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# Flow and Heat Transfer Characteristics during the Flow around Tandem of Circular Cylinders

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**Abstract.** The forced convection into the tandem circular cylinders is investigated using gradient heatmetry and particle image velocimetry-based experiments. The study's objective is to understand the effect of geometry on the flow characteristics and heat transfer coefficient distribution over the heat transfer surface. The experiments are conducted over Reynolds numbers Re = 9600 and Re = 20200, thereby uncovering there is highly complicated flow structure, depending on centre-to-center spacing and orientation of the two cylinders with respect to free-stream flow. Different transversal and longitudinal pitch ($S_1$ and $S_2$, respectively) between the cylinders are considered, and its effect on the flow and thermal characteristics are studied. Velocity fields and longitudinal and transversal velocity components obtained using Particle Image Velocimetry (PIV), and heat transfer parameters obtained using gradient heatmetry and temperature measurement. The distributions of the local heat transfer coefficient on the heat transfer surface are obtained. Based on these distributions, the surface-averaged Nusselt number for the studied Reynolds number is determined.

**Keywords:** flow over cylinders, convective heat transfer, gradient heatmetry, heat transfer coefficient.

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## Introduction

The flow into cylinder's system is one of the most important objectives in thermo-fluid mechanics.This is a result of the fact that flow around a cylinders has applications in different heat exchangers, such as pins in electronics, control bars in nuclear reactors, in cooling applications in gas turbine blades, etc. If considered separately the tube-in-shell heat exchangers, then besides aerodynamics, it is important to investigate the heat transfer of the internal system. Usually, one fluid moves over the tubes, while the other heat transfer agent, passes through the tubes. We are specifically interested in the forced convection heat transfer in cross-flow over the tubes. As a real heat exchanger' tubes, the flow around heated cylinders of circular cross section is considered. The banks are usually arranged in an in-line or staggered manner and are characterized by the dimensionless transverse, longitudinal, and diagonal pitches [1].

The flow around the tandem cylinders is a basic configuration and has been extensively studied. The vortex shedding from the structures and acting upon the downstream structures

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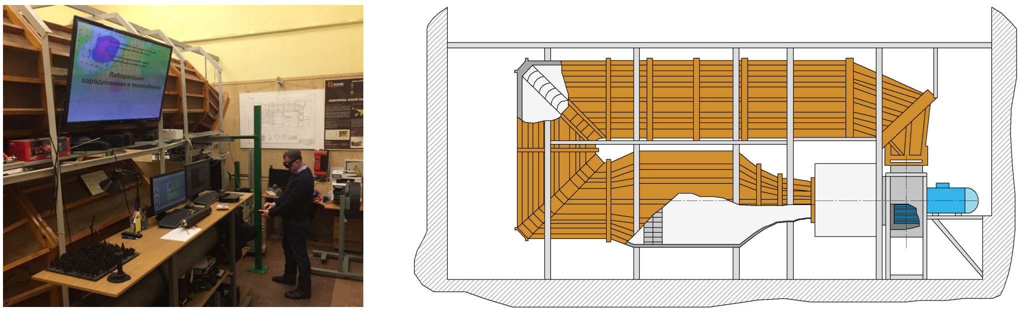
may produce a pressure fluctuating on the constructions. Apart from engineering applications, it includes aspects of flow physics, such as bluff body separating flow, shear layer reattachment and the interaction between several bodies and vortex shedding [2, 3]. The problem is made more difficult by numerous formations resulting from different flow patterns and the result of their interactions.

Most published research focuses on the influence of cylinder geometry on local or/and surface-averaged heat transfer coefficients (HTC) [4, 7] and drag coefficients [5]. A number of studies aim to obtain the distributions of local values of these quantities, as well as to consider them depending on time. Further, it is possible to investigate the influence of geometry [6, 7], blockage ratio [8], turbulence number [9], heat transfer surface roughness [10], etc.

Summarizing the literature, it can be said that the problem of flow around cylindrical heat transfer surfaces is relevant for scientific research and practice, and what is more there is a lack of experimental data for verification of numerical simulations. Therefore, the present paper is devoted to an experimental study of the flow and heat transfer near a pair of cylinders.

## 1. Experimental set-up

The experiments are conducted in a closed-loop wind tunnel of Science Educational Centre "Energy Thermophysics" (Fig. 1). The air flow in the tunnel was generated by a frequency-controlled centrifugal fan. The airflow was conducted into the test section through the nozzle with an area ratio of 7:1. The tube has test section 870 mm length and contraction cone outlet diameter is 450 mm. The test section features an Eiffel plexiglass chamber, which simplifies the PIV-experiments. The key technical know-how of the tunnel is the featuring of the heat exchanger. The heat exchanger is connected to the cold water supply system. This ensures the free-stream airflow's temperature is almost constant ($\Delta T = 0.1$ K). A detailed description of the experimental set-up is provided in [11].



(a) (b)

Fig. 1. Photo (a) and scheme (b) of the wind tunnel

Experiments were carried out on hollow circular cylinders. Cylinders were heated by the saturated steam under atmospheric pressure, thereby keeping the heat transfer surface temperature constant and close to 100 °C. Cylinders were coated with black paint, so the the heat transfer surface emissivity factor was about 0.99. Therefore, in experiments the first-type boundary condition (Dirichlet boundary condition) was allowed.

The experiment employed two sets of cylinders.The first set was designed to study heat transfer, which are cylinders of 66 mm in diameter, 600 mm in length and 0.1 mm thick are made of steel. The model's scheme is shown in Fig. 2.

The second cylinder set was designed to study flow structure by PIV. Aluminium cylinders with a diameter of 25 mm and a thickness of 0.5 mm were used. This made it possible to extend

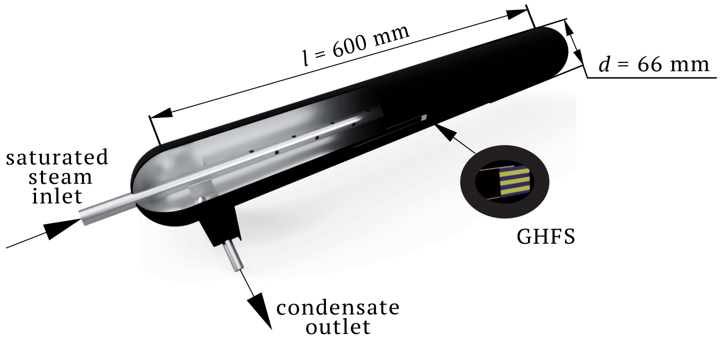



Fig. 2. Scheme of a cylinder

the area under investigation. Since the heat transfer and flow studies were carried out differently and separately, the experiments were conducted at the same Reynolds number. The Reynolds number is calculated from the cylinder diameter $d$:

$$Re = \frac{Wd}{\nu}, \tag{1}$$

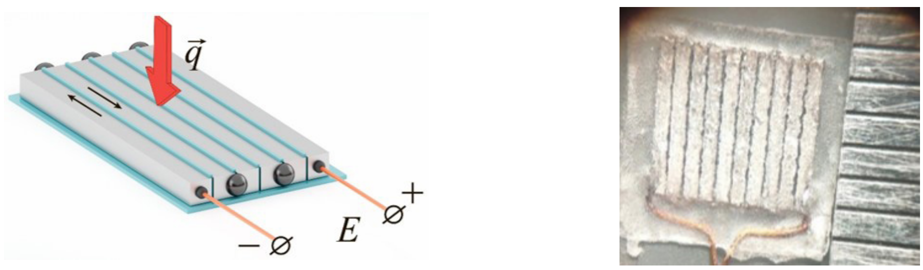
where $W$ is free-stream velocity, and $\nu$ is kinematic viscosity.

To measure the heat flux at the cylinders surface a gradient heatmetry was used. This method is based on gradient heat flux sensors (GHFS) application. GHFSs are belong to surface-mounted sensors. The primary benefit of these sensors is the ability to measure local heat flux. The GHFSs was created and manufactured by the scientific team of SEC "Energy Thermophysics", Peter the Great St. Petersburg Polytechnic University. The GHFS consists of a series of anisotropic thermopower elements (ATE), which is a material with anisotropic thermophysical and thermopower properties. When affected by heat flux, ATE generates thermopower normal to heat flux per unit area vector $\overline{q}$ and proportional to heat flux rate:

$$q = \frac{E}{S_0 A}, \tag{2}$$

where $E$ is generated thermopower, V; $S_0$ is volt-watt sensitivity, V/W, and $A$ is ATE cross-area, m$^2$.

A detailed description of the GHFS' working principle can be found in [12]. Today, the sensors have proven themselves in the heat transfer study during boiling [13], condensation [14] and single-phase convection [15]. We used a battery-type GHFS made of bismuth, the scheme and general view of which are presented in Fig. 3.




(**a**) (**b**)

Fig. 3. Scheme (a) and photo (b) of bismuth-based GHFS

Choice was due to the temperature on the surface is close to 100 °C, the operating environment is not aggressive, and the volt-watt sensitivity of bismuth-based GHFS is sufficiently high for the specified temperature. We used GHFS with dimensions of 2×2×0.2 mm, and a volt-watt sensitivity of about 5 mV/W. The surface mounted sensors disturb a temperature field, at whose surface they are installed. However, the GHFS thermal resistance less, than surface heat transfer resistance.

To obtain velocity fields PIV system made by Sigma-Pro LLC was used [16]. It includes a Quantel BSL dual pulse laser, digital camera, synchronization device, smoke generator and ActualFlow software. Principle of any PIV system operation is that tracers are fed into the optically transparent flow: fine tracers (particles with a diameter of 2. . . 10 $\mu$m) which are illuminated by laser light reshaped by lens system into the laser sheet. A digital camera fixed the image of tracers at moments of double flashes. The output data were transferred from the camera to the PC's memory, and software gives the velocity field for each time step.

To measure temperature of the heat transfer surface we used thermal imaging camera FLIR P640. Coincidently, we determined the temperature of the free-stream air flow at the outlet of the tunnel's nozzle using multifunctional device testo-435i. Thus, by measuring the heat flux and temperature, we determined the local heat transfer coefficient $\alpha_\varphi$ and, further, the local Nusselt number:

$$Nu_\varphi = \frac{\alpha_\varphi d}{\lambda}, \tag{3}$$

where $\lambda$ is heat conduction, W/(m×K).

In this study, we consider the flow around two cylinders for their in-line arrangement ($S_1 = 0$) and the staggered arrangement ($S_1 = d$). The purpose of the study was to determine the distribution of the Nusselt number and flow near the second cylinder (see Fig. 4).

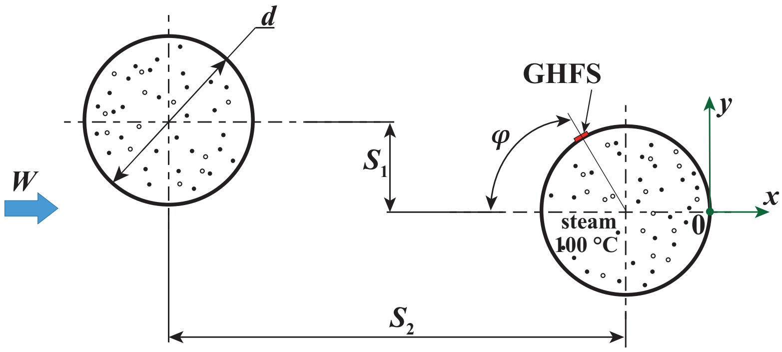



Fig. 4. Flow diagram of the experiment

The sensor was mounted on the second cylinder, and the cylinder itself rotates around the axis at an angle $\varphi$. The value $\varphi = 0$ corresponds to the stagnation point.

## 2. Results and discussion

As an example of the results obtained, Fig. 5 shows the time-averaged velocity fields obtained by the PIV for Re = 4800 and $S_2 = 2d$.

The velocity is negative in the re-circulation region and attains a positive value further downstream for both $S_1$. However, it is clearly seen that the region is much wider along the vertical axis, for an staggered arrangement. The flow around the front of the second cylinder also differs.

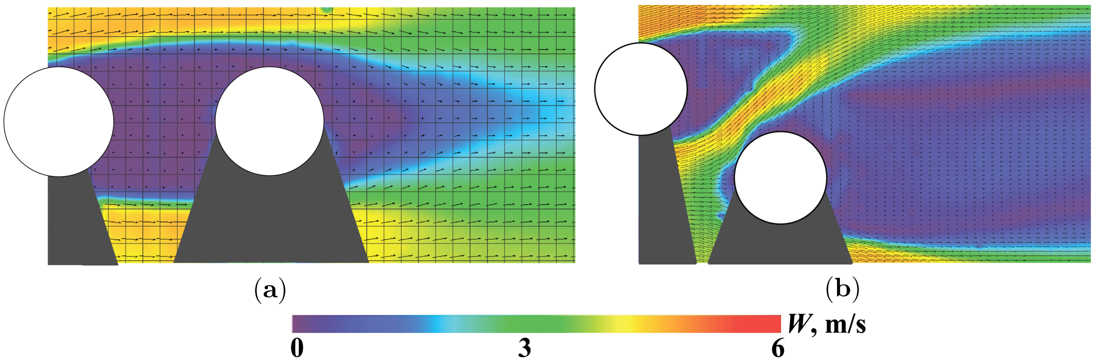



Fig. 5. Time-averaged velocity fields for Re = 9600 and $S_2 = 2d$: a — $S_1 = 0$; b — $S_1 = d$

For an in-line arrangement, Fig. 5, a present the "reattachment" regime [1], when two cylinders are placed with sufficient distance between them that the shear layers separated from the first one can't surround the second, and they connect to the second cylinder. Fi. 5, b represent the staggered configuration of "large-incidence-angle flow patterns". For this case it is typical vortex pairing and enveloping flow over the second cylinder. When the second cylinder are shifted vertically, local acceleration is observed and the flow structure is closer to the flow around a single cylinder. The time-averaged velocity fields for Re = 20200 are very similar to those shown in Fig. 6.

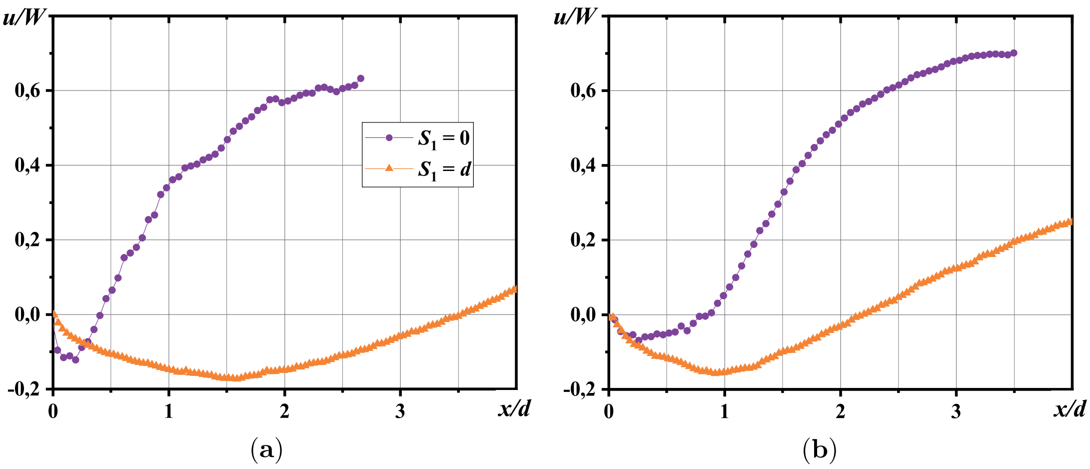



Fig. 6. Longitudinal velocity $u$ behind second cylinder for $S_2 = 2d$: a — Re = 9600; b — Re = 20200

An important characteristic during flowing around cylinders is the recirculation length. To determine it, Fig. 6 shows the distribution of the longitudinal velocity component in the middle section behind the second cylinder for various Re. In this and subsequent figures, the origin of the $x$-axis coincides with the aft critical point of the second cylinder (see Fig. 7).

It can be seen that the area of negative $u$ in that case ($S_2 = 2d$) of staggered arrangement is much larger than for in-line arrangement. On the other hand, the influence of the air-flow velocity is shown. With an increase in the Re number, the recirculation zone for the in-line arrangement increases, and for the staggered one it decreases. It can be added that the highest intensity of return flows is observed for Re = 9600 of in-line arrangement. The effect influence on extreme negative velocities u in a staggered arrangement is slight.

It is also interesting to consider the distribution of the longitudinal velocity' component $u$ behind the second cylinder along the vertical ($y$-axis).

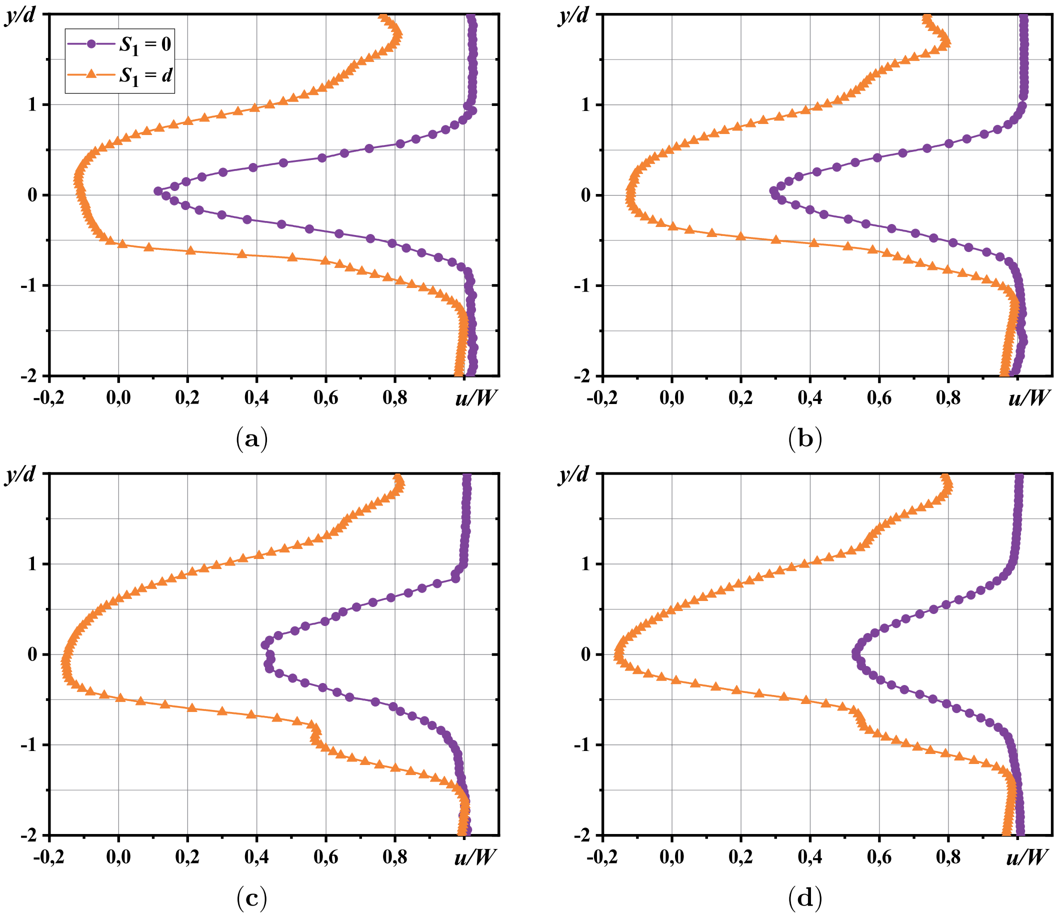



Fig. 7. Longitudinal velocity $u$ behind second cylinder along the $y$-axis for $S_2 = 2d$: a, c — Re = 9600 and b, d — Re = 20200; a, b — $x/d$=0.5 and c, d — $x/d$=1

For all section under consideration, it can be seen that the low-energy region for the in-line arrangement is narrower than for the staggered one by more than 2 times. For an in-line arrangement of cylinders, the longitudinal speed has a U-shape with a minimum on the horizontal axis of the cylinder. Moreover, there is an asymmetry in the distribution of the velocity $u$ for the flow past the cylinders with off-centre displacement. The flow regime significantly affects the velocity behind the cylinders arranged in-line, while for the studied Re numbers, the longitudinal velocity profile behind the second cylinder with a staggered arrangement becomes somewhat "sharper".

Fig. 8 shows transversal velocity $v$ in the wake at different distances from the second cylinder. It can be seen that neither the regime's influence nor its relative position here are entirely clear. All curves for in-lane arrangement are similar and have a N-shape. It is evident from them that if the airflow velocity is increased, the extreme $v$ decreases. Exactly the same trend is observed with an increase in the distance from the second cylinder to the seeding under consideration behind it. Since the size of the recirculation zone is relatively small, in both sections under consideration we observe an oncoming movement: $v < 0$ for $y > 0$ and vice versa.

As shown above, the region of reversing flow behind the second cylinder in a staggered arrange-

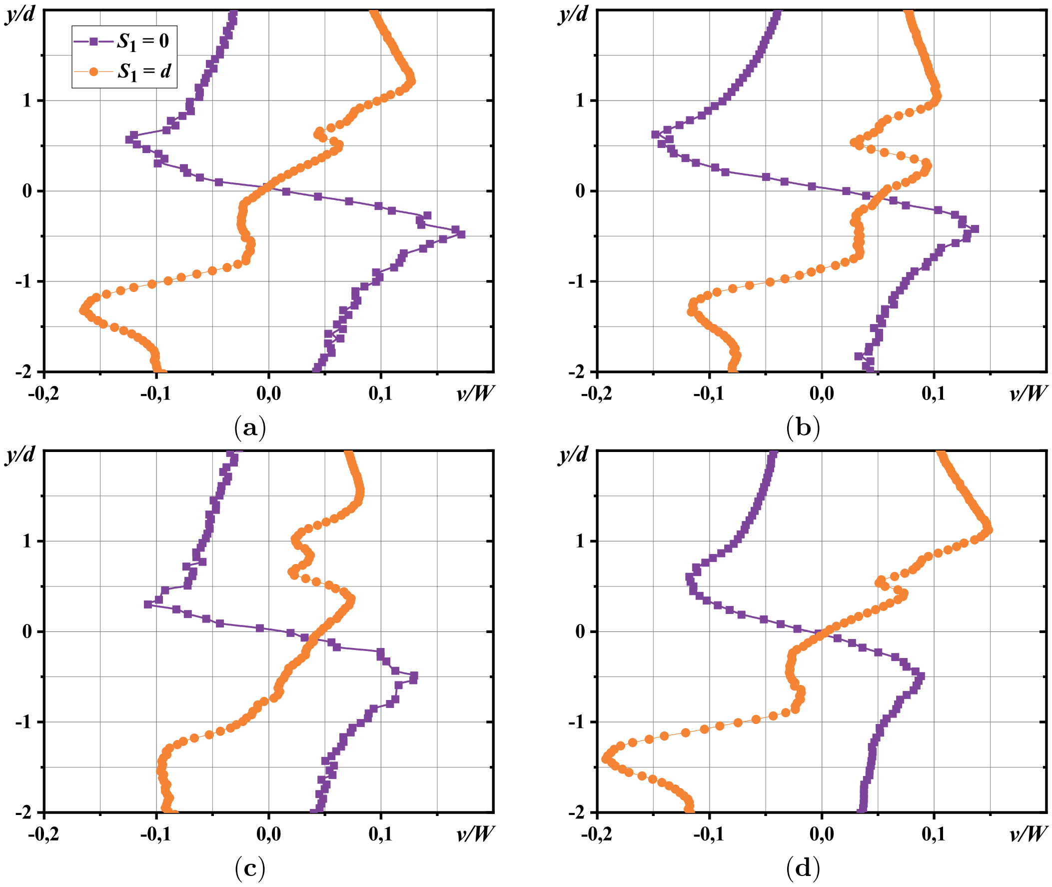



Fig. 8. Transversal velocity $v$ behind second cylinder along the $y$-axis for $S_2 = 2d$: a, c – Re = 9600 and b, d – Re = 20200; a,b – $x/d$=0.5 and c, d – $x/d$=1

ment is elongated along the x axis. Therefore, for the sections under consideration ($x/d = 0.5$ and $x/d = 1$), an contra-directional flow is observed. All curves here do not have a strong N-shape. The extreme values of $v$ are removed by a distance more than $d$ from $y = 0$, while for an in-line arrangement the distance between the extremes is approximately equal to 1 cylinder diameter. The profiles shown in Fig. 8, b and c seem interesting. The zero value of v here does not lie on the $x$-axis, and on the upper part of the graph there is a non-monotonicity of the curve with local extrema. It is in this area that the vortices which descended from the first and second cylinders interact.

Summarizing, we can say that two cylinders with their in-line arrangement have a much lesser effect on the flow than with a staggered arrangement. As a consequence, we can talk about a higher drag coefficient for the cylinder system installed with a shift which is consistent with the conclusions of [1].

At the second experimental stage the distributions of the local heat transfer coefficient (HTC) over the surface of the second cylinder were compared. To obtain the graphs shown in Fig. 9, the second cylinder with the GHFS mounted on it was rotated around the axis by an angle $\varphi$ from 0 to 180° with a step of 10°.

One can see noticeable differences between the HTC curves obtained for a various cylinder's arrangement. For the in-line arrangement the maximum is shifted from the front stagnation point, and its position is about 60. . .90° for both Reynolds number. This can be explained by

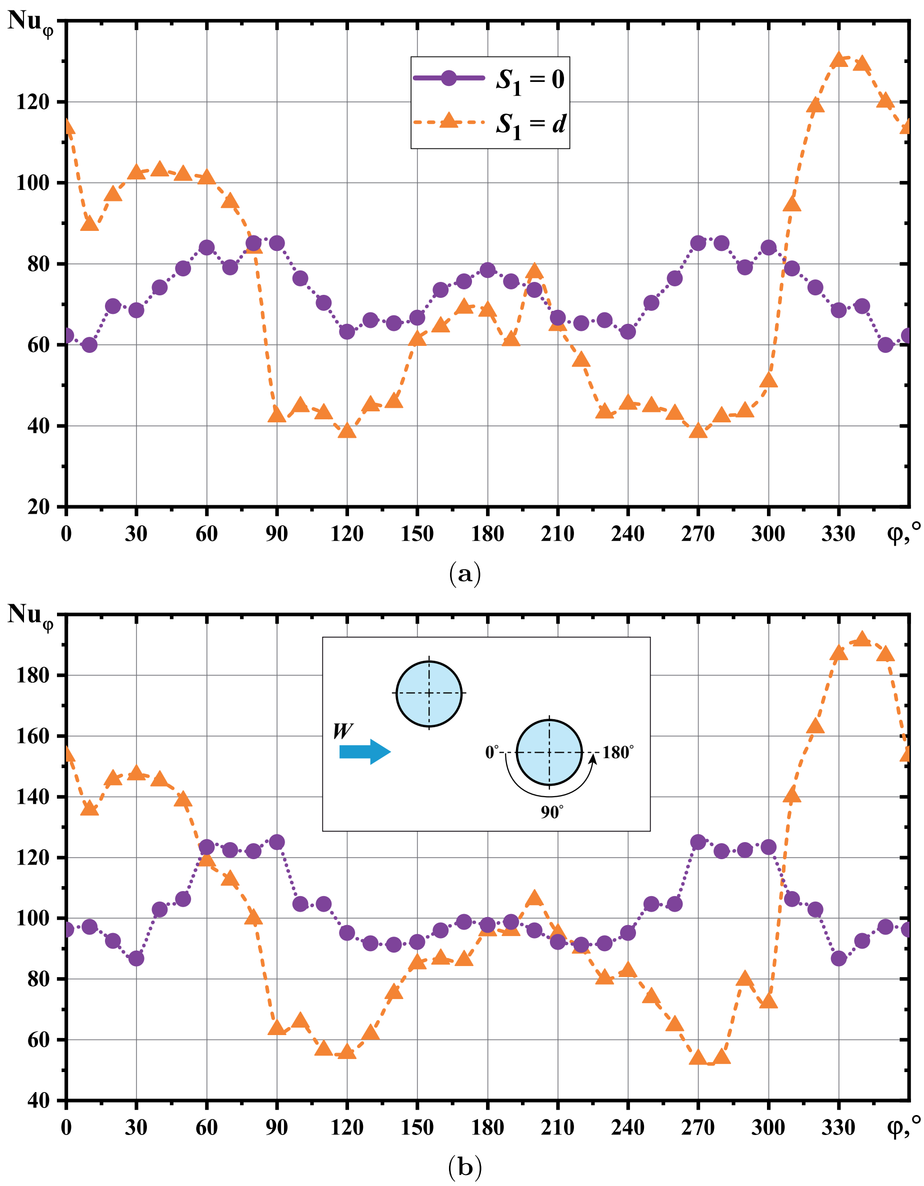



Fig. 9. Local Nusselt number over the second cylinder: a — Re = 9600 and b — Re = 20200

the repeated attachment of the boundary layer, which is typical of this flow pattern. The flow enveloping the first cylinder "hits" in the second approximately in this zone. There is also no obvious local minimum on the curves. The deviation from the surface-averaged HTC does not exceed 20% for the considered pitch $S_2$ and for the investigated Re.

The local Nusselt number on the second cylinder' surface for the staggered arrangement depends on whether the inner half-surface ($\varphi = 180\ldots360°$ on Fig. 8) or the outer half-surface ($\varphi = 0\ldots180°$) is considered. We can only say a certain similarity for the angles $\varphi = 100\ldots150°$ and $260\ldots210°$, respectively. For the outer half-surface, the distribution resembles the curves characteristic of heat transfer during the flow around a single cylinder [15], except for a slight decrease in the HTC at an angle $\varphi$ of 10°. Further, the heat transfer capacity decreases by almost

3 times relative to the frontal point. It is only in the part of backward part ($130 < \varphi < 180°$) that it increases to the intensity obtained for the in-line arrangement.

For the inner half-surface of the second cylinder, one can observe an increase (up to 15. . .20%) of the local HTC near the frontal current, which is clearly caused by the flow acceleration shown in the Fig. 5. Nextly, the local Nusselt number sharply decreases up to the separation point (at an angle $\varphi$ of about 300°), after which the behavior of $Nu_\varphi$ is similar to that for the outer half-surface. It should only be noted that the local maximum in this part does not lie at the backward stagnation point (as for a single cylinder or in-line arrangement), but is somewhat shifted upstream. In general, for a staggered arrangement, the curves both along the inner and outer half-surfaces are similar to the curves for a single cylinder. They move the maximum and minimum points. For the inner half-surface the curve seems to be compressed, and for the outer half-surface it is stretched.

With all the dissimilarity of the curves, the surface-averaged Nusselt numbers for the second cylinder turned out to be close: for Re = 9600 $Nu_s$ is equal to 78.5 and $Nu_{i-l}$ is equal to 76.3 (staggered and in-line arrangement, respectively) and for Re = 20200 $Nu_s$ is equal to 112.0 and $Nu_{i-l}$ is equal to 108.2. Our results are close to those of other authors, for example [17]. In comparison with the heat transfer from a single cylinder [15] for both arrangements, it is higher by 20. . .25% for Re = 9600 and 8. . .12% for Re = 20200. The last fact can be explained by the lack of development of the thickness of the laminar boundary layer and, as a consequence, the drop in the local heat transfer coefficient by 80% relative to the maximum.

# Conclusion

The paper described an experimental results of hydrodynamics and heat transfer investigation during flow around two circular cylinders. The study is based on multi-method including gradient heatmetry and particle image velocimetry, which are described in detail in the relevant part of the paper. Flow and heat transfer parameters investigated for Reynolds numbers of 9600 and 20200. Two variants of the mutual arrangement of the cylinders are considered, namely one behind the other (in-line) and with a vertical offset (staggered). In this case, the horizontal distance between the cylinders (depth pitch) was equal to 2 diameters $d$ for both cases. The the central takeaway is that complicated nature of the flow is reflected in the flow pattern and heat transfer.

The following conclusions can be drawn from the study:

- During the flow around two cylinders, the flow and heat transfer are more dependent on the relative position than on the flow regime.
- The length of the re-circulation zone behind the second cylinder installed in-line is several times less (8 and 2 for Re = 9600 and Re = 20200, respectively) than for the offset installation.
- The size of the re-circulation zone behind the second cylinder for in-line arrangement is smaller both in the longitudinal and transverse directions.
- The distribution of the local Nusselt number over the surface of the second cylinder in a staggered arrangement is asymmetric and strongly nonmonotone.
- The surface-averaged heat transfer coefficients over the second cylinder depend on the transverse pitch and Reynolds number.
- The combination of gradient heatmetry and PIV makes it possible to study the flow and heat transfer in a single experiment and get comprehensive information about the convective heat transfer.

Subsequently, it is planned to develop the research, namely:

- To investigate flows and heat transfer in the same regimes for a differ pithes $S_1$ and $S_2$
- To measure fluctuation characteristics for a deeper analysis of the separated flow and its effect on heat transfer.
- To increase the number of investigated cylinders.
- To change the cross-section of streamlined cylinders.

# References

[1] D.Sumner, Two circular cylinders in cross-flow: A review, *Journal of Fluids and Structures*, **26**(2010), 6, 849–899.

[2] S.Dong, G.Karniadakis, A.Ekmekci, D.Rockwell, A combined direct numerical simulation-particle image velocimetry study of the turbulent near wake, *Journal of Fluid Mechanics*, **569**(2006), 185–207. doi:10.1017/S0022112006002606.

[3] M.M.Alam, M.Elhimer, L.Wang et al., Vortex shedding from tandem cylinders, *Exp Fluids*, **59**(2018), 60. DOI: 10.1007/s00348-018-2501-8.

[4] W.A.Khan, J.R.Culham, M.M.Yovanovich, Fluid Flow Around and Heat Transfer From an Infinite Circular Cylinder, *J. Heat Transfer*, **127**(2005), 7, 785–790. DOI: 10.1115/1.1924629

[5] S.G.Pouryoussefi, M.Mirzaei, S.M.Pouryoussefi, Force coefficients and Strouhal numbers of three circular cylinders subjected to a cross-flow, *Arch Appl Mech*, (2011)**81**, 1725–1741. DOI: 10.1007/s00419-011-0514-3

[6] T.Aasland, B.Pettersen, H.Andersson, F.Jiang, Revisiting the reattachment regime: A closer look at tandem cylinder flow at Re = 10000, *Journal of Fluid Mechanics*, **953**(2022), A18. DOI: 10.1017/jfm.2022.960

[7] M.Abdelhady, D.H.Wood, Studying the flow dynamics and heat transfer of stranded conductor cables using large eddy simulations, *Physics of Fluids*, **33**(2021), 1, 015120. DOI: 10.1063/5.0038925

[8] G.West, C.Apelt, The effects of tunnel blockage and aspect ratio on the mean flow past a circular cylinder with Reynolds numbers between $10^4$ and $10^5$ , *Journal of Fluid Mechanics*, **114**(1982), 361–377. DOI: 10.1017/S0022112082000202

[9] R.Y.Sakr, N.M.Berbish, A.A.Abd-Aziz, Influence of Free Stream Turbulence Intensity on Heat Transfer and Flow Around Four In-Line Elliptic Cylinders in Cross Flow *International Journal of Chemical Reactor Engineering*, **8**(2010), 1. DOI: 10.2202/1542-6580.2133

[10] D.Lakehal, Computation of turbulent shear flows over rough-walled circular cylinders, *Journal of Wind Engineering and Industrial Aerodynamics*, **80**(199), 1–2, 47–68. DOI: 10.1016/S0167-6105(98)00122-6.

[11] A.A.Gusakov, M.A.Grekov, V.V.Seroshtanov, Aerodynamics and heat transfer over the surface of a single circular fin, *St. Petersburg Polytechnical State University Journal. Physics and Mathematics*, **11**(2018) no. 2, 138–148. DOI: 10.18721/JPM.11214

[12] S.Z.Sapozhnikov, V.Y.Mityakov et al., Gradient Heatmetry Advances, *Energies*, **13**(2020), 6194. DOI: 10.3390/en13236194

[13] A.V.Pavlov, P.G.Bobylev, S.Z.Sapozhnikov, Gradient Heatmetry in Study of Heat Transfer during Pool Boiling of Subcooled Water and Liquid with the Addition of $Al_2O_3$ Microparticles, *Therm. Eng.*, **70**(2023), 194–202. DOI: 10.1134/S0040601523030060

[14] S.Z.Sapozhnikov, V.Y.Mityakov, A.V.Mityakov, A.Yu.Babich, E.R.Zainullina, An Investigation into Film Condensation of Saturated Steam on Tube Surfaces by a Gradient Heatmetry, *Therm. Eng.*, **68**(2021), 794–801. DOI: 10.1134/S004060152109007X

[15] V.Seroshtanov, A.Gusakov, Gradient Heatmetry and PIV Investigation of Heat Transfer and Flow near Circular Cylinders, *Inventions*, **7**(2022), 80. DOI: 10.3390/inventions7030080

[16] http://www.polis-instruments.ru

[17] W.A.Khan, J.R.Culham, M.M.Yovanovich, Convection heat transfer from tube banks in crossflow: Analytical approach, *International Journal of Heat and Mass Transfer*, **49**(2006), no. 25–26, 4831–4838. DOI: 10.1016/j.ijheatmasstransfer.2006.05.042.

# Параметры течения и теплообмена при обтекании тандема круговых цилиндров

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**Аннотация.** Представлено экспериментальное исследование вынужденной конвекции в тандеме круговых цилиндров, выполненное с помощью градиентной теплометрии и цифровой трассерной визуализации. Цель исследования — определить влияние геометрии на характеристики потока и распределение коэффициента теплопередачи по поверхности теплообмена. Эксперименты проводились при числах Рейнольдса Re = 9600 и Re = 20200 для определения сложной структуры потока, зависящей от межцентрового расстояния и ориентации обоих цилиндров по отношению к набегающему потоку. Рассмотрены различные поперечный и продольный шаги ($S_1$ и $S_2$, соответственно) между цилиндрами, показано их влияние на параметры течения и теплообмена. С помощью Particle Image Velocimetry (PIV) измерены поле скорости, а также продольные и поперечные компоненты скорости, а с помощью градиентной теплометрии и термометрии – параметры теплообмена. Получены распределения местного коэффициента теплоотдачи по поверхности теплообмена. На их основе рассчитано усредненное по поверхности число Нуссельта для исследуемых чисел Рейнольдса.

**Ключевые слова:** обтекание цилиндров, конвективный теплообмен, градиентная теплометрия, коэффициент теплоотдачи.