Effect of the horseshoe-shaped vortex on heat transfer in vicinity of the leading edge of a cylinder immersed in the turbulent free convection boundary layer on a vertical plate

Yu S Chumakov, E M Smirnov, A M Levchenya and D O Panov

Higher School of Applied Mathematics and Computational Physics,
Peter the Great St.Petersburg Polytechnic University,
Polytechnicheskaya str. 29, St.Petersburg, 195251 Russia
E-mail: levchenya_am@spbstu.ru

Abstract. Measurement data obtained with a thermo-resistance (wolfram-wire) probe for fluctuating temperature field in the front of a finite-height adiabatic circular cylinder disturbing the turbulent free convection boundary layer on a heated vertical flat plate are presented. The measurements were focused on detection of the effects attributed to action of the horseshoe-shaped vortex structures developing in the flow separation zone upstream of the obstacle. It is shown that near-wall air temperature gradients at some measurement positions are dramatically higher, if compared with profiles measured far away from the obstacle. It points in particular to highly intensified heat transfer in the flow region under study. The experimental mean temperature profiles are compared with results of previous RANS- and LES-based numerical studies performed by the authors under conditions that were close to those adopted in the experiments. It is shown that the LES-predicted temperature distributions are in a good accordance with the experimental results. The steady-state solution obtained with the RANS approach partially overpredicts the deformation of the temperature field attributed to action of the horseshoe-shaped vortices, which are substantially unsteady in the reality.

1. Introduction
Heat exchange processes peculiar to free convection boundary layers play the most important role for performance of a number of devices. The generic case for studying these phenomena is the free convection layer developing along a vertical heated flat plate. In a more general case, the plate can have a series of protuberances (or a single protuberance), which are structural elements of an industrial device or a residential building. As well, obstacles can be intentionally introduced for sake of turbulent heat transfer intensification (see, for instance, [1]).

Results of numerical simulation of interaction of a turbulent free convection boundary layer (FCBL) with a finite-height cylinder submerged in the layer are reported in [2, 3]. The steady-state solutions presented in [2] for air convection (Pr=0.7) were obtained on the base of the Reynolds-averaged Navier-Stokes (RANS) equations added by the $k$-$\omega$ SST turbulence model [4]. Time-dependent large eddy simulation (LES) was carried out in [3] applying the WALE formulation [5] for sub-grid modeling. It has been revealed in particular that a system of horseshoe-shaped vortices arise in the front of the cylinder due to dynamic interaction of the layer with the obstacle. These vortices deform the temperature field significantly and cause strong non-uniformities of the plate-surface heat flux distribution upstream of the cylinder.
The present paper covers results of measurements of time-averaged temperature profiles and temperature fluctuations in the front of the finite-height adiabatic cylinder disturbing the turbulent free convection boundary layer developing on a vertical isothermally heated plate. The measurements are focused on detection of the effects attributed to action of the major horseshoe-shaped vortex. A comparison of the experimental data with results of RANS and LES predictions [2, 3] is given as well.

2. Experimental facility and case description

The measurements were performed using a research rig created at the Saint-Petersburg Polytechnic University in the nineties [6] for investigation of transitional and turbulent FCBL. Here, free convection of air develops along a heated aluminum plate 4.95 m height and 0.88 m width (Figure 1a). The plate is heated by 25 independently-controlled heaters. In the last years, the rig was modernized to improve, in particular, the plate-surface temperature control.

Effects of the horseshoe-shaped vortex on heat transfer in vicinity of the leading edge of a cylinder disturbing the turbulent FCBL (Figure 1b) were investigated under determining conditions that were close to those adopted earlier for numerical simulation [2, 3]. An adiabatic cylinder, the diameter of which \( d = 40 \) mm, was mounted on the plate midline at a distance of \( x^* = x - x_{LE} = 1.8 \) m from the plate leading edge \((x=0)\) at the cylinder leading edge, as shown in Figure 1c. The plate temperature, \( T_w \), was 60±0.5°C, and the ambient temperature, \( T_a \), was 26±1°C. The local integral thickness \( \delta \) of the undisturbed boundary layer measured at \( x^* = 1.8 \) m was evaluated as \( \delta = 60±3 \) mm, and, correspondingly, the ratio of \( \delta \) to the cylinder height \( h = d \) at the obstacle position, \( \beta = \delta / h \), was estimated as 3/2 with an uncertainty of 5%. As in [2, 3], the thickness \( \delta \) was defined as integral of the normalized vertical velocity distribution, \( u / u_{max} \), over the coordinate \( y \) normal to the heated plate. Setting \( \delta = \delta^* \), the local Grashof number defined as \( \text{Gr}_\delta = g \beta \left( T_w - T_a \right) \delta^3 / \nu^2 \) was estimated as \( 0.9 \cdot 10^6 \) with an uncertainty of 15%.

A single-wire probe was used for measurements of time-averaged temperature profiles and temperature fluctuations. The wolfram wire, served as a thermo-resistance sensor, was 5 µm diameter and 3 mm length. Using a coordinates device, the probe could be shifted both normal to the plate (\( y \)-coordinate) and in the spanwise direction (\( z \)-coordinate). Uncertainties of positioning of the wire center were evaluated as 20 µm for the \( y \)-coordinate and 0.5 mm for the \( z \)-coordinate. The experimental results chosen for the present report cover temperature measurement data for \((y-z)\)-plane positioned at a distance of 2.5 mm from the cylinder leading edge. Measurement points along the span coordinate, A to F, are shown in Figure 1c.

![Figure 1. (a) Experimental setup, (b) flow overview, surface streamlines [2], (c) measurement positions.](image-url)
3. Results and discussion

Figure 2a shows measured distributions of time-averaged temperature along the normal coordinate referred to the cylinder height. One can see that the effect of the vortex structures arising in the obstacle leading edge region on the temperature field is well pronounced at the flow section chosen for presentation. The near-wall temperature gradients at the measurement point positioned at the middle plane \((z=0)\) and at two neighboring points \((z=10 \text{ mm}, z=15 \text{ mm})\) are dramatically higher than for the profiles measured at points E and F, where the disturbing action of the obstacle on the FCBL is much weaker. All this gives an experimental confirmation of the numerically revealed fact \([2, 3]\) of highly intensified heat transfer in the flow region under study.

Profiles of the root mean square (RMS) value of temperature fluctuations, \(T_{\text{RMS}}\), are given in Figure 2b. Notably that in the near-wall layer, at \(y/h<0.025\text{m}\), which corresponds to \(y<1\text{mm}\), the measured \(T_{\text{RMS}}\)-values are almost same for all the measurement points. However, at larger distances from the plate, the \(T_{\text{RMS}}\)-profiles disperse considerably. The lowest level of temperature pulsations is detected for point A, where the mean temperature taken at \(y>0.05h\) has also the lowest value and changes there very slowly with increasing the \(y\)-coordinate. A further discussion of the temperature field peculiarities detected experimentally for the flow region near the obstacle leading edge is given below, after presentation of some flow maps from numerical simulation.

![Figure 2. Measurement data: (a) time-averaged temperature profiles and (b) RMS value of temperature fluctuations (Celsius degrees).](image)

Figure 3 presents middle plane distributions of normalized vertical velocity and temperature, which were prepared using results of the RANS-based simulation \([2]\). The velocity values are referred to the buoyancy velocity \(u_0=[g\beta(T_w-T_a)\nu]^{1/3}\); as well, streamlines are superimposed on the velocity map. The normalized temperature is defined as \(\theta=(T-T_a)/(T_w-T_a)\). The streamlines pattern distinctly shows formation of the flow separation zone upstream of the cylinder and two vortices being the “heads” of the three-dimensional horseshoe-shaped vortices, the footprints of which are illustrated in Figure 1b. Notably that at \(-0.2<x/h<0\ , \ y/h<0.25\) cooler fluid particles go to the plate that results in a dramatic thinning of the near-wall thermal layer (see the right plot) and in heat transfer augmentation.

RANS-predicted normalized temperature distributions over other mutually perpendicular sections are shown in Figure 4. The left plot presents computations data for the section corresponding to the measurement one, for which \(x=-2.5 \text{ mm}, x/h=-0.0625\); positions of the measurement points are marked at this plot as well. One can see that the flow zone covering a very thin thermal layer with high temperature gradients extends approximately up to \(|z|/h=0.4 \ (|z|=16 \text{ mm})\). That is in accordance with the above consideration of the measured temperature profiles given in Figure 2a.

The right plot in Figure 4 shows the temperature distribution over a plane parallel to the plate. The plane stands at a distance of 2 mm from the plate, \(y/h=0.05\); its position is marked in Figure 3 (right) and in Figure 4 (left) by black lines. The temperature distribution given in the plot helps understand physical reasons of temperature profile deformations detected experimentally in the vicinity of the obstacle leading edge. As well, such plots provide valuable supporting information for choice of the most interesting/representative flow zones in further experimental studies of the FCBL disturbed by the obstacle.
Figure 3. Middle plane flow patterns from the RANS-based numerical simulation [2]: (left) streamlines and velocity distribution and (right) temperature distribution.

Figure 4. Computed normalized temperature distributions over two mutually perpendicular sections: (left) $x/h=-0.0625$, and (right) $y/h=0.05$.

In the reality, due to conditions of substantially unsteady flow in the approaching FCBL, the horseshoe-shaped vortex structures formed upstream of the disturbing cylinder perform high intensive oscillations, and even change their form in time. Being an updated illustration from our previous LES study [3], Figure 5 shows typical instantaneous “footprints” of the horseshoe-shaped vortex structures on the plate in combination with instant maps of the plate heat flux $h$ normalized with the time-averaged value, $h_0$, evaluated for case of no obstacle.

Figure 5. Typical instantaneous surface streamline patterns and distributions of the wall heat flux upstream of the cylinder (results of LES computations [3]).

One can expect that the instantaneous behavior of the large-scale vortex structures might contribute significantly to smoothing temperature gradients outside the near-wall layer. This expectation is confirmed by a comparison (see Figure 6) of the mean temperature profiles predicted with the RANS model and with the LES technique. In particular, the RANS-predicted profile for point D is considerably nonmonotonic, whereas the profile from LES has a monotonic form.
Figure 7 shows a comparison of predicted mean temperature profiles with the present measurement data. One can see that the LES-predicted temperature distributions are in a good accordance with the experimental results. The RANS model partially overpredicts the deformation of the temperature field attributed to action of the horseshoe-shaped vortices.

![Figure 6. Comparison of mean temperature profiles predicted on the base of (a) RANS approach and (b) LES technique.](image)

![Figure 7. Comparison of measured temperature profiles with (a) RANS and (b) LES predictions.](image)

4. Conclusions
The temperature measurements presented were focused on detection of the effects caused by horseshoe-shaped vortex structures developing upstream of the obstacle disturbing the turbulent free convection boundary layer. It has been established that near-wall temperature gradients at some measurement positions are dramatically higher, if compared with profiles measured far away from the obstacle. It can be considered as an experimental confirmation of the numerically revealed fact of highly intensified heat transfer in the flow region under study. The LES-predicted temperature distributions are in a good accordance with the experimental results. The steady-state solution obtained with the RANS approach partially overpredicts the deformation of the temperature field attributed to action of the horseshoe-shaped vortices, which are substantially unsteady in the reality.

Acknowledgments
The study is supported by the Russian Scientific Foundation under grants no. 18-19-00082.

References
[1] Tsuji T, Kajitani T and Nishino T 2007 *Int. J. of Heat and Fluid Flow* **28** pp 1472–83
[2] Smirnov E M, Levchenya A M, Zhukovskaya V D 2019 *Int. J. of Heat Mass Transfer* **144** pp 118573-84
[3] Levchenya A M, Kolesnik E V, Smirnov E M 2019 *J. Phys.: Conf. Ser.* **1400** pp 077031-6
[4] Menter F, Kuntz M, Langtry R 2003 *Heat and Mass Transfer 4* pp 625-632
[5] Nicoud F and Ducros F 1999 *Flow, Turbulence and Combustion* **62** (3) pp 183–200
[6] Chumakov Yu S 1999 *High temperature* **37** (5) pp 714–719