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Heat transfer during transverse air flow around a cylinder

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Abstract

The principal objective of the present work is to conduct investigations leading to a fuller explanation of heat transfer process on the external wall of a heated cylinder under conditions of laminar flow at transverse of a flow around the cylinder under high pressures conditions. Investigations are aiming at determination of the limits of existence of mixed convection and explanation, amongst the others, of the influence of free convection on the disturbances of heat transport during laminar flow of a medium and finally explanation of the intensification of heat transfer process occurring during a flow under conditions of high pressures.

1. Introduction

A majority of convective heat transfer processes occur under moderate pressures (below 1MPa) and significant flow velocities (turbulent flow). However, there are branches of technology, where the velocities of the working medium are small and the flow is of laminar or transitional nature. There are also such cases, where the processes of heat transfer occur at very high pressures.

In the description of heat transfer at high pressures conditions are used the relations developed for pressures around normal pressure. On the other hand, the results of some works suggest that the convective processes under conditions distanced from normobaric conditions do not obey the relations generally acknowledged for the description of heat transport [3,4,6,8]. The phenomenon is best observed in the laminar flow regime. The analysis of the problem enables to draw a conclusion that the reason for such discrepancies is the superposition of free convection and forced convection, hence the existence of mixed convection. Under high pressures 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 present work is to conduct investigations leading to a fuller explanation of heat transfer process on the external wall of a heated cylinder under conditions of laminar flow around the cylinder. Investigations are aiming at determination of the limits of existence of mixed convection and explanation, amongst the others, of the influence of free convection on the disturbances of heat transport during laminar flow of a medium and finally explanation of the intensification of heat transfer process occurring during a flow under high pressures.

2. Pressurised research rig

In investigations of heat transfer processes under conditions of mixed convection utilised has been a unique research rig. The rig has been designed and manufactured at the Department of Heat Engineering of TU of Szczecin in connection with realisation of numerous works regarding the heat transfer processes under high pressure conditions [3,4,6,7,8]. View of a rig is presented in Fig. 1.

The main element of a rig is a pressure chamber with internal diameter of 113 mm and working length of 1500 mm, adequate for operation in the range of absolute pressures ranging from 0.1 MPa to 16 MPa. According to the needs, the research chamber can be positioned horizontally or vertically. Investigated element (for example the heat exchanger), of a specified geometry resulting from the research agenda, is placed inside the chamber. Such solution enables attainment of high Grashof numbers without the necessity of change of a kind of medium flowing through the heat exchanger, as well as enabling sustaining of small values of temperature differences inducing the free flow of medium [1,2,5].

Nomenclature

Gr	- Grashof Number	*Q*	- *heat, J*
L	- dimension of the cylinder, m	*Re*	- *Reynolds Number*
Nu	- Nusselt Number	*T*	- temperature of medium, K
Pr	- Prandtl Number	λ	- the thermal conductivity, W/mK

A detailed schematic of hydraulic installation of the rig has been presented in Fig. 2. A research chamber (1) is connected with a set of pressure tanks (2). The first tank (2a) has to separate water droplets from the compressed air. The next tank (2b) contains a dehydration substance in the form of an exchangeable insert (8), which objective is to remove moisture from the air supplied to the research chamber. In the last tank, (2c), installed is a mesh filter (9) for elimination of solid contaminants from pumped air.

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 air is a four-stage compressor set (4) with the 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 the efficiency rate of 20 m^3/h.

During measurements the research rig operated in the open mode, where the used air has been released to the atmosphere. Such solution is permissible due to the kind of a utilised working medium. The hydraulic installation (after small adaptations) enables operation in a closed-loop mode. Such solution can be interesting in the case of conducting experiments with other than air gases.

In conducted experiments the circulation of the medium (air) is as follows.

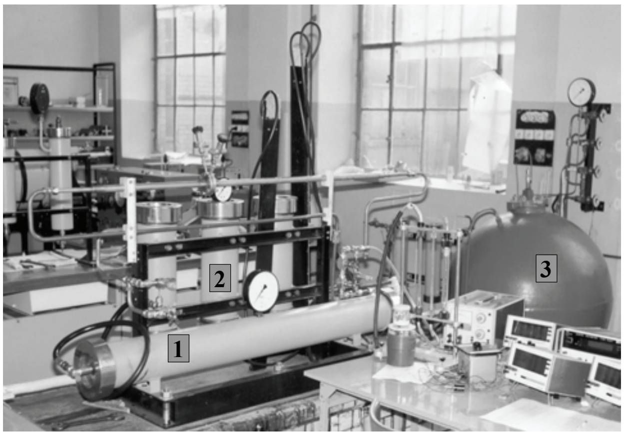

Fig. 1. A view of a rig for investigations of convective processes under high pressure conditions.
1-research chamber, 2-pressure tanks, 3-storage tank

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 (13) to the first tank (2a). Then, after eventual separation of contained water, the air flows through a controllable reductor (10), where initial regulation of pressure to the required level takes place, and then flows to the tank (2b) equipped with a dehydrator (8) and finally to the tank (2c), where filtration from solid particles takes place.

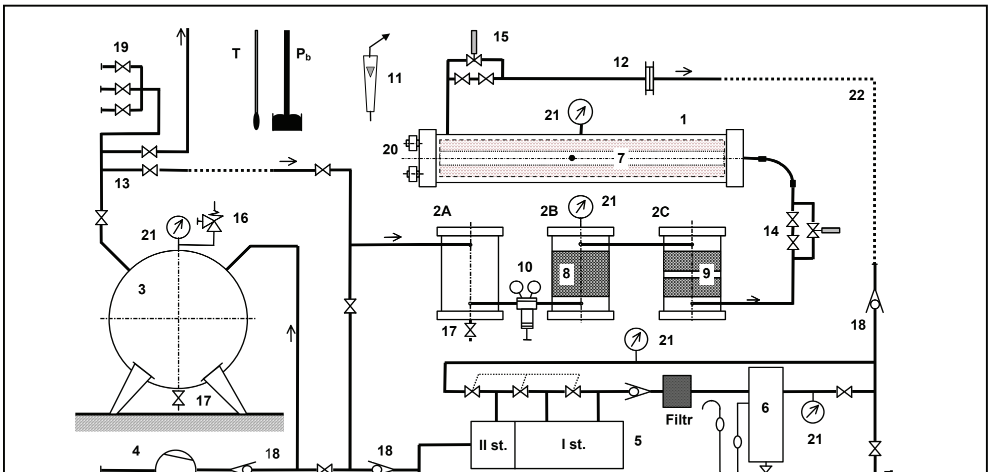

Fig. 2. A hydraulic schematic of a research rig for investigations of mixed convection (description in the text)

Air is supplied through the set of control valves (14) to the pressurised research chamber (1), where it flows through an investigated element (7) and heats up. Heated air leaves the chamber through the outlet pipeline equipped with a set of control valves (15) and flows out to surroundings. In the outlet pipeline installed are flowmeters, which enable measurement of the amount of flowing out air. There has been envisaged a possibility of measurement of the stream of air by means of a set of rotameters (11) or an orifice (12).

Pressure control in the research chamber and the control of a stream of flowing air takes place by means of the sets of valves (14, 15) installed at the inlet and outlet from the chamber. Manometers (21) serve for pressure control in the system.

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

3. The merit of investigations – heated cylinder

Experimental investigations regarded convection heat transfer during a flow of air around the cylinder. An experimental cylinder with circular cross-section, equipped with internal electric heater, is flown by a stream of air, during which the heat transfer to the flowing gas takes place. During investigations a specially designed cylinder has been used with external diameter of 10 mm and a total length of 60 mm. A construction of the cylinder is presented in Fig. 3.

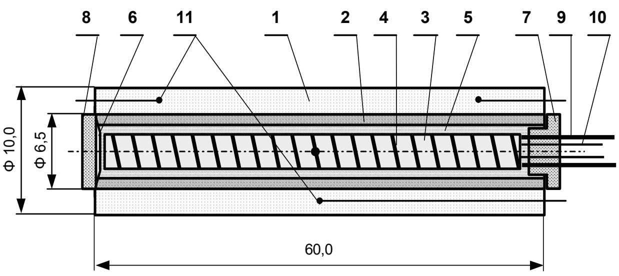

Fig. 3. Investigated cylinder – construction. (description in the text)

The body of a cylinder (1) consists of a copper sleeve, with external diameter of 10 mm, internal diameter of 6,5 mm and a total length of 60 mm. Inside the sleeve located is the heating insert, so called patron. The heating insert is manufactured from the chromium-nickel resistance wire (4), wounded up the ceramic core (3) and centrally placed inside the steel body (2). The space between the ceramic core and the wall are filled with the pulverised insulation material (5), in order to stabilise the heater position inside the body. The body of the heating insert is closed on one side with the steel bottom (6) with additional insulation sleeve (8), and on the other side with the ceramic insulator (7) with electric sockets (9). Additionally, inside the heater there is located a ferric-constantan thermocouple for measurements of the inner temperature. The connection sockets (10) are taken out through a ceramic culvert in the heater. In the selected external points of the cylinder body (the copper sleeve) fixed are sub-miniature measurement sensors for temperature determination on the cylinder surface. The copper-constantan thermocouples (11) have been used for that reason, where as a copper electrode is selected the sleeve of the body.

4. Cylinder positioning – investigation channel

In the work analysed have been three various cases of the flow of air around the cylinder, namely a transverse horizontal flow and transverse vertical flow (from the top and from the bottom). In all cases investigations have been conducted using the same model of the cylinder. The difference was only in the positioning of the cylinder and the direction of air flow. A schematic of the positioning of the cylinder in the measurement channel in the case of a horizontal flow of air around the cylinder is presented in Fig. 4.

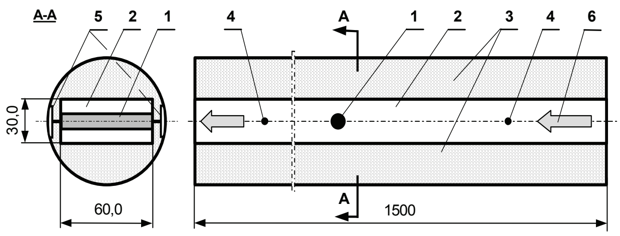

Fig. 4. Positioning of a cylinder in the measurement channel - transverse flow of air around the cylinder. (description in the text)

During conducted investigations the cylinder was placed inside the measurement channel with square cross-section in the half of it length and half of its height. The measurement channel has the following dimensions: width - 59,6 mm, height - 25 mm and length - 1500 mm. The channel has been manufactured from the axially divided wooden block, where the external form was of the form of the shaft with dimensions corresponding to the external dimensions of the pressurised research chamber. In both halves of the block milled are two parts of the channel, which after combination and fixing form a rectangular channel with given dimensions. The cylinder can be situated transversely with respect to the channel axis.

The channel is equipped with sensors for measurements of temperature at the inlet and outlet from the cylinder. For that reason sub-miniature measurement sensors Pt-100, are located at the initial and final part of the channel. Additionally, in order to determine the heat flux through radiation from the surface of a cylinder to the channel walls as well as conduction in the sockets and heater fixing, the channel walls have been equipped with a set of adequately distributed copper-constantan thermocouples.

A complete channel together with installed investigated model of a cylinder and measurement sensors is placed inside the pressure chamber.

5. A measurement system in the research rig

A schematic of the measurement installation for investigations of convection during the flow around the cylinder has been presented in Fig. 5.

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

A measurement of the amount of air flowing through a channel (10) and flowing past the investigated cylinder (1) was taking place by means of a set of calibrated (for air) rotameters (7), where their readings have been converted into the real conditions present inside the pressurised chamber (2) containing the investigated element (1). According to the needs, during the experiments the rotameters (7) could be used alternatively with the orifice (8). Both apparatus were placed in a low-pressure part of the outlet pipeline (4), removing the expanded air from the pressure chamber (2). At that location measured also has been a temperature of outlet air by means of copper-constantan thermocouple (20). Regulation of air stream flowing through the heat exchanger was taking place by means of valves (5,6) placed at inlet and outlet from the heat exchanger.

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

Determination of a mean surface temperature of the cylinder was made on the basis of measurement of electromotive force of a set of Cu-constantan thermocouples located just underneath the cylinder body (1). In the similar way, by means of Cu-constantan thermocouples, were conducted measurements of internal temperature of the channel and the heater contacts. A milivoltmeter (17) was used for measurements of voltage present at 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 measurement sensors of Pt-100 type (15) fed from a direct current source (16',19').

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

6. The analytical method

The heat transfer effect observed during the forced flux of working medium (air) in the measurement channels at the steady heat flux state can be described by means of a general dimensionless equation form, taking the following [6,9]:

$$Nu = f(Re, Pr, Gr, ...) \quad (1)$$

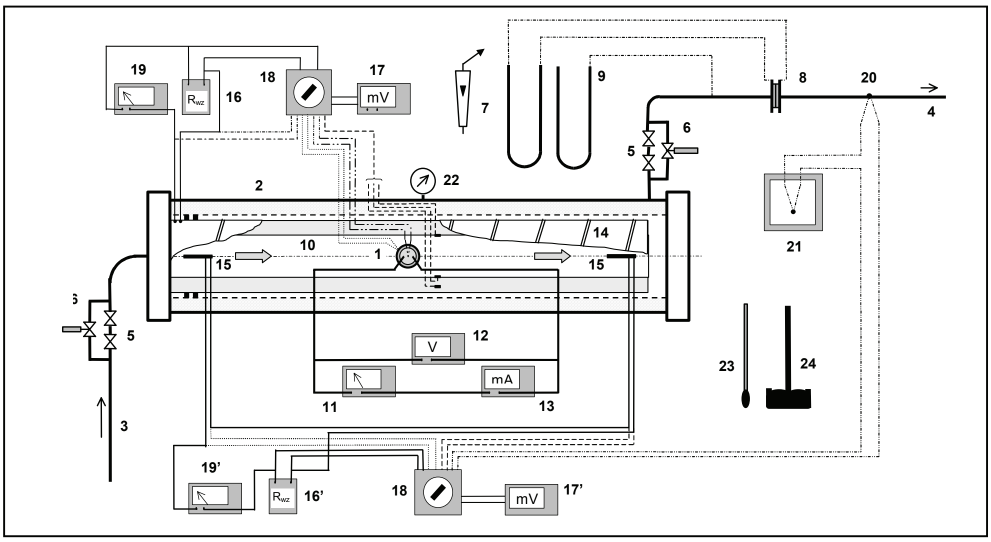

Fig. 5. A schematic of the measurement system in the research rig for investigations of mixed convection under conditions of high pressures (description in the text).

On the grounds of calculating such prime quantities, as heat flux transmitted in the experimental exchanger to the flowing medium, air temperature at the inflow and the outflow of the meassuring channel, temperature of the exchanger wall surface as well as the insulation layer etc., the quantities constituting the dimensionless equation were defined. For example, the Nusselt number was defined according to the following dependence [11]:

$$Nu = \frac{\dot{Q}}{\pi \cdot L \cdot \Delta T \cdot \lambda} \qquad (2)$$

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

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

7. Results of investigations

Experimental studies have been conducted at pressures ranging from 0.1 to 10 MPa [11]. In effect obtained has been a set of results describing the convective heat transfer in different geometrical arrangements as well as different flow regimes. In the present paper presented are only the results regarding a transverse horizontal flow and transverse vertical flow (from the top and from the bottom) of air around the cylinder (Fig. 6).

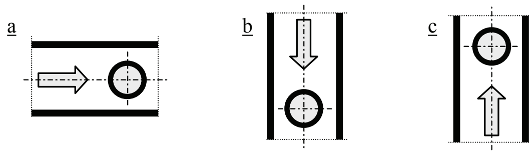

Fig. 6. Analysed configurations of the transverse air onflow on the cylinder:
a-horizontal, b-from the top, c-from the bottom

Sample results of investigations regarding the horizontal and vertical (from the top and from the bottom) air onflow have been presented graphically in Figures 7, 8 and 9. The results have been shown in the form of two-dimensional graphs with one variable depicting the dependence of the Nusselt number on the Reynolds number, developed for the subsequent values of pressures. Such a way of description in the form of relation *Nu = f(Re)* is typical for the forced convection, but implemented for the mixed convection depicts the influence of pressure on the heat transfer processes.

For comparison in the graphs presented also are the curves developed from the non-dimensional analysis according to Hilpert, Van der Hegge Zijnen and Mc Adams [2,11].

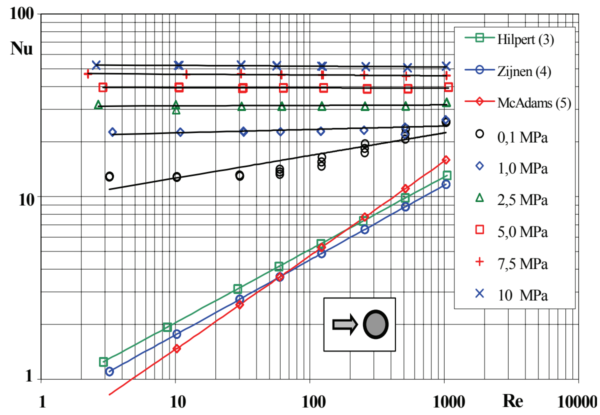

Fig. 7. Nu = f(Re) dependence for a horizontal transverse air onflow on the cylinder

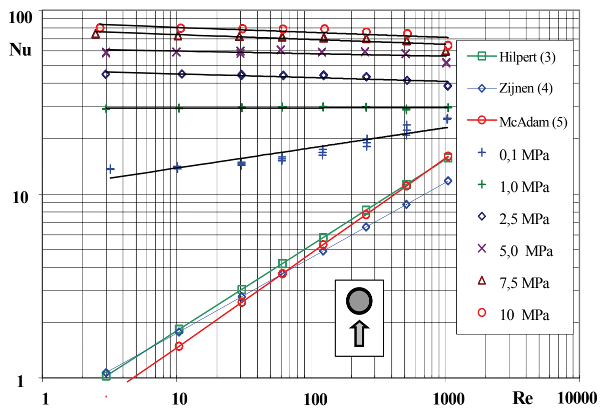

Fig. 8. Nu = f(Re) dependence for a vertical transverse air onflow on the cylinder (from the bottom)

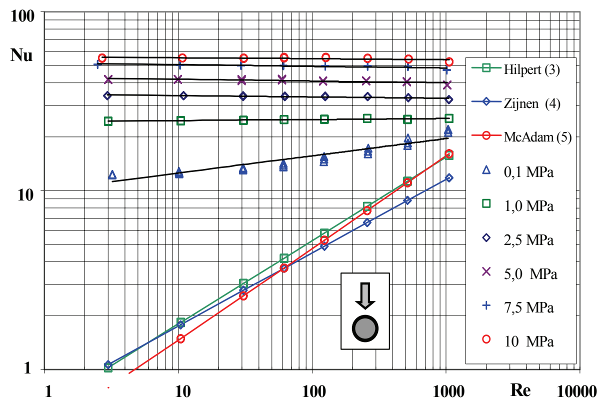

Fig. 9. Nu = f(Re) dependence for a vertical transverse air onflow on the cylinder (from the top)

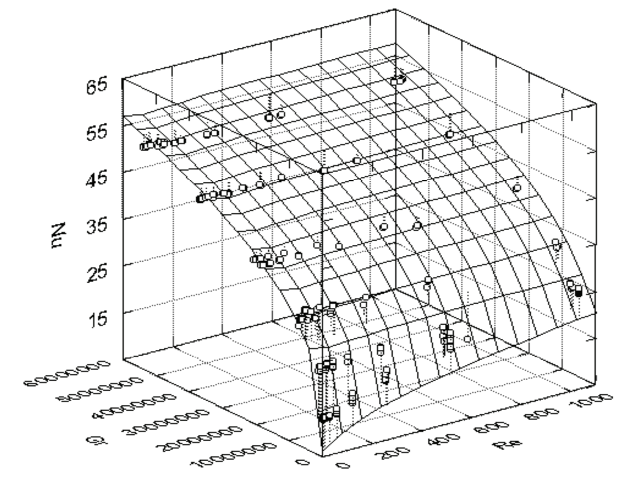

Fig. 10. Nu = f(Re,Gr) dependence for a horizontal transverse air onflow on the cylinder

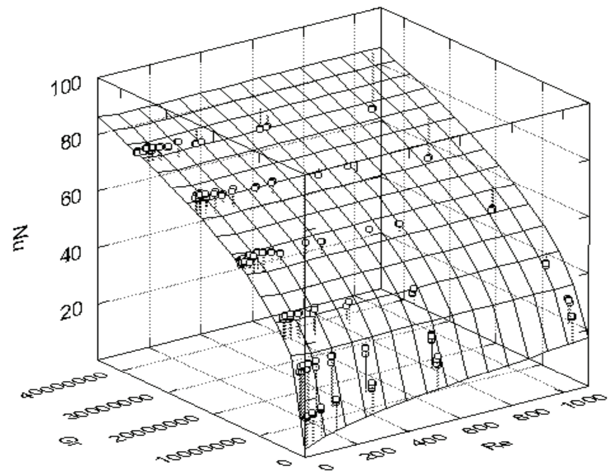

Fig. 11. Nu = f(Re,Gr) dependence for a vertical transverse air onflow on the cylinder (from the bottom)

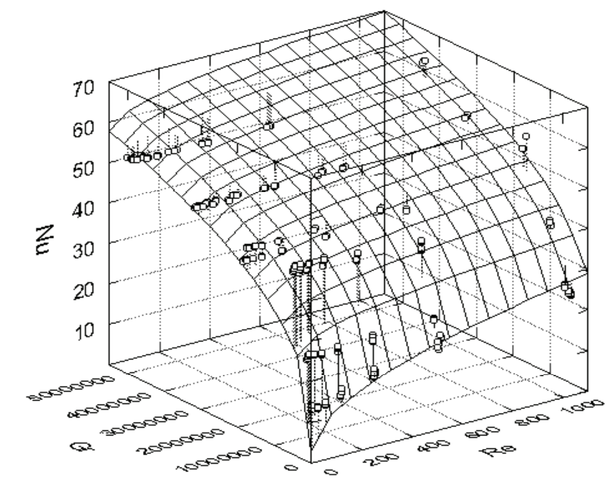

Fig. 11. Nu = f(Re,Gr) dependence for a vertical transverse air onflow on the cylinder (from the top)

Obtained results have also been presented in the form of three dimensional distributions depicting the *Nu = f(Re,Gr)* dependence. Such type of presentation is advantageous for the analysed cases of convection due to the fact that it reveals the influence of particular modes of convection (both of free and forced type) on values of the Nusselt number (Fig. 10, Fig. 11, Fig. 12).

A mathematical description of investigated phenomena of mixed convection has been conducted using the equation in the form of a sum of exponential terms, applied in such a way for the first time by Hausen [11]. Such way of description of convection has also been applied by Budzyński [1,11].

In such equation subsequent terms describe a certain part of considered phenomenon. The first term describes forced convection at small values of the Reynolds number whereas the second – forced convection in the full regime, and the third one – mixed convection. The specifics of the equation is that its particular terms cannot be applied in a sole description of „pure" types of convection. Obtained in such analysis equations describing particular modes of convection at axial flow around the investigated cylinder are presented in Table 1.

Table 1. Dimensionless equations describing heat transfer for cases of transverse flow of air around the cylinder

Cases of flow:	Equations
Horizontal	$Nu = 1{,}31\,\mathrm{Re}^{-0{,}44} + 3{,}01\,\mathrm{Re}^{0{,}11} + 0{,}5\left(5\cdot10^{-1}\,\mathrm{Re}^{6{,}04} + 4\cdot10^{-9}\,Gr^{4{,}31}\right)^{0{,}08}$
Vertical - from the bottom	$Nu = 0{,}63\,\mathrm{Re}^{-0{,}48} + 87\,\mathrm{Re}^{0{,}15} + 0{,}5\left(5\cdot10^{-1}\,\mathrm{Re}^{6{,}11} + 11\cdot10^{-9}\,Gr^{4{,}67}\right)^{0{,}08}$
Vertical – from the top	$Nu = 0{,}57\,\mathrm{Re}^{-0{,}57} + 1{,}67\,\mathrm{Re}^{0{,}31} + 0{,}5\left(5\cdot10^{-1}\,\mathrm{Re}^{6{,}08} + 7\cdot10^{-9}\,Gr^{4{,}35}\right)^{0{,}08}$

A reflection of dimensionless equations are presented in the figures surfaces expressing described in such way dependence between the Nusselt number and the Reynolds and Grashof numbers. On the basis of comparative analysis it can be concluded that those surfaces correlate well with presented in particular graphs point denoting values of the Nusselt number, determined as a result of performed measurements. Obtained consistency is satisfactory particularly in the range of high Grashof numbers, which corresponds to high experimental pressures.

6. Conclusions

Analysis of obtained results enables to conclude that in all considered cases the increase of pressure is accompanied by the increase of Nusselt number, which results from superposition of free convection on the forced convection. Such process has been described on the basis of obtained results using the non-dimensional numbers developed for particular variants of the flow around the considered cylinder.

In the performed experiments it has been concluded that the heat transfer intensity depends on the way of the air flow around the cylinder. The highest values of Nusselt number have been obtained for a vertical flow directed on the cylinder from the bottom. On the other hand the lowest values of Nusselt number have been achieved for a vertical air onflow from the top. Such phenomenon is observed in the entire range of investigated pressures and the discrepancy of developed results increases with the increase of pressure, particularly for the vertical onflow from the bottom.

Presented in the paper results regard only a narrow range of conduced experiments. For example in the present work have not been presented the results of investigations of convection at different configurations of the transverse flow around the cylinder [12]. Obtained results did not also give the answer to the all questions raised in the paper. For example the borders between the mixed convection and free and forces convection have not been set. Bearing that in mind, both experimental and theoretical studies regarding mixed convection at different configurations of the air onflow will be continued and the results successively published.

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