Study of the heat flux fluctuations intensity during flow around a circular cylinder

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Abstract. An experimental study performed in an air channel using gradient heatmetry is presented, for a configuration of three heated circular cylinders with different distance between them. Cylinders were installed one by one. The main objective is to analyze the heat flux fluctuations, employing gradient heat flux sensor. The behavior of the flow in the wake behind the first cylinder under various regimes, for the specified configuration, changes the fluctuations level at the surface of the second and third cylinders. By visualizing the flow using PIV, it was possible to see areas of stagnation, separation points and other features of flow around the model. The results showed that the fluctuations level for the second cylinder is an order of magnitude lower than for the first. We can say that the first cylinder stabilizes the flow. However, at the third cylinder, this level is comparable and even higher than on the first. Use of gradient heatmetry thus made it possible for the first time to estimate the fluctuating nature of the flow and heat transfer around cylinders.

1. Introduction

Circular cylinders are a typical configuration that appears in many applications in industry and engineering, being a common geometry in pipelines, heat exchangers, transmission lines and nuclear reactor etc. This problem in terms of time-averaged heat transfer has been investigated both in academia and industry, given their theoretical and practical significance. If we talk about nonstationarity, then the Von-Karman street inherent in the flow around cylindrical surfaces has been thoroughly studied by previous researchers. The mechanisms of tandem cylinders especially under different scales of vortices structures are still undergoing investigation. Flow patterns around cylinders (for the two-dimensional case) were systematically generalized by Sumner [1] and Zhou [2].

The vortex shedding phenomenon behind a circular cylinder develops over a wide range of Reynolds number \( \text{Re} = \frac{Wd}{v} \), where \( d \) – is cylinders dia, m; \( v \) – kinematic air viscosity, \( \text{m}^2/\text{s} \), starting from \( \text{Re} \sim 49 \), above which the symmetry behind the body becomes unstable. This phenomenon is due to a wake instability associated with a rather sudden inception and growth in amplitude of wake fluctuations, as one increases the Reynolds number [3]. Vortex shedding is a periodic phenomenon characterized by frequency \( f \). It is normalized with the free-stream velocity \( W \) and the cylinder dia \( d \). Thus obtaining the Strouhal number \( \text{St} = \frac{f}{d}W \), which is a function of the Reynolds number. The relationship between the Strouhal number and the Reynolds number for single circular cylinders has been reported by many authors in the literature [4].

Complex flow and heat transfer in the turbulent wake were studied by both experimental and numerical techniques. An experimental study of variation of momentum and heat transfer associated
with these vortices was carried out by Antonia et al. [5]. They concluded that, vortices transport the heat effectively than momentum in the far wake zone. Several researchers have investigated using numerical simulations, in order to understand this flow. The effect of vortex shedding frequency on forced convection heat transfer from bank of circular tubes, in heat exchangers, under cross flow was studied by Kumar and Jayavel [6].

Thus, we can say that the research topic is relevant, and the use of new research methods may open up new prospects.

2. Experimental model

Experimental model consists of three circular cylinders, which were installed one by one. The diameter of cylinders is 66 mm. Wall thickness of the cylinders is 0.1 mm. Cylinders could rotate around the axis at an angle $\varphi$. All cylinders were heated by saturated steam with temperature $T_s \approx 100 ^\circ C$. Heat transfer surface’ temperature was constant during all experiments. The distance $S$ between the cylinders could be changed. The model was installed into the subsonic wind tube of REC “Engineering Thermophysics”. The velocity range developed in the wind tunnel provided a range of $Re$ from 500 to 42000 ($Re = \frac{Wd}{\nu}$, where $d$ – is cylinders dia, $m$; $\nu$ – kinematic air viscosity, $m^2/s$). Heated hollow cylinder models and their installation is similar to that described in the work [7].

3. Experimental methods

Study of heat transfer during flow around a cylinders row, we used a gradient heatmetry. This method is based on the use of gradient heat flux sensors (GHFS). Operating of GHFS is based on the transverse Seebeck’s effect [8]. In this study we used GHFS a single-crystal bismuth, its size is 2×2×0.2 mm. The volt-watt sensitivity of the sensor was about 8 mV/W.

Another most important characteristic of any sensors is their response time. It was found by calibration: the “hot” surface of the GHFS was irradiated by calibrate monochromatic pulsed laser ray (wavelength 635 nm, peak power 50–120 mJ, pulses frequency 1–10 Hz). There is a contact between “cold” surface of the GHFS and the aluminium plate. The GHFS signal is recorded by the Tektronix oscilloscope. Results of the experiment are shown on Fig. 1. The peak value is late (concerning the front of a pulse) on 10 ns [8].

![Figure 1. GHFS based on bismuth response time calibration results.](image)

According to Fourier theory the “working” layer of semi-boundary media is about 0.2…0.6 μm, which is enough for realization of Seebeck’s effects. So, the GHFS signal is proportional to temperature gradient in “working” (heated) layer. That is why we have suggested response time order of $10^{-9}$ s. If we take into account that, according to the literature [4-6], the velocity fluctuations during flowing around a cylinder for our sizes and regimes does not exceed tens of Hz, then the use of the GHFS to estimate these fluctuations is legitimate.

It is also important to note that PIV was used to identify the most interesting points. Features of our PIV system by POLIS [9] are also described in [8].
4. Results
The instantaneous velocity fields which was obtained using PIV help us to divide the cylinder into zones where the cylinder flows more actively and areas where there is stagnation. For example, figure 2 shows the velocity fields near the second and third cylinders for the Reynolds number $Re = 9600$. The off-design area under the cylinders is marked in gray. Since the laser sheet shines from top to bottom this area is in the shadow. It can be seen, that velocity near the second cylinder in the aft section practically does not differ, while the separation on the third cylinder is clearly noticeable. A further vortex street can be observed far from the model.

![Instantaneous velocity fields near second and third cylinder](image)

**Figure 2.** Instantaneous velocity fields near second and the third cylinder at different times: for a – $\tau = 14$ s, for b – $\tau = 17$ s ($Re = 9600$, $S = d$).

Flow visualization near the cylinders made it possible to observe unsteady flow processes, which, in turn, should affect the heat transfer parameters. Figure 3 shows heat flux fluctuations intensity on the rotation angle $\phi$ for all cylinders.

Because investigated cylinder could rotate around the axis, and the GHFS mounted on its surface, thus, fixed the heat flux at each angle $\phi$. How the angle $\phi$ was determined is also added in figure 3 as a diagram. The GHFS’ signal was measured with a frequency of 100 Hz by DAC NI 9238.

The intensity value was determined by the formula

$$
\eta = \frac{q''^2}{\bar{q}'}
$$

where $\bar{q}'$ and $\sqrt{q''^2}$ (W/m²) are the time-average heat flux per unit area and the root mean square (RMS) of the heat flux fluctuations at a fixed cylinder rotation angle $\phi$, respectively.
Figure 3. Time-averaged heat flux (a, b) and heat flux fluctuations intensity (c, d) over : a, c -first cylinder; b, d - the second cylinder ($S = 2d$).

At each angle $\varphi$, the heat flux was measured for 10 s. In studies for a pair of cylinders, the distance $S$ between the cylinders varied from $0.5d$ to $4d$. The maximum intensity for the second cylinder is lower, by almost a third, and the dependence differs depending on the flow regime.

The distributions for the single and second cylinder differ in both level and shape. For a single cylinder, the fluctuation intensity increases in the range $\varphi = 70...180$ °.

The influence of the regime in the investigated range of Reynolds numbers for the first cylinder is expressed in the region behind the separation point of the boundary layer. With an increase in velocity the fluctuation level of pulsations decreases since the flow is turbulent. For the second cylinder the dependence of the fluctuation intensity on the angle $\varphi$ is less pronounced and does not exceed 15 % in the investigated range of regimes. Heat transfer near the second cylinder depends on which zone of the wake formed by the first cylinder is the second cylinder located. With an increase in the distance $S$ between the cylinders, the intensity $\varphi$ distribution becomes similar to the first cylinder.
Conclusions
In the future, it is planned to obtain the distributions of the power spectrum of the heat flux fluctuations at each corner for cylinders. Having obtained the dependence of the power spectrum on frequency for the heat flux, it will be possible to compare them with the energy spectrum of the velocity, which will make it possible to compare the flow and heat transfer when flowing around cylinders at the level of velocity and heat flux fluctuations.

References
[1] Sumner D 2010 Two circular cylinders in cross flow: a review Journal of Fluids and Structures 26 pp 849-899
[2] Zhou Y, Yiu M W 206 Flow structure, momentum and heat transport in a two-tandem–cylinder wake. J Fluid Mech 548 pp 17–48
[3] Williamson C H 1996 Vortex dynamics in the cylinder wake. Annu. Rev. Fluid Mech. 28 (1) pp 477–539
[4] Norberg C 2003 Fluctuating lift on a circular cylinder: review and new measurements. J. Fluids Struct. 17 pp 57–96
[5] Antonia R A, Zhou Y, Matsumura M 1993 Spectral characteristics of momentum and heat transfer in the turbulent wake of a circular cylinder, Exp. Therm. Fluid Sci. 6 pp 371–375
[6] Kumar R S, Jayavel S 2017 Influence of flow shedding frequency on convection heat transfer from bank of circular tubes in heat exchangers under cross flow Int. J. Heat Mass Transf. 105 pp 376–393
[7] Sapozhnikov S Z et al 2019 J. Phys.: Conf. Ser. 1421 012064 http://dx.doi.org/10.1088/1742-6596/1421/1/012064T1
[8] Sapozhnikov S Z, Mityakov V Yu, Mityakov A V 2020 Heatmetry The Science and Practice of Heat Flux Measurement (Springer International Publishing)
[9] http://polis-instruments.ru/