DOI: 10.18721/JPM.13106
УДК 532.526.4, 533.6.08

AN EXPERIMENTAL STUDY OF THE FLOW IN THE AREA OF INFLUENCE OF A CYLINDER IMMERSED IN THE FREE CONVECTIVE BOUNDARY LAYER ON A VERTICAL SURFACE

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New experimental data that quantitatively characterize fields of the mean velocity and temperature, the intensity of temperature and velocity pulsations, and also velocity-temperature correlations in the near zone of a circular cylinder placed on the vertical heated surface at the height corresponding to the fully turbulent flow regime have been presented. Systematic measurements in the middle vertical plane (the plane that contains the cylinder axis) were performed using constant temperature anemometer and resistance temperature detectors. The experimental data was compared with numerical simulation one obtained through solving the RANS equations. The overall data were in good agreement and indicated the cardinal restructuring of the flows both before the cylinder (where the horseshoe-shaped vortex formed) and behind the obstacle (in the near separated area and the recovery one of the natural convective near-wall layer).

Keywords: circular cylinder, free-convective heat exchange, hot wire anemometry, area of influence

Citation: Chumakov Yu.S., Levchenya A.M., Khrapunov E.F., An experimental study of the flow in the area of influence of a cylinder immersed in the free convective boundary layer on a vertical surface, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 13 (1) (2020) 62–72. DOI: 10.18721/JPM.13106

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ТЕЧЕНИЯ В ЗОНЕ ВЛИЯНИЯ ЦИЛИНДРА, ПОГРУЖЕННОГО В СВОБОДНОКОНВЕКТИВНЫЙ ПОГРАНИЧНЫЙ СЛОЙ НА ВЕРТИКАЛЬНОЙ ПОВЕРХНОСТИ

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Представлены новые экспериментальные данные, количественно характеризующие поля осредненной по времени скорости, осредненной температуры, интенсивности пульсаций скорости и температуры, а также корреляции пульсаций скорости и температуры в окрестности круглого цилиндра, установленного на вертикальной нагретой поверхности, на высоте, соответствующей развитому турбулентному режиму течения. Систематические измерения в средней вертикальной (проходящей через ось цилиндра) плоскости выполнены методами термоанемометрии и термометра сопротивления. Проведено сравнение измеренных профилей осредненной скорости и температуры с результатами численного моделирования на основе уравнений Рейнольдса. Достигнуто хорошее соответствие опытных и расчетных данных, которые в целом указывают на кардинальную перестройку течения как перед цилиндром в области формирования подковообразных вихревых структур, так и за препятствием, в ближней отрывной зоне и зоне восстановления свободноконвективного пристенного течения.

Ключевые слова: круглый цилиндр, свободноконвективный теплообмен, пограничный слой, термоанемометрия, зона влияния

Ссылка при цитировании: Чумаков Ю.С., Левченя А.М., Храпунов Е.Ф. Экспериментальное исследование течения в зоне влияния цилиндра, погруженного в свободноконвективный пограничный слой на вертикальной поверхности // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2020. Т. 1 № .13. С. 66–77. DOI: 10.18721/JPM.13106

Introduction

Characteristic features of heat transfer in case of turbulent natural convection developing on vertical heated surfaces are very important for different applications, such as cooling large surfaces of heat exchangers, construction of high-rise buildings and structures, fire safety, energy industry, safety of nuclear reactors, etc. Many studies consider the problem of a turbulent natural-convective boundary layer developing along a vertical heated plate as a simplified model of such flows.

Most experimental studies on the boundary layer with natural convection analyzed air flow at relatively small differences in absolute temperature (not exceeding 30% of the ambient temperature). The main parameters of the flow and heat transfer, such as profiles of mean temperature and mean velocity distributions, shear stress on the wall were measured by Warner and Arpaci [1], Cheesewright [2], Pirovano et al. [3], Smith [4], Tsuji and Nagano [5], Chumakov [6, 7]. The experiments measuring different turbulence characteristics were carried out by Smith [4], Cheesewright and Doan [8], Miyamoto et al. [9], Cheesewright and Ierokipiotis [10], Tsuji and Nagano [5, 11], Nikolskaya and Chumakov [12], Kuzmitskiy et al. [13]. The accumulated experimental results can be generalized, contributing to a deeper understanding of the basic properties of the flow and the specifics of the turbulent regime for this general case.

The natural-convective boundary layer formed on a heated vertical surface can be substantially disturbed by a single obstacle or a combination of several obstacles in many practical applications. Industrial structures or residential buildings (large-sized containers for storing spent nuclear fuel, buildings with solar panels, etc.) can act as such macro-roughnesses. In some cases, obstacles are deliberately introduced into the natural-convective boundary layer in order to control or control its behavior and thus intensify heat transfer. Refs. [14–16, 17] are examples of such studies. A system of vertical fins is typically installed on the heated surface to improve heat transfer in the natural convective regime. A recent focus has been on *V*-shaped fins capable of susbstantially enhancing heat transfer [18–20]. There is much interest towards problems of flow control and heat transfer enhancement in boundary layers evolving on extended vertical heated plates under turbulent natural convection. Some issues related to using fins of different heights for enhancing heat transfer were studied experimentally in [21, 22]. Ref. [23] compared the effectiveness of enhancers in the form of a long plate and a series of short plates located at the same distance from each other and mounted across the boundary layer flow. The experiments carried out confirmed that using a transverse row of short plates can help achieve greater disturbance of the flow in the wake of these obstacles, significantly enhancing heat transfer.

Flow structure and heat transfer in front of a semi-infinite cylinder piercing the turbulent natural convective boundary layer formed on a vertical heated surface were considered in [24, 25]. Particular attention was paid to using RANS-based three-dimensional simulations to study the effects from horseshoe-shaped vortex structures. Ref. [26] reported on an extended RANS-based study of for the case of a cylinder of finite height disturbing the boundary layer. The authors analyzed the influence of cylinder height and thermal conditions on the cylinder surface, transforming the flow structure and heat transfer in the front and rear parts of this cylinder.

In this study, we measured the mean and fluctuation characteristics of the velocity and temperature fields near a circular cylinder mounted on a vertical heated surface at a height corresponding to developed turbulent flow, analyzing the obtained data.

Experimental setup

Experimental studies were carried out with the testbed set up in the Laboratory of Hydroaerodynamics of the Institute of Applied Mathematics and Mechanics at Peter the Great St. Petersburg Polytechnic University in the 1990s [6, 7], modernized in the last three years (Fig. 1). Natural-convective airflow is generated by vertical aluminum plate *4* 90 cm wide and 495 cm high. 25 heaters (not shown in Fig. 1) are mounted on the back side of the plate; they are controlled by an electronic system capable of maintaining the thermal regime set for a long time.

Setting a specific heating mode for each of the 25 sections, we can simulate different laws for heating the surface along its height, in particular, giving a constant surface temperature. Because the plate is very high, all three regimes of airflow, i.e., laminar, transitional, and fully developed turbulent can be simulated up to the Grashof number of $4.5 \cdot 10^{11}$.

A coordinate device is used to move measuring sensor *13* in the evolving flow; it provides accuracy of about 0.5 mm for motion along the vertical coordinate X, and of about 0.001 mm along the coordinate Y normal to the surface (across the boundary layer); the sensor moves along the normal coordinate using stepper motor *14* by a preset algorithm. Flow parameters are measured fully automatically in one section of the boundary layer.

Notably, sensor *13* can move across the boundary layer with such high accuracy only in one direction, for example, away from the surface. The algorithm moving the sensor to the first point near the surface uses a reversible form of motion, greatly reducing the accuracy with which the coordinates of this point are determined. The accuracy with which the normal coordinate of the first measurement point was determined in this study was not worse than 0.1 mm. The sensor subsequently moves in one direction and the accuracy of movement corresponds to that given above (0.001 mm).

The same procedure is used for measuring velocity and temperature at a given point in space. It consists in the following. The analog signal corresponding to temperature (or velocity) is digitized using an analog-to-digital converter by the parameters set: sample number (N) and sampling rate (Hr). N = 2000, and Hr = 100 Hz in our study; thus, the signal processing time at a given point is 20 s. Next, the mean and root-mean-square (RMS) fluctuation of the given quantity are found.

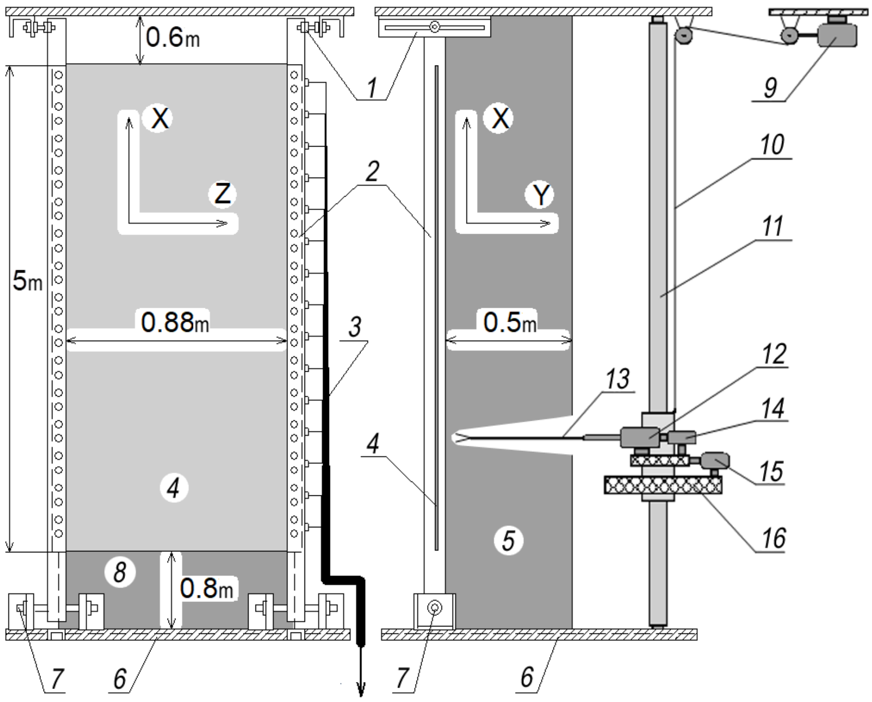


Fig. 1. Schematic of test bench with heated vertical plate and coordinate device:
upper mount *1*; vertical supports *2*; cables *3* of temperature sensors; heated plate *4*; side curtains *5*; foundation *6*; lower hinge mount *7*; rear curtain *8*; electric motors *9* and *15*; cable *10*; guide posts *11*; fixation system *12* for sensor holder; probe *13*; stepper motor *14*; movable carriage *16*

Measuring section and measurement procedure

We considered the region of interaction of a fully developed turbulent layer with a three-dimensional obstacle in the form of a poorly conducting (adiabatic) cylinder 40 mm in diameter, with the same height (Fig. 2, *a*). The cylinder was mounted at a height of 1800 mm, measured from the leading edge of the plate, which corresponds to a Grashof number (determined by the standard technique) of approximately $2 \cdot 10^{10}$ with the plate heated to 60 °C and the ambient air temperature of about 26 °C. The layer flowing onto the cylinder is turbulent with the given Grashof number, and its thickness is approximately four times the height of the cylinder.

We used a thermal anemometer (TA) and a resistance thermometer for systematic combined measurements of mean velocity and temperature fields in the vertical midplane (passing through the cylinder axis), the intensity of velocity and temperature fluctuations and their correlation.

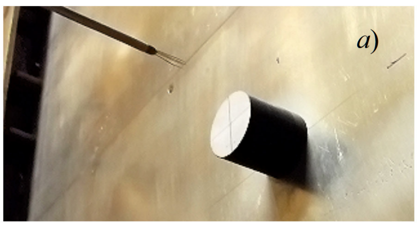
If velocity is measured by the TA in nonisothermal flow, the anemometer readings should be interpreted taking into account the effect of temperature. The given flow is characterized by low mean velocities and a high level of fluctuations, so the current velocities measured by the common method of thermal compensation by mean temperature can be largely inaccurate. The original method of thermal compensation, described in [27], was used for measurements in our study. According to this method, the TA reading corresponding to the current velocity at a given point in space is interpreted taking into account the current temperature at the same point. We used a special calibration setup [27] with uniform motion of the sensor along unevenly heated still air. The setup allows to calibrate the sensors at velocities from 1 to 50 cm/s with air temperatures ranging from 20 to 80 °C. Calibration results are represented as the voltages from the TA depending on flow velocity, and the coefficients in this dependence are functions of temperature.

Thus, to measure velocity in nonisothermal flow, the probe must consist of at least two sensors. One sensor (cold wire) is used to measure temperature, and the other (hot wire) is used to measure voltage, depending on the velocity and temperature of the flow. The measured temperatures are used to determine the calibration coefficients and calculate the velocity at a given point in the flow.

Fig. 2*, b* shows a photograph of a two-wire probe used in this study to measure the current values of temperature and velocity. Tungsten wires 5 μm in diameter and 3.5 mm long serve as sensitive elements. The probe is oriented so that the cold wire is upstream of the hot wire: this reduces the effects from the thermal “microflow” from the hot wire. Both wires are located horizontally parallel to the plate surface, so the probe can be brought very close to it. It should be borne in mind that the given location of the velocity sensor (hot wire) corresponds to the measured magnitude of the current velocity vector lying in the vertical midplane.

Measurement results and discussion

Flow parameters measured in several normal sections in front of the cylinder and behind it are shown in Figs. 3–5. Notably, the “temperature” and “velocity” wires of the sensor are spaced 2 mm apart; as noted above, the velocity wire is located above the temperature one. This explains the small shifts in the vertical coordinate X on the distributions of different measured quantities. The distributions here and below are marked by the distance dX from the corresponding measuring wire to the nearest (leading or trailing) edge of the cylinder. The distance to the plate along the normal to it is normalized to the height of the cylinder h= 40 mm.



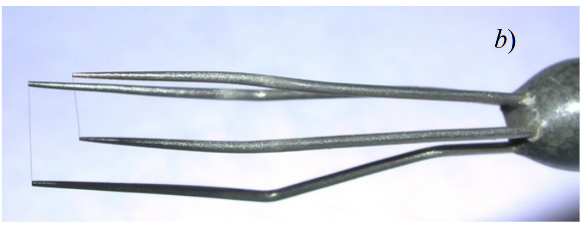


Fig. 2. Fragments of experimental setup: plate *a* with cylinder mounted on it (the measuring probe can be seen nearby); two-wire probe *b* for simultaneously measuring the current values of flow velocity and air temperature.

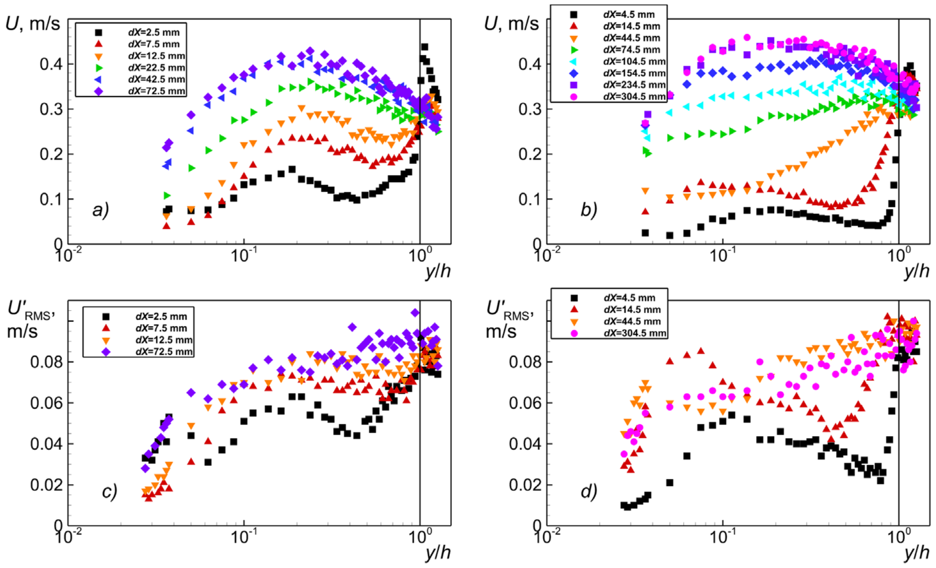


Fig. 3. Measured flow velocity field: mean velocity in front of the cylinder (*a*) and behind it (*b*); velocity fluctuations in front of the cylinder (*c*) and behind it (*d*);

dX are the distances from the corresponding measuring wire to the nearest edge of the cylinder; vertical lines indicate the position of the cylinder end

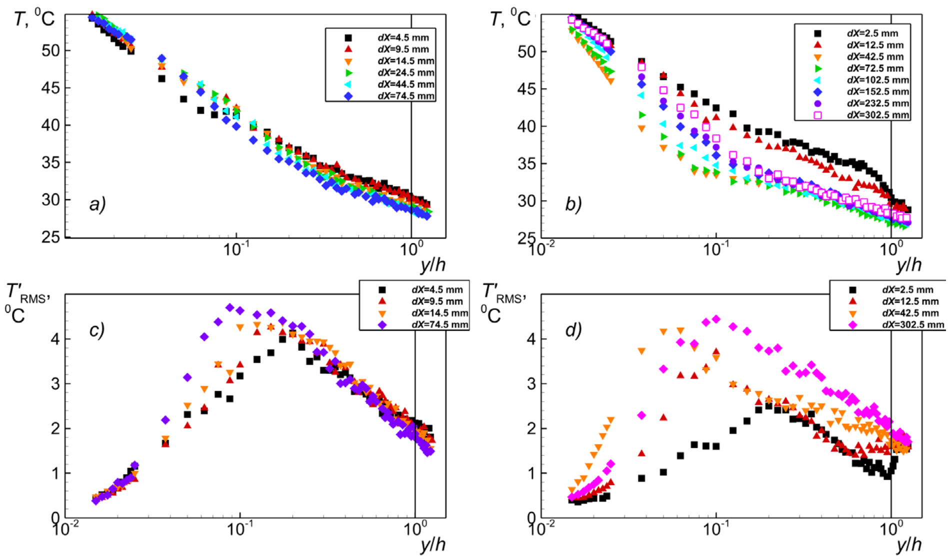


Fig. 4. Measured temperature fields: mean air temperature in front of the cylinder (*a*) and behind it (*b*); temperature fluctuations in front of the cylinder (*c*) and behind it (*d*);

dX are the distances from the corresponding measuring wire to the nearest edge of the cylinder; vertical lines indicate the position of the cylinder end

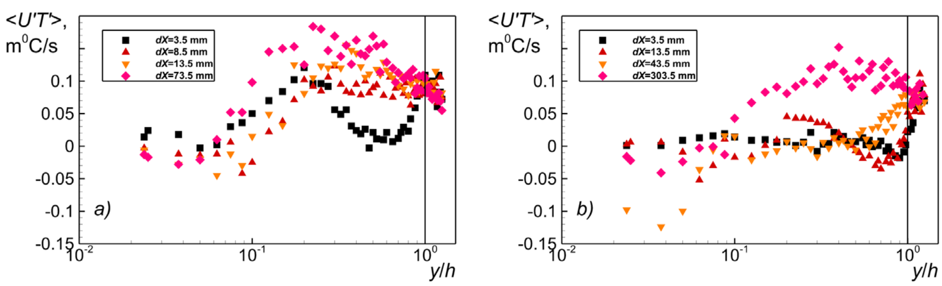


Fig. 5. Measured correlation distributions $\langle U'T' \rangle$ in front of the cylinder (*a*) and behind it (*b*);

dX are the distances from the corresponding measuring wire to the nearest edge of the cylinder; vertical lines indicate the position of the cylinder end

Fig. 3 shows the distributions of mean velocity and its fluctuations. The vertical line marks the position of the cylinder end in this and the following figures with experimental data. The statistically two-dimensional natural-convective boundary layer developed on the plate, with the maximum flow velocity of about 0.4 m/s, slows down as it approaches the leading edge of the cylinder (Fig. 3, *a*), while an increase in velocity magnitudes is observed in the region $y/h > 1$ in the three sections nearest to the leading edge, which corresponds to the zone where the flow through the end of the cylinder accelerates. The region of accelerated flow above the end persists in the first sections after the trailing edge in the near wake behind the cylinder (Fig. 3, *b*), and a substantial decrease in the velocity magnitude is observed near the surface, in the stagnation region of the cylinder, as well as in front of it, especially in recirculation zone. The natural-convective boundary layer is gradually restored downstream. Fig. 3, *c*, *d* shows individual measured distributions of RMS velocity fluctuations. Unfortunately, the TA method does not allow to reliably measure the velocities in the immediate vicinity of the highly conductive wall. In our case, the thickness of the “forbidden zone” is about 2 mm, which corresponds to 5% of the obstacle height.

Similar to Fig. 3, Fig. 4 shows the distributions of mean temperature and its fluctuations in the sections in front of the cylinder and behind it. The temperature distributions in most sections in front of the cylinder and far from it are very similar. The temperature distributions appear to be somewhat less monotonic near the leading edge of the obstacle, and a significant local decrease in temperature is observed at a distance of several mm in front of the edge (in the region less than 10% from the cylinder height). The results of numerical simulation given in [26] indicate that this decrease corresponds to the region where a horseshoe-shaped vortex structure forms, with relatively cold flow from the outer part of the boundary layer attaching to the surface of the plate under the action of a horseshoe-shaped vortex. Greater stratification between the distributions in different sections is observed in the wake of the cylinder (Fig. 4, *b*). The flow is well-mixed in the recirculation area close to the trailing edge of the obstacle, warmed by heat from the hot surface of the plate. The temperatures observed downstream, behind the point where the boundary layer that separated in front of the obstacle at a relatively small distance from the plate (for example, at a normal distance of about 10% of the cylinder height) reattaches, are significantly (10°) lower than those characteristic for an undisturbed

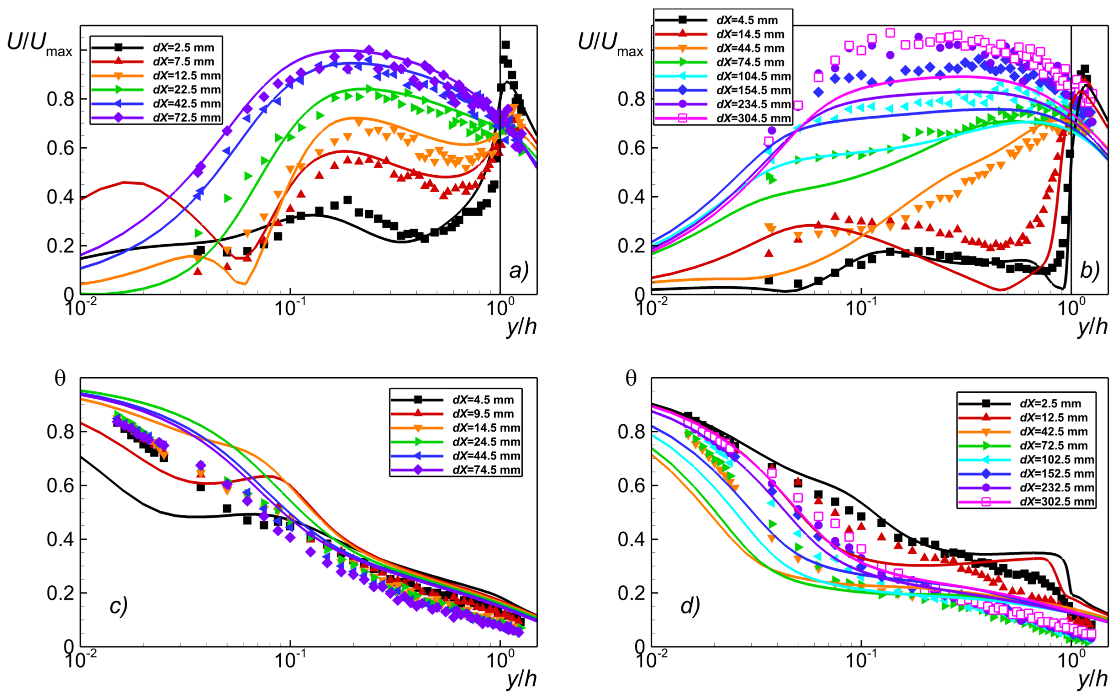


Fig. 6. Comparison of experimental data (symbols) with RANS-based numerical simulation (solid lines): the mean normalized flow velocity in front of the cylinder (*a*) and behind it (*b*) are shown, as well as the mean dimensionless air temperature in front of the cylinder (*c*) and behind it (*d*); *dX* are the distances from the corresponding measuring wire to the nearest cylinder edge

boundary layer at this distance from the plate. The temperature distribution is gradually restored further downstream, corresponding to the case of an undisturbed boundary layer.

The distributions of RMS temperature fluctuations shown in Fig. 4, *c* and *d*, as well as the distributions shown in Fig. 5 for the normalized correlated fluctuations of velocity and temperature make it possible to compare the positions of the fluctuation peaks in front of the cylinder and behind it, and also to estimate the general magnitude of these quantities.

Comparison of experimental results with numerical simulation data

It is of interest to compare the obtained experimental data with the recently published results on numerical simulation of the flow under similar conditions [26]. The numerical study in [26] reports on the structure of three-dimensional flow and heat transfer in the vicinity of a circular cylinder disturbing a turbulent natural-convective boundary layer. The computations were performed using the Reynolds averaged Navier–Stokes equations (RANS) according to Menter's SST turbulence model. The geometric configuration and the conditions adopted in the computations for one of the cases (cylinder sizes, thermal conditions on its surface, parameters of the incident boundary layer) are close to the conditions of the experiments described above. In fact, the computations described in [26] acted as auxiliary for the experiments in our study, making it possible to predict some characteristics of the real flow developing in the vicinity of the given cylinder. Fig. 6 compares the measured mean values with the data obtained by numerical simulation. The velocity U is normalized to its maximum value U_{max} 72.5 mm away from the cylinder, and the dimensionless temperature θ is determined by the standard formula for such problems

$$\theta = \frac{T - T_a}{T_w - T_a},$$

where T_w, T_a are the temperatures of the heated surface and external space, respectively.

Notably, the computed components of the mean velocity vector were recalculated to obtain the "effective" values of U obtained in measurements with a sensor with one "velocity" wire, which is not sensitive to the direction of the velocity vector but only responds to the current magnitude of the velocity transverse to the wire. Recalculation is based on simple relations using the computational data on the local direction of the averaged velocity vector at the measurement point. Analyzing the data in Fig. 6, we concluded that fairly satisfactory or excellent (for individual distributions) agreement was obtained between the experimental and compational data, generally pointing to major restructuring of the flow both in front of the cylinder, where horseshoe-shaped vortex structures are formed, and behind the cylinder, including the near separated region and the region where natural-convective near-wall flow is restored. Notably, however, there is a pronounced difference between the results of experiments and RANS computations for the latter region. It can be seen from Fig. 6, *b* that the natural-convective region is restored more slowly in the computational model.

Conclusion

We have obtained new experimental data for a fully developed turbulent natural-convective boundary layer interacting with a circular poorly conducting cylinder immersed in it, quantitatively characterizing the fields of time-averaged airflow velocity, mean air temperature, velocity and temperature fluctuation rates, as well as the correlation of velocity and temperature fluctuations.

The family of measured distributions of averaged velocity and temperature was used to compare the results obtained experimentally and by numerical simulation based on RANS approximation. We have obtained fairly satisfactory or excellent (for individual distributions) agreement between the experimental and computational data, generally pointing to major restructuring of the flow both in front of the cylinder, where horseshoe-shaped vortex structures are formed, and behind the obstacle, including the near separated region and the region where natural-convective flow is restored. At the same time, the results of RANS computations indicate that the natural-convective boundary layer is restored with a delay in the far wake of the cylinder, compared with the experimental data.

Measurements have been performed this far only for the vertical midplane passing through the axis of the cylinder; we plan to continue studies on the three-dimensional structure of the flow, analyzing other sections of the working area.

The study financially supported by a Russian Science Foundation grant (project 18-19-00082). RANS computations were carried out using the resources of the Supercomputer Center at Peter the Great St. Petersburg Polytechnic University (www.scc.spbstu.ru).

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Received 17.01.2020, accepted 31.01.2020.

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Статья поступила в редакцию 17.01.2020, принята к публикации 31.01.2020.

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