

## EXPERIMENTAL STUDY OF THERMAL EFFECTS IN COOLING A CIRCULAR CYLINDER IN LOCK-ON CONDITIONS

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### ABSTRACT

The paper presents a simple method for determining the phenomenon of unsteady thermal effects in cooling a circular cylinder. The research has been undertaken in order to explain the thermoaerodynamic processes, which are characterized by the turbulent structure of the flow around a stationary rigid heated cylinder cooled by the oscillating flow. The forced convection of heat occurs in the presence of not only random velocity fluctuation but also in the conditions of periodical forms of motion caused mainly by the process of vortex going down and externally formed oscillations of the inflow. The Nusselt number was evaluated at various frequencies of disturbances of the inlet velocity field, especially in lock-on conditions, on the surface of the circular cylinder versus angular location  $\Theta = 0-180^\circ$ . The subject of the study focuses on the analysis of current state of the problem and development of the method to measure and calculate basic values that characterize unsteady processes of thermal effects on the circular cylinder surface and indication of the directions of further work.

**Keywords:** thermal effects, circular cylinder.

### INTRODUCTION

The substantial degree of complexity of the phenomena that occur with non-isothermal turbulent flow represents the reason for the primary focus of researchers on isolated flow systems. The thermoaerodynamic processes have been mostly analysed with the example of the circular cylinder, square cylinder or the cuboid objects set on the ground [1, 2]. These are not only the most popular objects of the flow systems, but they also represent the physical model that is characterized by presence of three various flow categories: boundary layer formed in the attack zone, flow separation and wake. This leads to many opportunities for simultaneous observation of the process of convection-based heat transfer in flow conditions.

Development of the methods and research techniques, which contributed to extending the knowledge about dynamics of flow around bodies, has not been reflected in the examinations of non-isothermal flow. The first findings concerned mainly local and global coefficients of heat transfer and basic characteristics of thermal turbulence in the wake [3].

Another group of publications has focused on the effect of geometry of the cooled object and its location with respect to the incoming homogeneous stream on the convection heat transfer occurring around the object. An interesting element of the analysis contained in some of these studies [4] is the correlations between fluctuation of pressure with heat transfer parameters. In practice, most actual flow systems are characterized

by time-dependent conditions of inflow to the object. The most frequent parameter in the examinations concerning the effect of random field of inlet velocities on the thermal and flow processes occurring near the cooled object is the intensity of turbulence of the inlet stream [5, 6] and different flow medium [7]. The investigations presented in the above mentioned studies do not concern the situations where random variability of the flow near the cooled object is affected by the changes of pulsating character. A new tide of interest in the problems of forced heat convection is primarily focused on the circular cylinder in the case of periodical determined disturbance of the velocity field in its area resulting from the external effects on the flow system. Organized pulsation is generated by means of the body with flow around it and the vibrating motion of the body or through external formation of the inflow oscillation. Both methods of generating periodical flow around the body should be treated as equivalent. Intuitively, it should be believed that the vibrating cylinder should lead to the increased intensity of heat transfer from its surface. The study of Kezios and Prasanna [8] report nearly 20% increase in heat transfer intensity even for small amplitudes in conditions where frequency of these disturbances was similar to the natural frequency of generation of vortices. Karanth et al. [9] is one of the first publications concerning the numerical calculations of the flow around the cylinder with heat transfer in conditions of pulsating inflow with low RE number ( $Re=200$ ). The results, however, did not provide the evidence for a substantial increase in heat transfer intensity as it was presented in previous studies. For similar Re numbers in the range of 0-300 and similar amplitudes of disturbance, these computations were reproduced by Cheng and Hong [10] obtaining about 35% increase in heat transfer intensity for the resonance expressed by the Nusselt number (Nu). The results of numerical calculations were verified experimentally by Cheng et al. [11].

The authors of these studies documented the increase in heat transfer on the cylinder surface caused by lock-on synchronization but failed to identify the mechanisms behind this phenomenon. Extension of the range of frequencies of cylinder transverse vibrations led to identification of the lock-on effect in the cases when the vibration frequency equals or is even three times greater than natural frequency of vortices going down [12, 13]. The substantial intensification (40% and

60%, respectively in the above mentioned studies) of the heat transfer process observed for this phenomenon is correlated with shortening of the zone of vortex formation [14-17]. This led some authors [12, 13] to conclude that intensification of the process of heat outflow from the cylinder to the fluid is mainly caused by the large-scale vortex structures generated on the cylinder surface. This conclusion is not consistent with that presented later in the study by Gau et al. [18], whose results point to the different mechanism of reinforcing the heat transfer in the case of the transverse and longitudinal vibrations of the object with instability generated in the point of cylinder stagnation. With large degree of difficulty with numerical calculations of such flow, the group of studies in this field is insignificant, with most valuable papers presented above Karanth et al. [9] and Cheng et al. [10]. One of the most important is the study of Fu and Tonga [19] where authors successfully used the method connecting the description of the fluid particle motion according to Lagrange with the Euler description. Therefore, the authors obtained, the increase in heat exchange intensity determined by the increase of the Nusselt number, which is consistent with experiments [11, 12].

The above description of the current state of knowledge from the narrow range of heat transfer around the object under conditions of existence of a distinct periodical component in the flow points first and foremost to the controversial conclusions contained in the publications. According to the author of this study these discrepancies result from the limitations of the experimental measurement techniques and on the other hand limitations of applicability of the used numerical models despite its very dynamic development. Therefore, the need arises for continuous verification of current results and experimental examinations aimed at obtaining comprehensive and more reliable picture of the phenomena occurring with unsteady heat transfer on the object surface.

The complex structure of non-isothermal turbulent flows forces the researchers to use more and more sophisticated measurement techniques. Attempts to determine heat transfer coefficient under conditions of turbulent flow have been already made at the beginning of the 20th century but one of the early works is a paper published by Reichera and cited by Lowery and Vachona [20]. Due to large dimensions of the sensor, the limited measurement opportunities of the used apparatus allowed for obtaining not

only time-averaged but also spatial profiles of heat transfer process.

The performed review of designs of measurement systems used in the analysis of thermal phenomena during cooling the object with the turbulent oscillatory stream points to the limitations of the application. The major limitation in applicability of these methods for the measurement of unsteady heat streams is the lack of possibilities of using them in the hardly accessible areas in the case of objects with small dimensions and the necessity of frequent change in the location of the measurement point on the model.

The study proposed the method of measurement of local instantaneous and mean values that characterize heat transfer on the surface of any object while maintaining possibility of relocating the sensor. The method assumes the use of two identical DANTEC surface foil sensors used for determination of the profiles of the boundary layer. One on another, the measurement sensors were glued on the surface of non-heated circular cylinder, with the external sensor being assumed as a heat source. The idea of the used measurement system was to ensure the lack of outflow of heat from the “upper” (main) measurement sensor to the model due to the application of the additional (bottom) sensor with slightly lower temperature. This configuration allows for the assumption that the stream of heat energy dissipated from the main sensor is received through convection forced by flow, with its insignificant part (dependent and proportional to the level of the difference in temperature of both sensors) transferred to the object through conduction. The method presented in this study allowed for identification of the qualitative dependency of heat transfer intensity on the conditions of pulsating inflow, including the param-

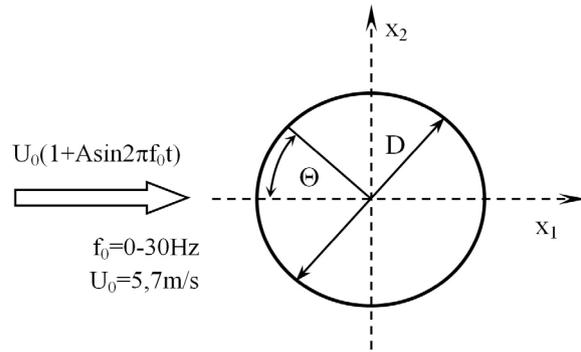


Fig. 1. Schematic sketch of the considered flow [1]

eters characteristic of the scope of the lock-on frequency resonance. The indisputable benefit of the proposed method is the opportunity to use it for the measurement of unsteady streams, measurements in the case of objects with insignificant dimensions and in the areas which are hardly accessible to other measurement techniques. However, the obtained results need to be verified using the system with heated cylinder. Controversial conclusions contained in the publications, not fully comprehensive picture of the problem, the limitations of the research techniques, necessity of verification of the previous study results and foremost the importance of the problems provided the motivation for this study.

### EXPERIMENTAL ARRANGEMENT AND CALCULATION METHODOLOGY

The study was performed in an open-circuit wind tunnel equipped with flow pulsation generator. The most important component of the system is the heated cylinder equipped with the measurement apparatus. Detailed analysis of the

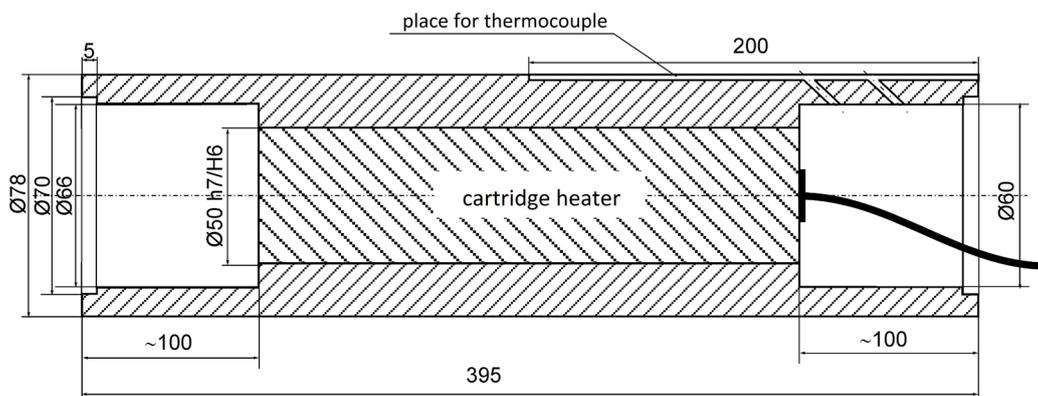


Fig. 2. Structure diagram of the cylinder with cartridge heater

process of unsteady heat transfer on the surface of the body with turbulent stream flowing around the body requires using the measurement system which should ensure broad frequency bandwidth that allows data acquisition in conditions of the turbulent heat transfer and opportunities for the measurement over the whole surface of the object. On the other hand, the heated cylinder should ensure the peripheral distribution of temperature on the object surface.

The review of the methods and systems of measurements of unsteady thermal phenomena [21-24] reveals that only the system with foil thermoanemometric probe meets the above requirements. Therefore, the designs that allow for application of the foil measurement sensor placed on the object surface were analysed. The solution was chosen from many designs and after careful analysis of the benefits and drawbacks of each design (Figure 1). The cylinder was made in the form of a dedicated pipe with diameter  $D=0.078\text{m}$  and with sliding-fit internal hole with diameter  $d=0.05\text{m}$  for the cartridge heater (Figure 2).

The heat flux dissipated by the foil sensor into the flow is calculated as stream supplied electricity to the effective surface of the sensor ( $A_{eff}$ ):

$$\dot{q}_{diss} = \dot{Q}_{diss}/A_{eff} \quad (1)$$

where:

$$\dot{Q}_{diss} = I^2 \cdot R_s \quad (2)$$

$$I = E_{out}/(R_{in} + R_{dec}) \quad (3)$$

This surface is larger than the geometric surface of the sensor due to the heat loss carried

by the polyamide film surface in the longitudinal direction [25].

The unit heat flow taken over by the flow medium depends on the value of the heat transfer coefficient on the surface of the object  $\alpha$  and the temperature difference between the sensor  $T_s$  and the environment:

$$\dot{q}_\alpha = \alpha \cdot \Delta T = \alpha \cdot (T_s - T_\infty) \quad (4)$$

Taking into account the temperature difference between the foil sensor and the cylinder surface (set at  $\Delta T = 0.5\text{C}$ ), the unit heat flow to the object (bypassing the conductivity of the thin adhesive layer) is:

$$\dot{q}_{cond} = \lambda_{kaption} (T_s - T_b/\delta) \quad (5)$$

Hence, the total heat input fed with the electricity is the sum of the stream received by the flowing liquid and returned to the substrate by conduction:

$$\dot{q}_{conv} = \dot{q}_{diss} + \dot{q}_{cond} \quad (6)$$

and the Nusselt number is determined by the relationship:

$$Nu = \dot{q}_{conv} \cdot D/\lambda_{air}(T_s - T_\infty) \quad (7)$$

However, this type of measuring system requires the introduction of a procedure for the correction of measurement data due to the presence of a sensor in the thermal boundary layer of the object and its sensitivity to the measurement of tangential velocity components [26]. Defining one-dimensional heat transport in the normal direction to the surface:

$$\dot{q}_{se} = -k \partial T/\partial y \quad (8)$$

By entering the coordinates of the wall, the temperature gradient may be approximated:

$$\dot{q}_{se} = k \left( T_{se} - \frac{T_{y^+}}{y^+} \right) = k \left( T_{surf} + T_{ov} - \frac{T_{y^+}}{y^+} \right) \quad (9)$$

where  $T_{se}$  is the temperature of the sensor,  $T_{y^+}$  is the temperature in the position  $y^+$ ,  $T_{surf}$  is the surface temperature of the object, and  $T_{overheat}$  is the temperature difference of the surface of the cylinder and the sensor. This equation can be extended to:

$$\dot{q}_{se} = k \left( T_{se} - \frac{T_{y^+}}{y^+} \right) = k \left( T_{ov} + T_{y^+,unh} - \frac{T_{y^+,unh}}{y^+} \right) \quad (10)$$

where  $T_{y^+,unh}$  is the temperature at the distance  $y^+$  from the surface of the unheated object (Fig. 3).

The first term of the right side of the equation presents the heat stream released by the sensor plunged in the boundary layer with temperature close to the sensor temperature, whereas the second term represents the stream of the dissipated heat during the measurement of shear stresses on the object surface. Therefore, evaluation of the heat stream moved by the flow through conduction requires reduction in the heat stream by the amount of contribution of the shear stresses in the process of its transfer. The

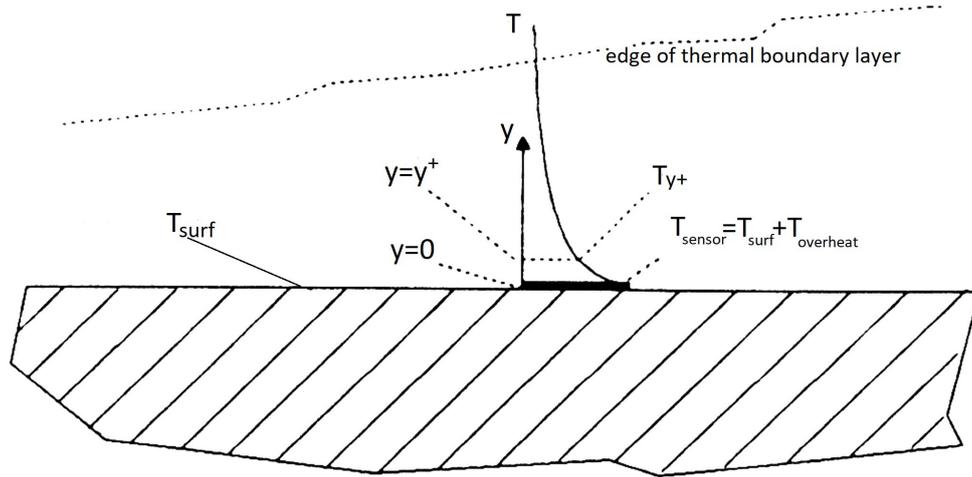


Fig. 3. Temperature profile in thermal boundary layer [26]

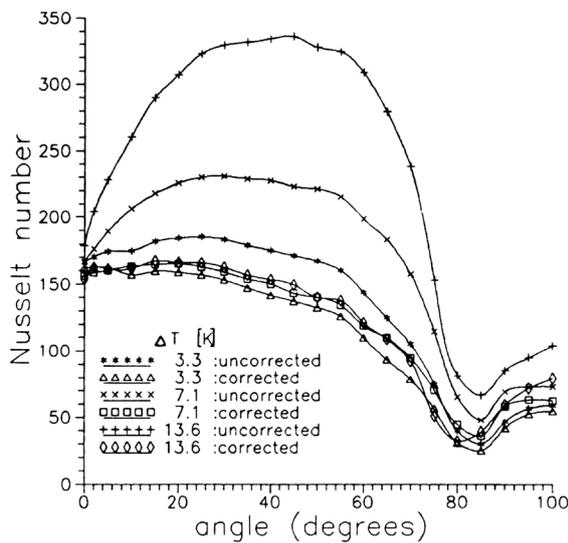


Fig. 4. Distribution of Nu numbers before and after correction versus angular position according to the geometry according to Scholten et al. [26]

presented procedure of correction of heat loss measurement can be used only in the range from the stagnation point to the point of boundary layer separation. The example profiles of non-corrected signal and profiles with correction procedure are presented in Figure 4.

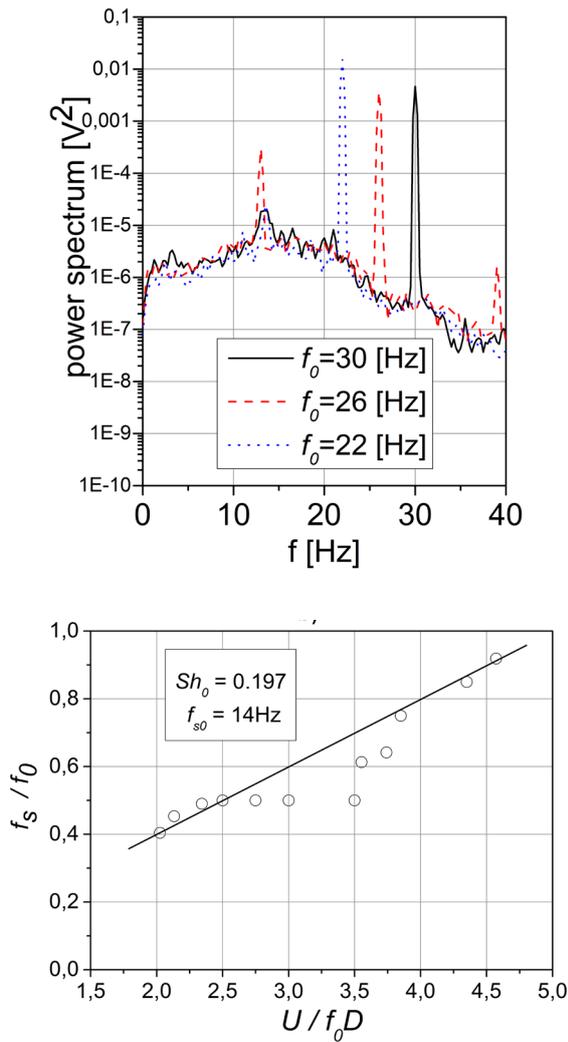
The design of the circular cylinder proposed in this study and the methodology of calculations is characterized by the undoubtedly high transmission frequency of the foil sensor, whereas the drawbacks include the necessity of using the procedure of correction and the lack of quick (easy) moving the measurement point to another place. The above inconveniences do not reduce the reliability of in-

stantaneous values of heat stream on the object surface. Furthermore, they will represent the basis for verification of the study results [24, 27].

The main source of measurement uncertainty lies in the identification of the effective heat transfer surface, which differs from the geometric surface of the sensor. The area of the surface should be determined on the basis of literature data. This value of the effective sensor surface, being between the range defined in the study of Beasley et al [25], should be used for various values of inlet disturbances of the velocity field. However, this value represents the main source of the systematic error, which should be at the level not greater than 15%, whereas reproducibility of the measured and computed Nu values ranges within  $\pm 2\%$ .

### CONDITIONS OF THE LOCK-ON

The identification of the inlet conditions which make it possible to study the vortex lock-on in flow around the circular cylinder has a great importance in this work. A result of the earlier studies (Jarza et al. [14, 15], Gnatowska [16, 17]) is that the limits of lock-on occurrence can be characterized by a group of mutually related features, which consists of the amplitude  $A$  and frequency  $f_0$  of external disturbances and the bluff body natural shedding frequency  $f_{s0}$ . The process of synchronization lock-on of periodical events in the flow around the cylinder in oscillating inflow can be detected on the basis of a relation describing the variation of vortex-shedding frequency versus reduced incident velocity for the considered range of  $f_0$ . In the cited experi-



**Fig. 5.** a) Sample power spectra of pressure fluctuations at cylinder wall for different values of  $f_0$ , b) Vortex shedding frequency versus reduced inflow velocity for the considered range of  $f_0$  [14]

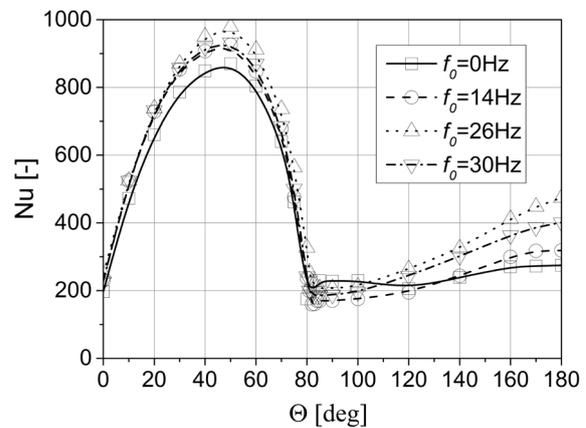
ment work [14], the vortex shedding frequency was determined from power spectra of surface pressure fluctuations recorded near the separation point at the cylinder wall. Sample results of spectral analysis are shown in Fig.5a. The inverse of the Strouhal number is plotted versus  $f_s/f_0$  in Fig. 5b. The slope of the line drawn here is a constant equal to 0.197 and it represents the Strouhal number  $Sh_0$  for the Karman vortex street in the case of steady inflow. The locking phenomenon occurs as a plateau near  $f_s/f_0 = 0.5$ . It means that over a range of reduced velocity  $U_0/f_0 D$  the vortex shedding frequency remains at half of the inlet oscillation frequency.

According to data from study of Jarza and Podolski [14] presented in Fig.5b, the ratio  $f_s/f_0$  is kept constant over a relatively wide range of inlet

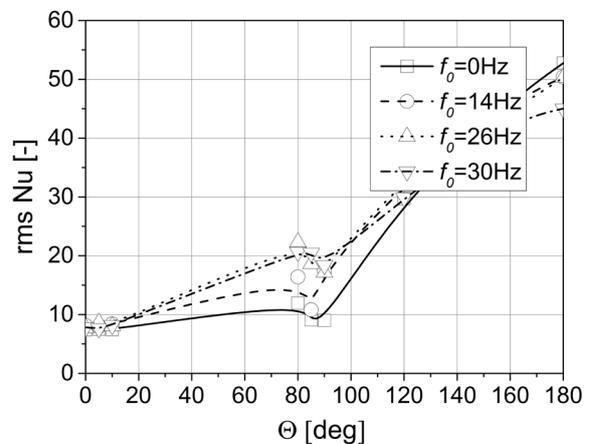
conditions. For the constant inflow velocity  $U_0 = 5.7$  m/s, lock-on occurrence is limited to the range of driving frequency  $f_0 = 22-28$  Hz. Out of this range, the vortex shedding frequency tends again to the steady inflow value  $f_{s0}$ .

## RESULTS

The basic value that characterizes the process of heat transfer on body surface with the turbulent stream of medium flowing around the body is local Nusselt number, which depends on a number of factors connected with flow conditions. This section presents averaged distributions of Nu for homogeneous flow and lock-on conditions and, moreover, the effective Nu values versus angular location in terms of  $\Theta = 0-180^\circ$  and different



**Fig. 6.** Distribution of the local Nusselt number in function of the angular position for the different oscillation frequencies of the inflow stream



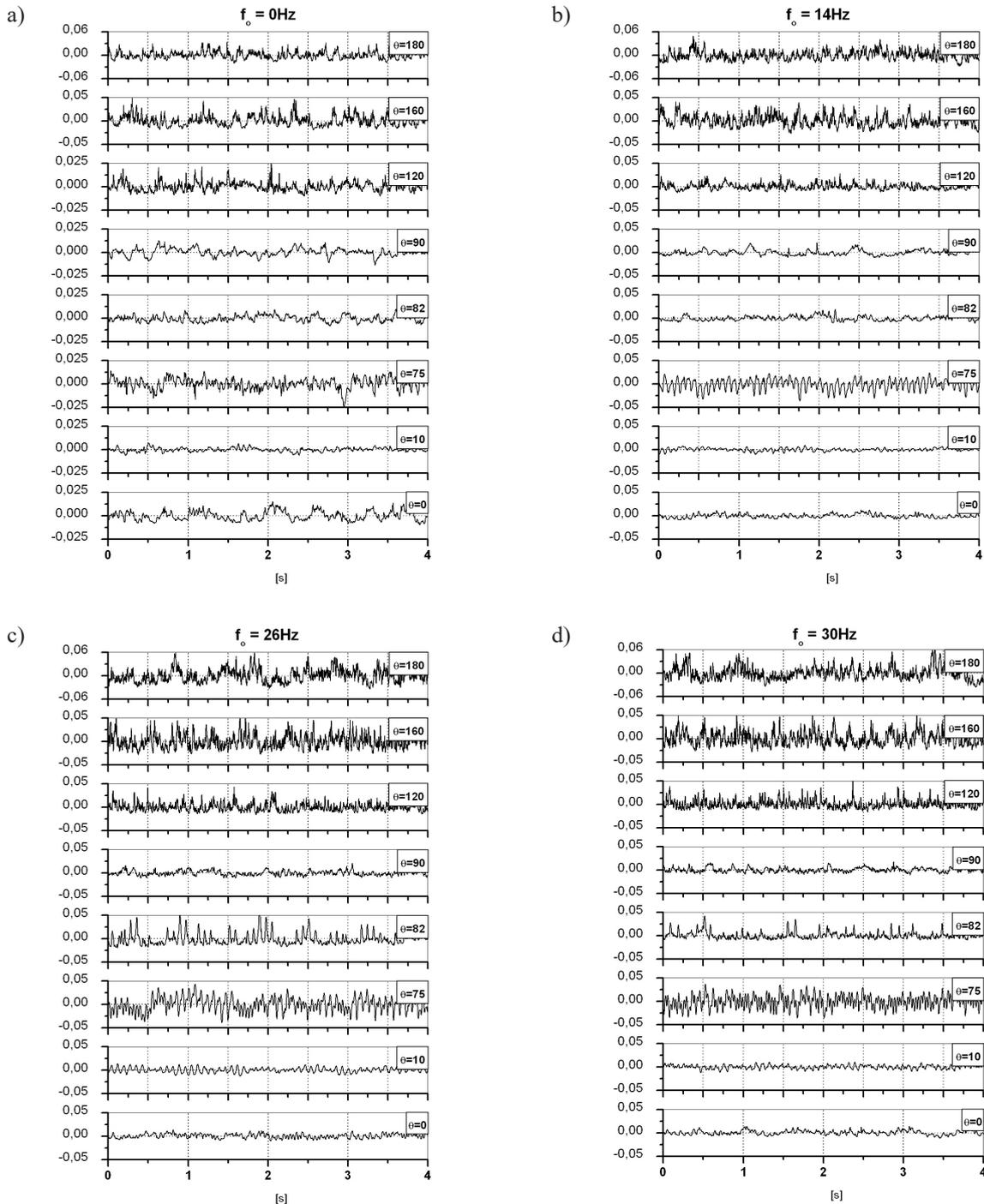
**Fig. 7.** The root-mean-square values of the Nusselt number distributions in function of the angular position for the different oscillation frequencies of the inflow stream

frequencies of disturbances of the inlet velocity field. Furthermore, the measurement results will be presented in the form of instantaneous heat streams for selected angular positions in conditions of frequency resonance and apart of them.

Figure 6 presents variability of the value of local Nu versus angular position for the set conditions of inflow disturbances. It can be observed

that the characteristic minimum of Nu occurs near the separation point. The introduction of inflow oscillation leads to an insignificant shift in the minimum Nu in the downstream direction, especially visible for the resonance frequency.

A gradual increase in heat transfer intensity is observed for further angular positions. The presented Nu distributions are affected by the mea-



**Fig. 8.** Variability of the voltage signals on the surface of the heated cylinder for different flow conditions: a) homogeneous  $f_0 = 0\text{Hz}$ , b)  $f_0 = 14\text{Hz}$ , and c) lock-on  $f_0 = 26\text{Hz}$  and d)  $f_0 = 30\text{Hz}$  for selected angular positions  $\Theta = 0 - 180^\circ$

surement error caused by the presence of foil sensor in the thermal boundary layer and require, in further research, the use of correction procedure for the obtained and presented data, e.g. based on the procedure [10].

Observation of the effect of inflow pulsation on object cooling intensity makes it easier to compare time-averaged values of Nu number

at characteristic points of the cylinder: the stagnation point and the base point. As expected, the resonance range of flow parameters leads to the increase in Nusselt number level, particularly in the point  $\Theta = 180^\circ$ .

The effect of inflow conditions is also visible in the profiles of root-mean-square value of Nusselt number (Figure 7). The low level of fluctuation

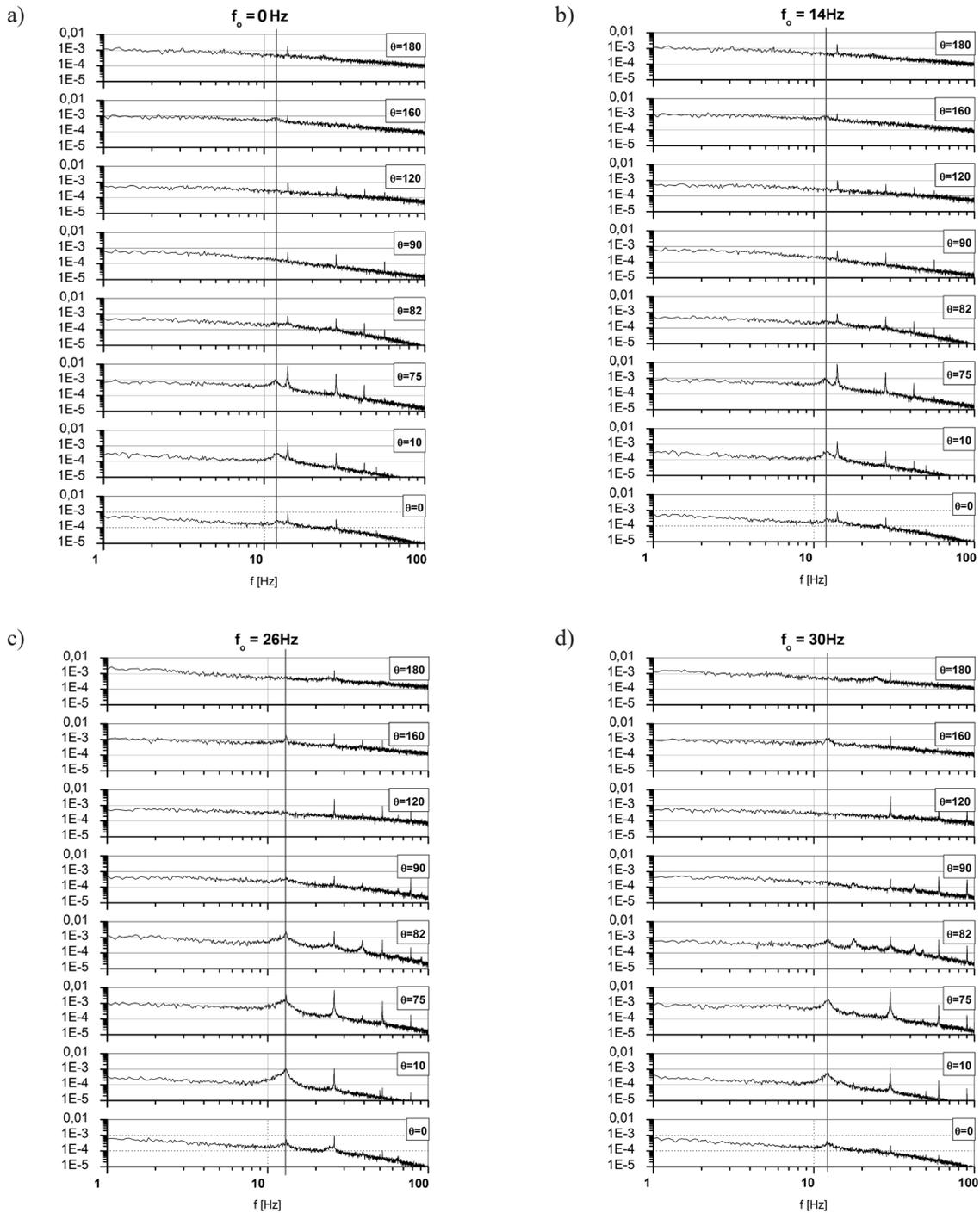


Fig. 9. The power spectra of voltage signal for different flow conditions: a) homogeneous  $f_0 = 0\text{Hz}$ , b)  $f_0 = 14\text{Hz}$ , c) lock-on  $f_0 = 26\text{Hz}$  and d)  $f_0 = 30\text{Hz}$ , for selected angular positions  $\Theta = 0 - 180^\circ$

at the stagnation point can be observed, regardless of the inflow conditions and their increasing contribution to further angular positions. The effect of the periodical disturbances is most visible in the region before the separation point, where the effect of lock-on synchronization on the value of effective Nu is the most marked. In the region after the separation point, the effect of oscillation is not that strong and clear. The level of Nu number fluctuation in the rear part is caused by intensive mixing processes and presence of the recirculation zone.

The temporal analysis of aerodynamic processes of the heat transfer from the cylinder surface was shown in Figure 8. It depicts not only random, but mainly periodic character caused by the formation of vortices generated alternately on both sides of the object. To limit the complexity of external influences, a monoharmonic flow in the longitudinal direction with negligible transverse component was generated. Figure 8a shows outlines of the voltage signal for uniform flow on the surface of the object for different angular positions. The zone-varied character of flow can be observed and it confirms the presence of the five zones of flow around the object identified in [14] for the uniform inflow on the object.

The periodicity inflow disturbances does not modify the zone-model of flow around the circular cylinder and the lock-on synchronisation deepens on this effect.

The subsequent figures 8b-d show the voltage signals for the variable force intensities. It can be seen that increased heat exchange coefficients can be recorded in the detachment zone (about 80°) which is accompanied by an increased level of intensity of the signal fluctuation, especially noticeable in the lock-on regime.

On the basis of spectral distributions of the voltage signals from a hot-film sensors one can observe the qualitative relation between the inflow pulsations level and fluctuations of the heat flux over the frequency range. The juxtapositions of spectral distributions in Fig. 9 reveal an increase of energy of heat flux fluctuations especially in frequency range corresponding the vortex shedding  $f_s$ , which means  $f=f_s/f_0=0.5$  for lock-on condition of heat transfer fluctuations is visible for all the range of spectral frequencies.

## CONCLUSION

The lock-on synchronization between the periodicity of vortex shedding and free stream oscillations is an important factor affecting the processes

of heat transfer on the body surface. The presented heated cylinder allows for the measurement of the local (mean and instantaneous) Nusselt number, which depends on a number of factors related to the inflow conditions such as Reynolds number, the level of turbulence or amplitude and pulsation frequency. The recorded measurement signals contain information about the temporal, spatial and frequency-based relationship between heat transfer intensity and variable parameters of inflow. The conclusions of the study are as follows:

- lock-on frequency synchronization between periodicity of vortex shedding and inflow oscillations plays an important role in the heat transfer processes (Nusselt number value);
- significant effect of inlet conditions (especially in the lock-on regime) on the level of object cooling intensity in the zone near the separation point (about 80°);
- dominant role of the large-scale structures of flow on the heat transfer process at the rear side of the object (level of the effective heat stream in the resonance is the lowest in the base point).

In summary, lock-on synchronization intensifies the heat convection from the cylinder surface, because for other analyses of inlet disturbance parameters (also for  $f_0 = 0$ ), the Nusselt number profiles, time waveforms and spectra do not reach a comparable level of  $f_0 = 26\text{Hz}$ .

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