flow around a single cylinder with vortex wake.}
\end{figure}
In the paper [6] the model of a cylinder of square section is used. The authors have probed drag coefficient and aerodynamic efficiency. In addition, there are also studied the features related to non-cross flow.

In the papers [7-11] authors examined in detail the effect of roughness and adhesion of a cylindrical surface on aerodynamic quality, separated vortices’ type, frequency and amplitude of vibrations and noise. Note, however, that most work has been done for a single cylinder. Numerous results of experiments on the heat transfer study allow using them to calculate the cylindrical surfaces of heat transfer. However, the results are most often limited to studies of either single cylinders or tube bundles by integral values at the inlet and outlet of the heat exchanger. Local distribution of heat flux and heat transfer coefficient (HTC) over the each cylinder’s surface makes it possible to intensify heat transfer, while maintaining acceptable hydraulic parameters.

The study of pulsations in a stream flowing around a cylinder is also an important task. By measuring the static pressure pulsations of the velocity and heat flux density, it is possible to obtain a more complete physical picture of convective heat transfer.

2. Water tunnel experiments

The first part of the experiments was carried out in VVT. The Krylov State Research Centre’s VWT has a diaphanous working section of 150×150 mm [12,13]. Velocity range may vary from 4 to 50 cm/s. The investigated cylinders’ diameter $d$ was 12 mm. The second cylinder of the same diameter was located at a distance $S$ from the first, equal to $d$, $2d$, $3d$ and $4d$. In addition, the second cylinder was held on a free hanging, allowing to move across the current.

When the second cylinder is located in the flow separation zone behind the first, a return flow zone arises between the cylinders [14]. A short separation zone and a vortex wake appear behind the second cylinder. In this case, there are no periodic variable forces on the second cylinder, and it remains motionless (Figure 3). In this photo obtained at the VGT, the structure of internal flows, the trajectories of external streamlines, and the vortex wake are clearly visible.
As the distance between the cylinders increases, the second cylinder leaves the zone of the return separated flow into the zone of the vortex wake. Periodic vortices of opposite directions alternately capture the cylinder. It begins to oscillate across the flow with the frequency of vortex vanishing (Figure 3). The amplitude $A$ of the oscillations is approximately the diameter of the cylinder $d$. As the second cylinder moves away, the vortex intensity decreases, and the transverse forces decrease accordingly.

**Figure 2.** Internal streamlines between a pair of cylinders and a vortex wake, $S = d$

**Figure 3.** Oscillations of the second cylinder captured by vortices descending from the first cylinder at a distance between cylinders $S = 3d$, $Re = 12000$, a) and b) - various positions of the second cylinder.
3. Wind tunnel experiments
The wind tunnel’s experiments were performed in the Peter the Great Saint-Petersburg Polytechnic University [15]. The method includes two techniques: a widely used PIV and a unique gradient heatmetry. Gradient heatmetry based on the gradient heat flux sensors (GHFSs). GHFSs have been created at Peter the Great St. Petersburg Polytechnic University in 1996. It is actively used in laboratory and industrial experiments. To visualize the air flow near the cylinders using the PIV we used the POLIS system. The system is described in more detail in the papers [16-17].

The model consists of two circular hollow cylinders mounted on a special frame. The frame allowed to move the second cylinder and thus change the distance $S$ between the cylinders. The model was placed into the Eiffel chamber of the tunnel (Figure 4). Models was heated with the saturated steam under the atmospheric pressure; therefore keeping the surface temperature of the cylinders constant. A bismuth-based GHFS was installed on the second cylinder’ surface. The size of the GHFS is $2 \times 2 \times 0.2$ mm. The second cylinder was rotated around its axis, therefore, the GHFS measured heat flux in the angle range from frontal to supply point ($0 \leq \varphi \leq 180^\circ$).

![Figure 4](image)

**Figure 4.** A pair of cylinders’ experimental design

Our research was carried out for Reynolds number $Re = (W \times d) / \nu$ from 4000 to 40000. Figure 5 illustrates velocity fields between cylinders for varied free-stream velocity. Vectors show the flow direction and colors show the velocity’ value. The shaded area from the cylinders is shown in gray.

![Figure 5](image)

**Figure 5.** Instantaneous velocity fields near the pair of cylinders, $S = d$:

a - $Re = 9600$; b - $Re = 4800$
As in experiments in the VWT, a vortex wake behind the second cylinder is observed. In addition, in the PIV pictures you can see the stagnant zone between the cylinders, where the flow rates are minimal. It is also important to note that the flow rate in the wake exceeds the free-stream velocity. For comparison, Figure 6 shows the velocity fields for a higher distances $S$. It is seen that with increasing distance $S$, the vortex path opening angle also increases.

**Figure 6.** Instantaneous velocity fields near the pair of cylinders, Re = 4800:  
\[ a - S = 2d; \quad b - S = 3d \]

The use of gradient ducts of the gradient heatmetry made it possible to obtain the heat flux distribution along the second cylinder’ surface depending on the regime.
It can be seen that the HTC distribution over the angle \( \varphi \) of the second cylinder is different from the distribution characteristic for a single cylinder [5-10]. The maximum HTC lies in the region of 60…90° degrees, not at the frontal point. With increasing air velocity, the heat transfer rate increases.

The GHFS response time [16] also allowed us to estimate the magnitude of the heat flux and HTC’ fluctuations on the cylinder surface. In the experiments, we managed to obtain a set of the heat flux per unit area, which can be considered a discrete and randomly variable value (Fig. 8).

Dispersion \( D \) is calculated here as the square root of the standard variation or arithmetic mean of the measured local heat flux. The maximum fluctuations’ level for the second cylinder is also located near angle \( \varphi = 90^\circ \), while in the aft zone it drops to a minimum. On average, the fluctuations level for the second cylinder is 10 times less than the fluctuations for a single cylinder.
4. Conclusion
The research results showed the identity of the patterns of the flow structure and the vortex wake for a pair of cylinders obtained in hydrodynamic and wind tunnels. At the same time, the obtained patterns of currents complement each other.
Gradient heatmetry made it possible to identify the features of heat transfer near the second cylinder, depending on the geometric and operating parameters.
The results obtained allow us to get an idea of the physical fields and forces arising at real objects: marine equipment, heat exchangers, and other engineering structures.

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Acknowledgments
This research work was supported by the Academic Excellence Project 5-100 proposed by Peter the Great St. Petersburg Polytechnic University.