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MISCELLANEOUS

CONVECTIVE HEAT TRANSFER IN AIR FLOW AROUND A CYLINDER AT LOW REYNOLDS NUMBERS

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UDC 536.2

The principal objective of the present work is to conduct investigations leading to a more complete explanation of heat-transfer processes on the external wall of a heated cylinder in laminar axial flow around it under high pressures. Investigations are aimed at determination of the limits of existence of mixed convection, explanation of the influence of free convection on the disturbances of heat transfer during laminar flow of a medium, and final explanation of intensification of heat-transfer processes occurring in a flow at high pressures.

Introduction. In the description of heat transfer under high-pressure conditions, relations are used that were developed for nearly normal pressures. On the other hand, the results of some works suggest that convective processes under conditions far from normobaric do not obey the relations generally acknowledged for the description of heat transfer [3, 4, 7, 8]. The phenomenon is clearly observed in the laminar flow regime. The analysis of the problem enables one to draw a conclusion that the reason for such discrepancies is the superposition of free and forced convection, i.e., the existence of mixed convection. Under high-pressure conditions the process is much more intense.

The present work is an experimental attempt to understand the issue of mixed convection under hyperbaric conditions. The principal objective of the work is to conduct investigations to obtain a more complete explanation of heat-transfer processes on the external wall of a heated cylinder under the conditions of a laminar flow around it. Investigations are aimed at determination of the limits of existence of mixed convection, explanation, among others, of the influence of free convection on the disturbances of heat transfer in a laminar flow of a medium, and a final explanation of the intensification of heat-transfer processes occurring during flow under high pressures.

1. Pressurized Research Rig. In investigations of heat-transfer processes under the conditions of mixed convection, a unique research rig was used that has been designed and manufactured at the Department of Heat Engineering of the Technical University of Szczecin in connection with the realization of numerous works regarding heat-transfer processes under high-pressure conditions [2, 3—5, 7, 8, 13]. A view of the rig is presented in Fig. 1.

The rig has been described in detail in [10]. Its main element is a pressure chamber with an internal diameter of 113 mm and a working length of 1500 mm, adequate for operation in the range of pressures from 0.1 to 16 MPa. According to the needs, the research chamber can be positioned either horizontally or vertically. An investigated element of a geometry specified by the research program is placed inside the chamber. Such an approach enables one to attain high Grashof numbers without the necessity of changing the kind of medium flowing through the heat exchanger, as well as to sustain small values of temperature differences inducing the free flow of the medium [1, 2, 5].

The hydraulic schematic of the rig is presented in Fig. 2. A research chamber 1 is connected with a set of pressure tanks 2. The first tank 2a separates water droplets from the compressed air. The next tank 2b contains dehydration substance 8, whose role is to remove moisture from the air supplied to the research chamber. A mesh filter 9 designed for elimination of solid contaminants from pumped air is installed in tank 2c.

The system of pressure tanks 2 is connected with a spherical storage air tank 3, which also serves as a balancing tank, where gas pulsations from the compressor operation are initially damped. The major source of compressed

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Fig. 1. A view of a rig for investigation of convective processes under high-pressure conditions (research chamber positioned horizontally): 1) research chamber; 2) pressure tanks; 3) storage tank.

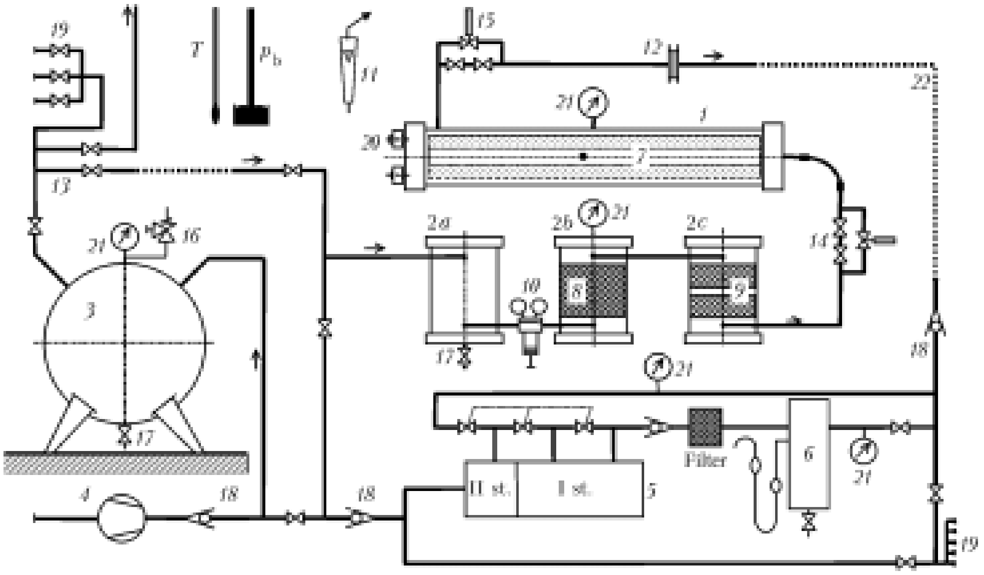

Fig. 2. A hydraulic schematic of a research rig for investigation of mixed convection: 1) pressure chamber; 2a) water separator; 2b) air dehumidifier; 2c) filter for impurities; 3) storage tank; 4) reciprocating compressor; 5) membrane compressor; 6) expansion set; 7) experimental heat exchanger; 8) dehumidifier; 9) filtering insert; 10) pressure reducer; 11) rotameter; 12) orifice; 13) cut-off valves; 14) inlet control valves; 15) outlet control valves; 16) safety valves; 17) dehumidification valves; 18) return valves; 19) gas cylinder collector; 20) electric socket; 21) manometers; 22) closed-loop switch.

air is a four-stage compressor set 4 with an efficiency rate of 50 m^3/h and maximum pumping pressure of 16 MPa. An additional source of air is a membrane compressor 5 with an efficiency rate of 20 m^3/h.

During measurements, the research rig operates in the open mode, when the used air has been released to the atmosphere. In the experiments conducted, the circulation of the medium (air) is as follows. Air pumped by the compressor 4 and/or 5 is directed to the spherical tank 3 and further through the set of cut-off valves to tank 2a. Then, after eventual separation of contained water, the air flows through a controllable reducer 10, where the initial regula-

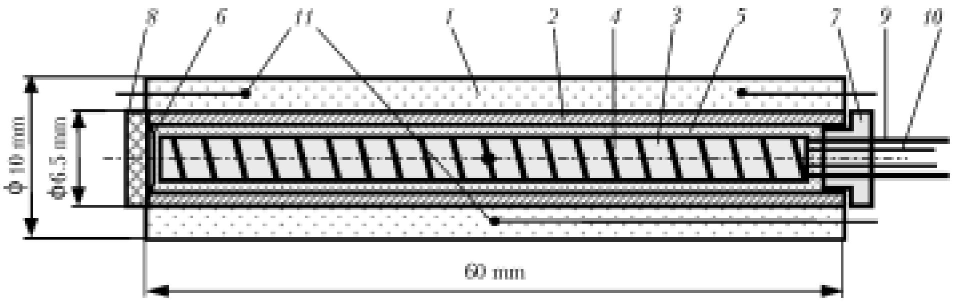

Fig. 3. Design of the investigated cylinder: 1) body of a cylinder (copper sleeve); 2) steel body; 3) ceramic core; 4) resistance wire; 5) insulation material; 6) steel bottom; 7) ceramic insulator; 8) insulation sleeve; 9) electric sockets; 10) inner thermocouple; 11) temperature sensors.

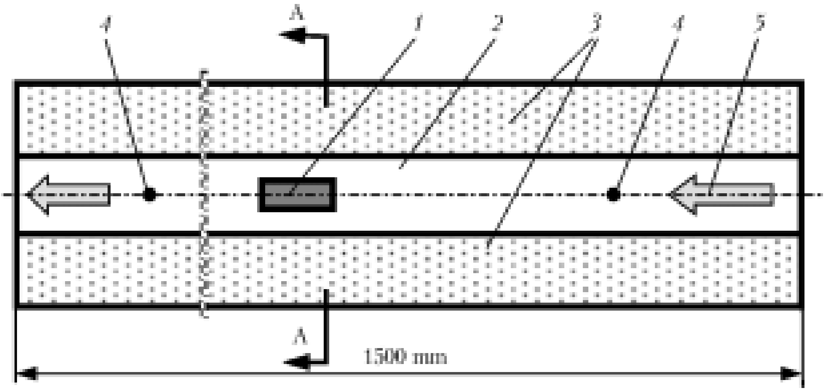

Fig. 4. Positioning of the cylinder in the measurement channel for axial air flow around it: 1) cylinder; 2) measurement channel; 3) parts of the channel; 4) measurement sensors; 5) direction of flow

tion of pressure to the required level takes place, then to 2b equipped with a dehydrator 8, and finally to tank 2c, where filtration from solid particles occurs.

Air is supplied through the set of control valves 14 to the pressurized research chamber 1, where it flows through an investigated element 7 and is heated up. The hot air leaves the chamber through the outlet pipeline fitted with a set of control valves 15 and flows out to the surrounding. In the outlet pipeline, flow-meters 11 and 12 that enable one to measure the amount of flowing-out air are installed.

A research chamber 1 is equipped with two electric multi-sockets 20 enabling connection of measurement sensors situated inside the chamber with the necessary equipment.

2. The Merit of Investigations — Heated Cylinder. Experimental investigations are related to convection heat transfer during a flow of air around the cylinder. An experimental cylinder with a circular cross section, equipped with an electric heater, is streamlined by an air flow such that heat is transferred to the flowing gas. In investigations, a specially designed cylinder was used (Fig. 3).

The body of cylinder 1 consists of a copper sleeve with an external diameter of 10 mm, an internal diameter of 6.5 mm, and a total length of 60 mm. The heating insert is located inside the sleeve. The insert is manufactured from chromium-nickel resistance wire 4 wound up the ceramic core 3 and centrally placed in the steel body 2. The space between the ceramic core and the wall is filled with pulverized insulation material 5 for stabilization of the heater position inside the body. The body of the heating insert is closed on one side by the steel bottom 6 with an additional insulation sleeve 8 and on the other side by the ceramic insulator 7 with electric sockets 9. Additionally, thermocouple 10 is located inside the heater for measurements of the inner temperature. In the selected external points of the cylinder body (the copper sleeve), sub-miniature sensors 11 for temperature measurement on the cylinder surface 1 are fixed.

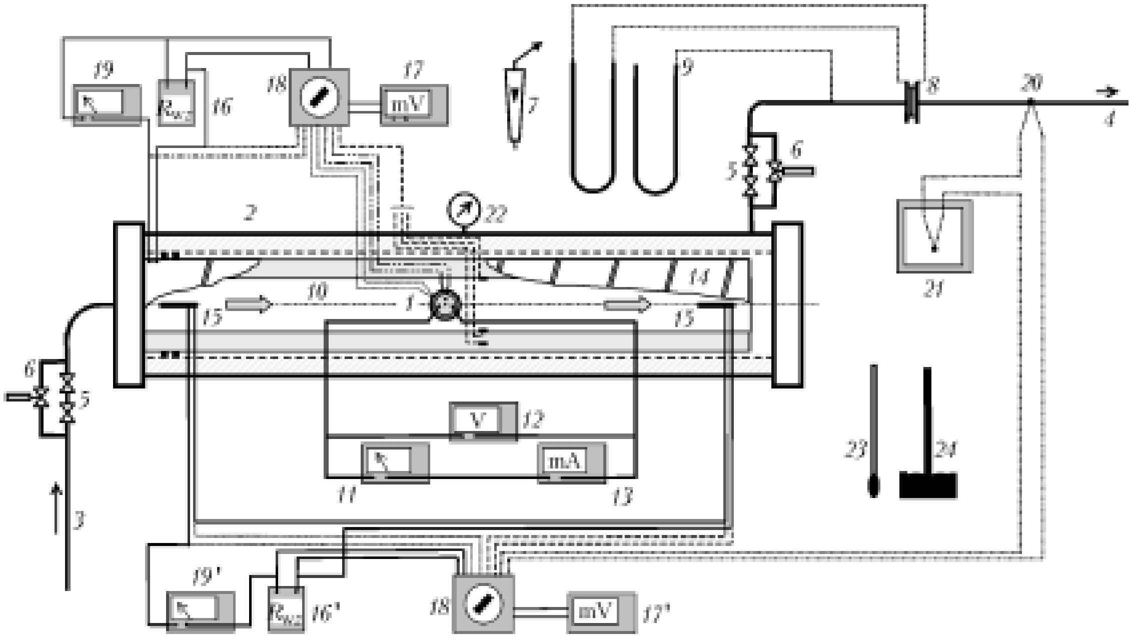

Fig. 5. A schematic of the measurement system in the research rig for investigation of mixed convection under high-pressure conditions: 1) heat exchanger; 2) pressurized research chamber; 3) inlet pipeline; 4) outlet pipeline; 5) control valves; 6) fine-tuning valves; 7) rotameter; 8) orifice; 9) U-tube liquid manometer; 10) heater of the heat exchanger; 11) laboratory feeder; 12) digital voltmeter; 13) laboratory multimeter; 14) Cu measurement resistor; 15) measurement sensor Pt-100; 16 and 16′) reference resistor; 17 and 17′) digital voltmeter; 18 and 18′) measurement switch; 19 and 19′) laboratory feeder; 20) copper-constantan thermocouple; 21) flask with ice; 22) precision manometer; 23) thermometer; 24) mercury barometer.

3. Cylinder Positioning — Investigation Channel. In the work, three different cases of air flow around the cylinder are analyzed, namely, axial horizontal and vertical flows (from the top and bottom). A schematic of the positioning of the cylinder in the measurement channel in the case of a horizontal air flow around the cylinder is presented in Fig. 4.

The measurement channel has the following dimensions: width 59.6 mm, height 25 mm, and length 1500 mm. The channel 2 was manufactured from an axially divided shaft-like wooden block with external dimensions corresponding to the internal dimensions of the pressurized research chamber. The cylinder is axial relative to the channel axis.

The channel is equipped with sensors for measuring temperature at the inlet to and outlet from the cylinder. For this purpose, sub-miniature Pt-100 measurement sensors are located in the initial and final parts of the channel. Additionally, to determine the radiative heat flux from the cylinder surface to the channel walls as well as conduction in the sockets and heater fixing, the channel walls were equipped with a set of adequately distributed thermocouples.

The channel, together with the installed investigated model of the cylinder and measurement sensors, is placed inside the pressure chamber.

4. A Measurement System in the Research Rig. A schematic of the measurement installation (Fig. 5) for investigations of convection in flow around the cylinder is presented in detail in [10].

The heat flux released by the heating element of cylinder 1 was determined on the basis of measurements of current 13 and voltage drop 12 through the heating spiral. The heater was fed from a stabilized laboratory feeder of direct current 11.

The amount of air flowing through channel 10 past the investigated cylinder 1 was measured by a set of calibrated (for air) rotameters 7, where their readings were converted to the real conditions in the pressurized chamber 2 containing the investigated element 1. According to one’s needs, in the experiments rotameters 7 can be used alterna-

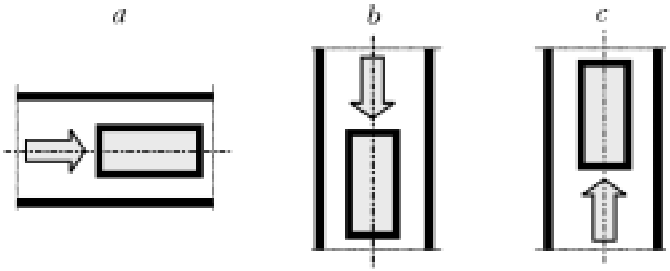

Fig. 6. Analyzed configurations of the axial air onflow around the cylinder: a) horizontal; b) vertical from the top; c) vertical from the bottom.

tively with an orifice 8. Both apparatuses were placed in a low-pressure part of the outlet pipeline 4, removing the expanded air from the pressure chamber 2. In this location, temperature of the outlet air was measured by a copper-constantan thermocouple 20. Regulation of an air flow through the heat exchanger was performed by valves 5 and 6 placed at the inlet and outlet of the exchanger.

For measurement of pressure in the research chamber, precision piezoelectric pressure transducers 22 with adequate measurement ranges were used. Static pressure of air in the outlet pipeline 4 and the pressure drop in the case of using an orifice 8 were measured by means of precision liquid manometers 9.

The mean surface temperature of the cylinder was determined on the basis of measurement of electromotive force of a set of copper-constantan thermocouples located just underneath the cylinder body 1. In a similar way, internal temperatures of the channel and the heater contacts were measured by means of copper-constantan thermocouples. Millivoltmeter 17 was used for measuring voltage in particular thermometric sensors. A selection between the measurement sensor and the measured temperature was made by means of a switch 18. Inlet and outlet air temperatures in the heat exchanger were determined by means of measurement of voltage drop $17'$ by the resistance sensors of the Pt-100 type 15 fed from a direct current source $16'$ and $19'$.

The values of temperatures, humidity, and atmospheric pressure necessary for data reduction were determined on the basis of indications of laboratory thermometers 23, capacity-based humidity meters, and precision mercury barometer 24.

5. The Analytical Method. The heat-transfer effect observed in forced flow of working medium (air) in the measurement channels at the steady heat flux can be described by the following general dimensionless equation [6, 9]:

$$\mathrm{Nu} = f(\mathrm{Re}, \mathrm{Pr}, \mathrm{Gr}, ...) \,. \tag{1}$$

On the basis of calculation of the main quantities like heat flux transmitted to the flowing medium in the experimental exchanger, air temperature at the inlet to and outlet from the measuring channel, and temperature of the exchanger wall surface as well as the insulation layer, etc., the quantities constituting the dimensionless equation were determined. For example, the Nusselt number was found according to the following dependence [11, 12]:

$$\mathrm{Nu} = \frac{\dot{Q}}{\pi L \Delta T \lambda} \,, \tag{2}$$

where $\dot{Q}$ is the heat flux transmitted to the flowing medium (air) in the experimental cylinder.

The values of Nusselt, Reynolds, Prandtl, and Grashof numbers for the tested cases were calculated based on the data obtained from the measurements.

6. Investigation Results. Experimental studies were conducted at pressures ranging from 0.1 to 10 MPa [11]. The obtained set of results describes convective heat transfer in different geometrical arrangements as well as in different flow regimes. In the present paper, the results are given for axial horizontal (Fig. 6a) and vertical (from the top (Fig. 6b) and the bottom (Fig. 6c)) air flows around the cylinder.

These results are presented in Fig. 7. They show the dependence of the Nusselt number on the Reynolds number for different values of pressure. Such a way of description in the form of the relation Nu = f(Re) is typical

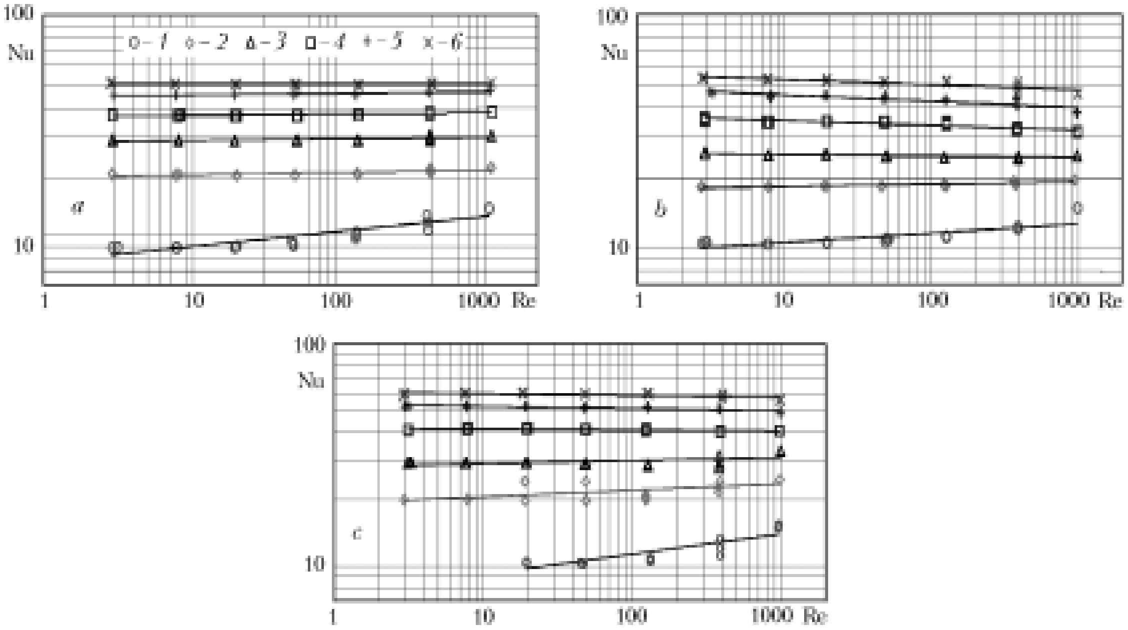

Fig. 7. Nusselt number as a function of Re for axial horizontal (a) and vertical (from the top (b) and the bottom (c)) flows around the cylinder: 1) p = 0.1; 2) 1; 3) 2.5; 4) 5; 5) 7.5; 6) 10 MPa.

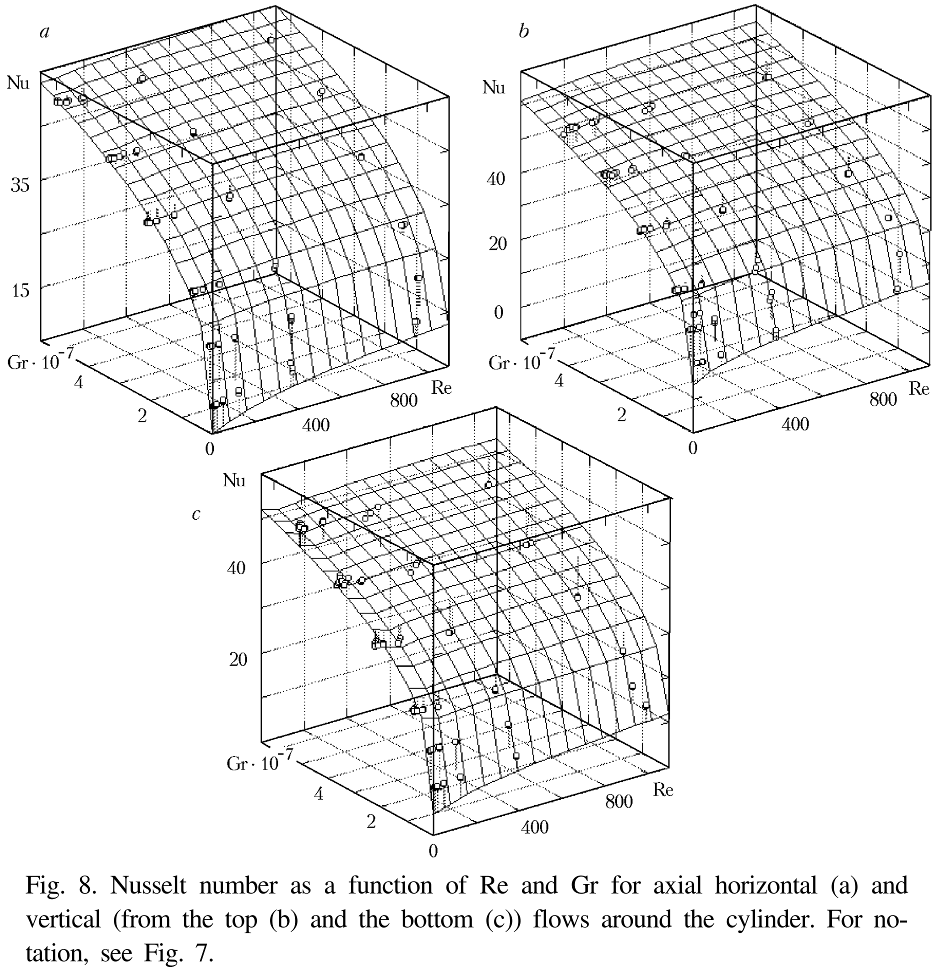

Fig. 8. Nusselt number as a function of Re and Gr for axial horizontal (a) and vertical (from the top (b) and the bottom (c)) flows around the cylinder. For notation, see Fig. 7.

TABLE 1. Dimensionless Equations Describing Heat Transfer for the Cases of Axial Air Flow Around the Cylinder

Axial flow	Dimensionless equations
Horizontal	$\mathrm{Nu} = 0.48\ \mathrm{Re}^{-0.68} + 1.98\ \mathrm{Re}^{0.15} + 0.5(5 \cdot 10^{-1}\ \mathrm{Re}^{4.85} + 4 \cdot 10^{-9}\ \mathrm{Gr}^{4.25})^{0.08}$
Vertical from the top	$\mathrm{Nu} = 0.87\ \mathrm{Re}^{-0.52} + 1.75\ \mathrm{Re}^{0.21} + 0.5(5 \cdot 10^{-1}\ \mathrm{Re}^{4.75} + 8 \cdot 10^{-9}\ \mathrm{Gr}^{4.24})^{0.08}$
Vertical from the bottom	$\mathrm{Nu} = 0.75\ \mathrm{Re}^{-0.68} + 1.57\ \mathrm{Re}^{0.18} + 0.5(5 \cdot 10^{-1}\ \mathrm{Re}^{4.65} + 8 \cdot 10^{-9}\ \mathrm{Gr}^{4.07})^{0.08}$

of forced convection, but being implemented for mixed convection it depicts the influence of pressure on heat-transfer processes.

The results obtained are also presented in the form of the three-dimensional distributions Nu = *f*(Re, Gr) (Fig. 8). Such a type of presentation is advantageous for the analyzed cases of convection due to the fact that it reveals the influence of particular modes of convection (both free and forced) on values of the Nusselt number.

A mathematical description of investigated phenomena of mixed convection was conducted using an equation in the form of a sum of exponential terms, first applied by Hausen in such a way [11]. This method of describing convection was also used by Budzyński [1, 11]. In this equation, each term describes a certain part of the considered phenomenon: the first term corresponds to forced convection at small values of the Reynolds number, whereas the second term corresponds to forced convection in the full regime and the third term corresponds to mixed convection. The specifics of the equation is that these terms taken separately cannot be applied to description of "pure" types of convection. The equations obtained in this analysis and describing particular modes of convection in axial flow around the investigated cylinder are given in Table 1.

The results of the solution of dimensionless equations are shown in Fig. 8 as surfaces representing the dependence between the Nusselt number and the Reynolds and Grashof numbers. From a comparative analysis we can conclude that these surfaces correlate well with the points corresponding to the values of the Nusselt number determined as a result of measurements. The obtained consistency is satisfactory, particularly in the range of high Grashof numbers, which corresponds to high experimental pressures.

Conclusions. An analysis of the results obtained enables us to draw a conclusion that in all cases considered an increase in pressure is accompanied by an increase in the Nusselt number, which results from superposition of free and forced convection. This process is described on the basis of the results obtained using the dimensionless numbers for particular variants of the flow around the cylinder.

It follows from the experiments that heat-transfer intensity depends on the direction of an air flow around the cylinder. The highest values of the Nusselt number were obtained for a vertical flow directed from the bottom, whereas the lowest values were obtained for a vertical flow from the top. This tendency is observed in the entire range of investigated pressures, and the discrepancy between the results increases with pressure, particularly for the vertical flow from the bottom.

The results presented cover only a narrow range of experiments conducted. For example, the present work does not describe the results of investigations on convection for different configurations of the transverse flow around the cylinder [12]. The results obtained also do not give an answer to all of the questions raised in the paper. For example, the borders between mixed convection and free and forced convection have not been set. With this in mind, both experimental and theoretical studies of mixed convection for different configurations of the air flow will be continued and the results will be successively published.

NOTATION

Gr, Grashof number; L, dimension of the cylinder, m; Nu, Nusselt number; p, pressure, MPa; Pr, Prandtl number; $\dot{Q}$, heat power, J/s; Re, Reynolds number; T, temperature, K; λ, thermal conductivity, W/(m·K).

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