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# ENHANCING HEAT EXCHANGE IN FORCED CONVECTION WITH VARIABLE AIR FLOW DIRECTION

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***Abstract***

*In this article there are presented tests results of the process of heat exchange between a flat plate placed vertically behind a stream element being a mono-stable jet nozzle with two states of the air outflow. Depending on the state of the air outflow, the air stream flows round a part of the wall in a different direction. In this work there are presented results of measurements recorded for selected parameters of the air outflow.*

***Keywords***: *heat transfer, airflow control, impining jets, air nozzle.*

## 1. Introduction

In the processes of heat exchange (heating, cooling) the thermal efficiency of a device is of great importance as well as the temperature distribution on the heated or cooled element. This article deals with the problems connected with the heat exchange process, involving heated air, being the heat carrier, flowing out of the nozzle thus enabling occurrence of two characteristic states of the air stream. As regards intensity of the heat exchange between a solid body and a liquid flowing around it, this is the fluctuation of its speed and direction, while flowing around the obstacle, that really matters. Properly matched parameters of the stream flow should inhibit formation of a boundary layer considered to be the main thermal resistance during heat exchange between a solid body and an air stream flowing around it.

One of the ways of heating by hot air is directing the stream perpendicularly to the heated body. The flow of hot air hits the wall (flat, stiff wall) and, flowing into direction radial to the axis of the nozzle, heats it (fig. 1).

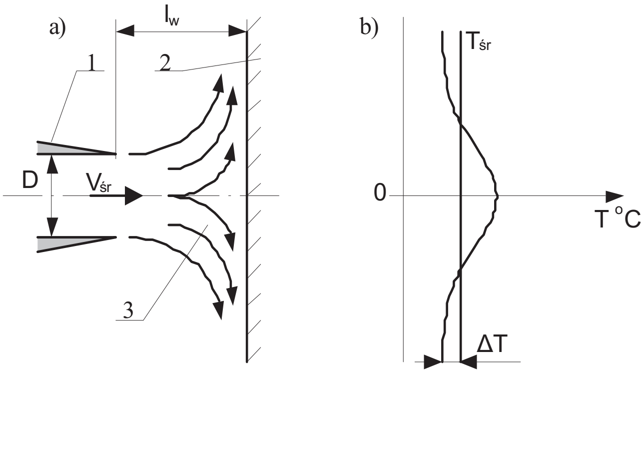


*Fig. 1. Flow around flat wall; a) diagram of airflow, b) temperature distribution on the wall; 1-nozle, 2-wall, 3- lines of airflow directon*

The mean value of temperature $T_{śr}$ and the degree of its non uniformity $\delta_T$ depend on the conditions of the heat inflow within a given area. Thus, the task involves providing proper conditions for the inflowing air. It is possible through using a controlled stream element with pulsing exhaust jet. A direction change of the speed vector of air, flowing round the studied flat surface, is a distinctive feature of the produced air stream.

Improving the efficiency of the heat exchange process will make it possible to reach a higher value of temperature for the heated element, in the same time. Analyzing the amount of thermal energy taken over by the element from the air flowing round it will make it possible to reach the same value in a shorter time. Shortening of the heating process time is also connected with a reduction of energy used in this process. Attempts to find a way to reduce the amount of energy have been made in many works on the subject of micro-pneumatics in which stream micro-valves find application. Reduction in energy consumption is connected with environment protection. Ecological aspects play a more and more important role in construction, utilization and recycling and are being focused on by more and more researchers [2].

## 2. Test stand

The test stand is presented in figure 2. The designed and constructed control systems make it possible to control the main stream (flowing out of the nozzle) following parameters [1.3]:

- main stream volume rate $Q_{vm}$;
- control stream volume rate $Q_{vc}$;
- temperature of stream T;
- frequency of stream oscillation fc;
- space filling of signal PWM (refers to the time of the flow duration in its particular states).

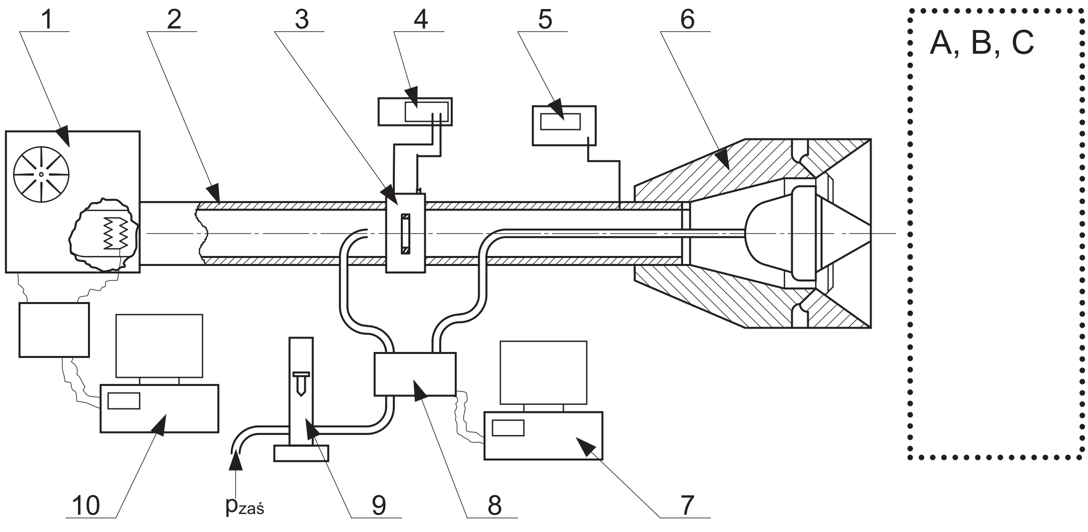


*Fig. 2. Scheme of a test stand: 1 – supply and heating systems for the main stream, 2 – the main pipe, 3 – orifice, 4 – digital micro-manometer CMR 10A, 5 – system for measurement and recording temperature of the flow flowing into the nozzle, 6 – the tested axial-metrical nozzle with internal core, 7 – computer PC with measurement card producing control signals $f_c$ and PWM, 8 – electropneumatic throw-over valve of the control flow, 9 – rotameter (measurement of the control flow rate ), 10 – computer PC with measurement card for control of the flow rate and the main flow temperature, $p_{zaś}$ -source of control flow A,B,C – measurement systems of the heated wall, speed distribution of air flowing out of the nozzle and visualization of the air flow behind the nozzle*

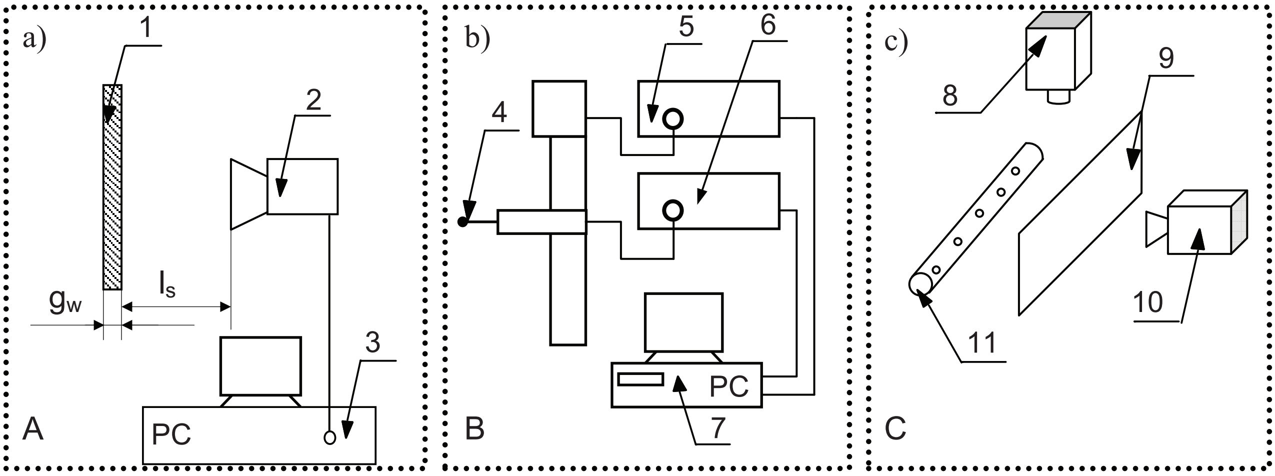


*Fig. 3. Schemes of measurement systems used in tests (to fig.2): a) measurement of the heated wall temperature, b) measurement of speed of the air flowing out of the nozzle, c) visualization of the air outflow from the nozzle and its flowing round the resistance wall; 1 heated element (resistant wall) by the air flowing out from the nozzle, 2-thermographic video camera, 3-PC computer recording data from the thermographic video camera 4-single-fiber measurement probe 55P11, 5-uniaxial system of traversion Dantec Light Weight Traverse, 6-thermal anemometer StreamLine with one channel module CTA90C10,7- computer PCwith software for control of the traversion system, 8-digital video camera recording the visualized air flow, 9- transparent resistant wall, 10-lighting system with regulation of the light beam width,11-system of paraffin vapor generation visualizing the air flow*

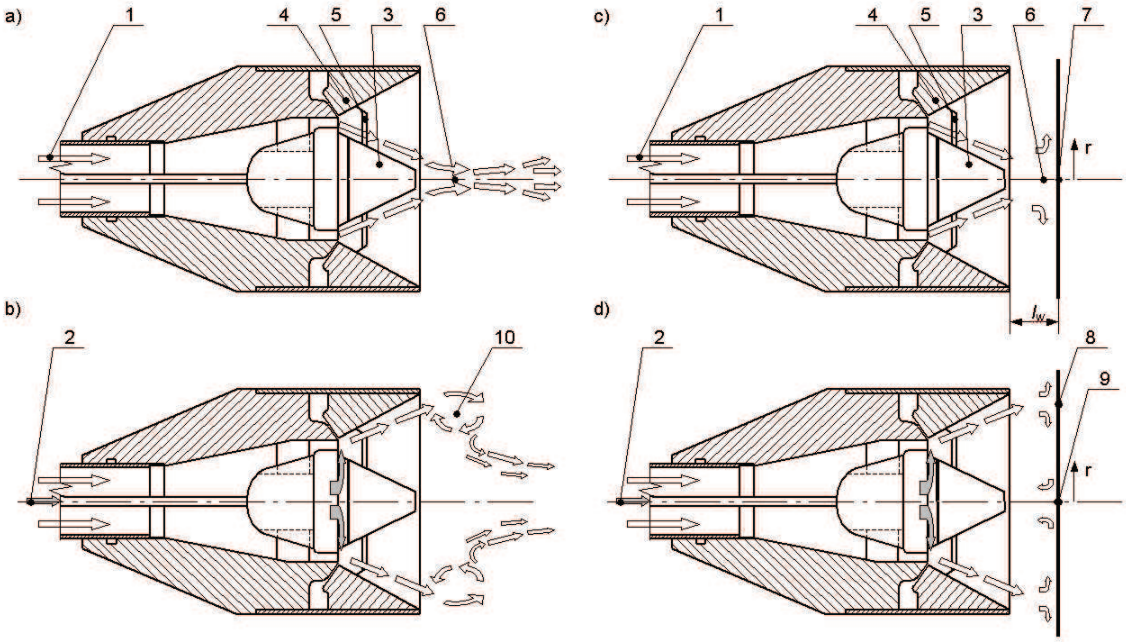


*Fig. 4. Scheme of the nozzle operation, air flow through the nozzle and its flowing round the wall; a) first steady state – free outflow, b) second steady state –free outflow, c) the first steady state –outflow onto a flat perpendicular wall, d) the second steady state-outflow onto a flat perpendicular state, 1-main straeam,2-control stream,3-the nozzle inner core, 4- the nozzle male cone, 5-spoiler, 6-point of the stream connection, 7-stagnation point, 8-stagnation circle, 9-the reverse stream stagnation point, 10-triodal whirl formed in the second fixed state with a free flow*

The measuring equipment shown in Figure 3 allows to perform the following measurements:

- measurement of the heated wall temperature
- measurements of the average velocity of air stream flowing from the nozzle;
- visualization of air flow behind the nozzle (flow without and with the wall)..

Measuring devices are placed behind the nozzle as shown schematically in fig. 2.

The analyzed nozzle is a monostable stream element whose distinctive feature is the internal core to which a stream controlling the outflow of the main stream is supplied. This element is monostable with two steady states of the main stream outflow. In the first steady state (while the control stream is switched off) the air flows out along the inner cone (core). In the second steady state (while the control stream is switched on) the air flows out along the outer cone. These sates are characterized by different concentrations of the stream. In order equalize rates of the flow volume of the air flowing out of the nozzle for both fixed states, the control stream is not only turned on and off but also switched within valve 8 in fig.2. A scheme of the nozzle operation has been shown in figure 4 [4.5.6].

As the flow control, which allows you to change the steady state flow can be used a synthetic jet with adequate power. Research of such a synthetic jet generated by the speaker were carried out among others in Institute of Thermomechanics of the Academy of Sciences of the Czech Republic [1.2].

## 3. Experimental tests

Thermographic tests were conducted for a definite range of input parameters. Values of particular quantities within the accepted ranges were measurable and controllable [1]. The values of particular input variables were:

- the stream oscillation fraequency $f_c$=0,5; 0,8; 0,9; 1,0; 1,1; 1,2; 1,3; 1,5; 2,0 Hz;
- space filling of signal PWM=20; 50; 80 %;
- distance of the wall from the end of nozzle $l_w$= 70; 80; 90; 100 mm.

The direction of the flow round the wall in the first and second state underwent a distinct change within the range of accepted distances of the wall from the nozzle end in the first and second state [2,3].

Before measurements the nozzle was initially heated in order to decrease heat losses from the stream through raising the temperature of the housing during the resistant wall heating process. Initial heating involved 30 min. flow of air through a nozzle, the air was heated to temperature T=50 $^{o}$C. Thermographic measurements were started at the time when the environment mean temperature was $T_o$=24±0,5 $^{o}$C.

Thermographic video camera of VIGO S.A. was used for the wall temperature measurements. Actually this was a thermographic scanner with resolution 240x240 points. The time of measurements was fixed and equal to 8 min. and 20 seconds for fixed values of input parameters. This was a time necessary to carry out 20 measurements, that is, runs of the video camera head [7].

## 4. Results of thermographic tests

The results of temperature measurements of the wall flowed round by air can be presented:

- in the form of thermographic image;
- in the form of a table with temperature values.

Different temperature distributions have been obtained for the air flow with different values of input variables. In figure 5 there are selected results of these measurements. The amount of heat taken over by the wall from the heating air was calculated for the wall unit volumes provided by the thermographic video camera resolution and the difference in temperatures recorded at the beginning and at the end of the heating process.

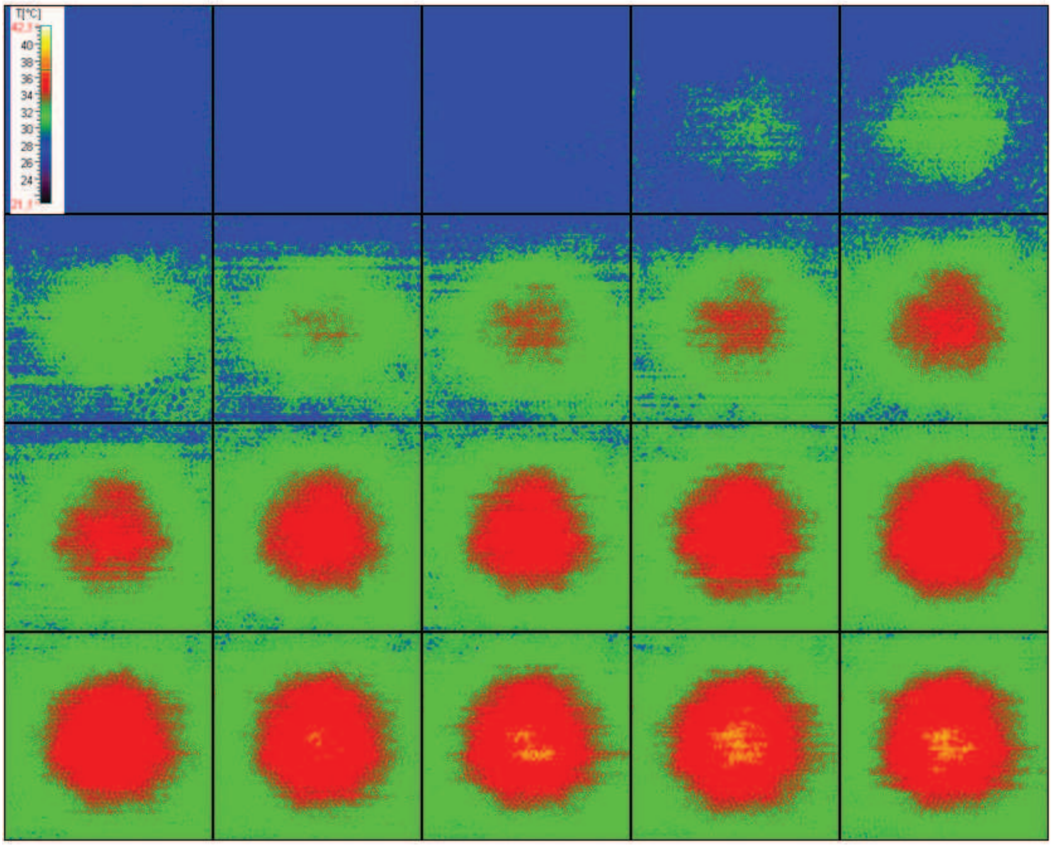


*Fig. 5. The results of thermographic measurements for the flow, in the first steady state, when the wall distance from the nozzle is $l_w$=70mm. The figure shows 20 successive measurements, in the first image there is a scale of temperatures*

In order to compare and analyze the influence of the air stream flow oscillation on the process of heat transfer, dimensionless indicators have been determined for different values of input parameters.

a) indicator of the heat exchange process

$$w_Q = \frac{Q_{uz}}{Q_{nom}}, \tag{1}$$

where:
$Q_{uz}$ - amount of heat taken over by the wall for a flow with defined parameters,
$Q_{nom}$ - amount of heat obtained from the flow in the steady state one.

b) indicator of the wall distance from the nozzle $l_w / D_{zd}$

where:
$l_w$ - distance of the wall from the nozzle,
$D_{zd}$ - external diameter of the nozzle.

c) coefficient of the temperature distribution non-uniformity

$$\delta_T = (T_{max} - T_{min}) / T_{śr}, \tag{2}$$

where:
$T_{max}$ - maximum temperature of the wall,
$T_{min}$ - minimum temperature of the wall,
$T_{śr}$ - mean temperature of the wall.

Selected results of measurements of wall temperature for different flow parameters are shown in fig. 6. The values of the coefficients wq and dT will determine the impact of the air flow parameters for the transfer of heat by the wall from the air flowing from the nozzle. Figures 7, 8 and 9 shows the values of these coefficients calculated for the flow of air with different values of the parameters fc, PWM, lw.

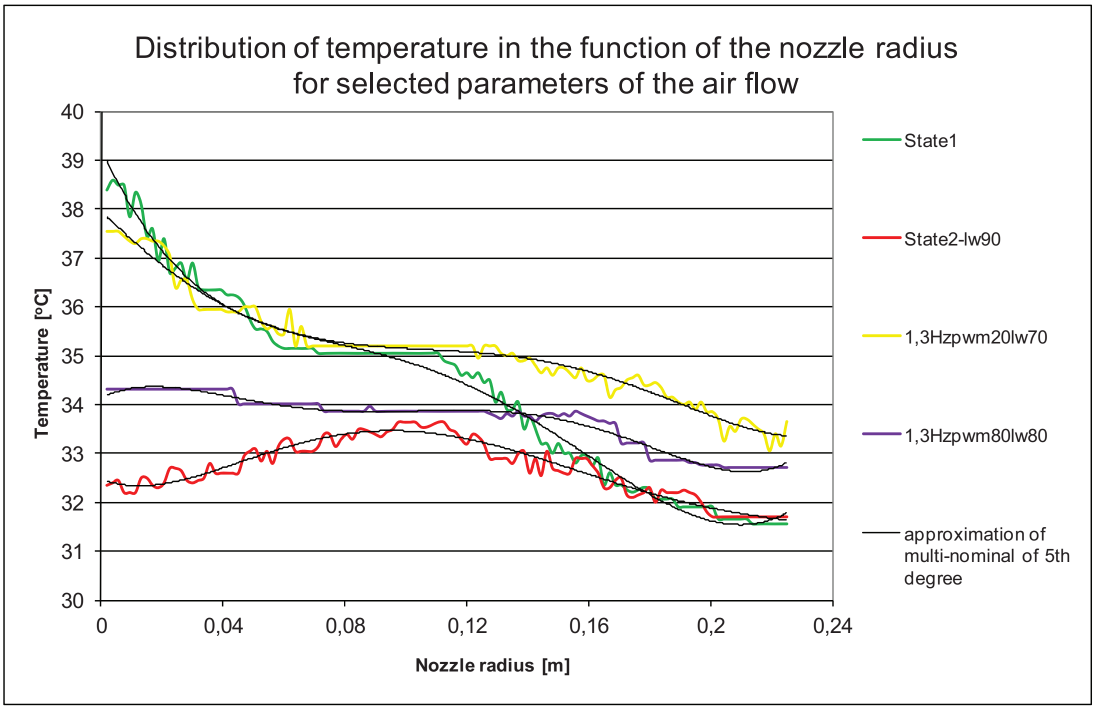


*Fig. 6. Selected temperature measurement results of the wall flowed round by heated air, obtained for different parameters including approximation of multi-nominal of 5$^{th}$ degree*

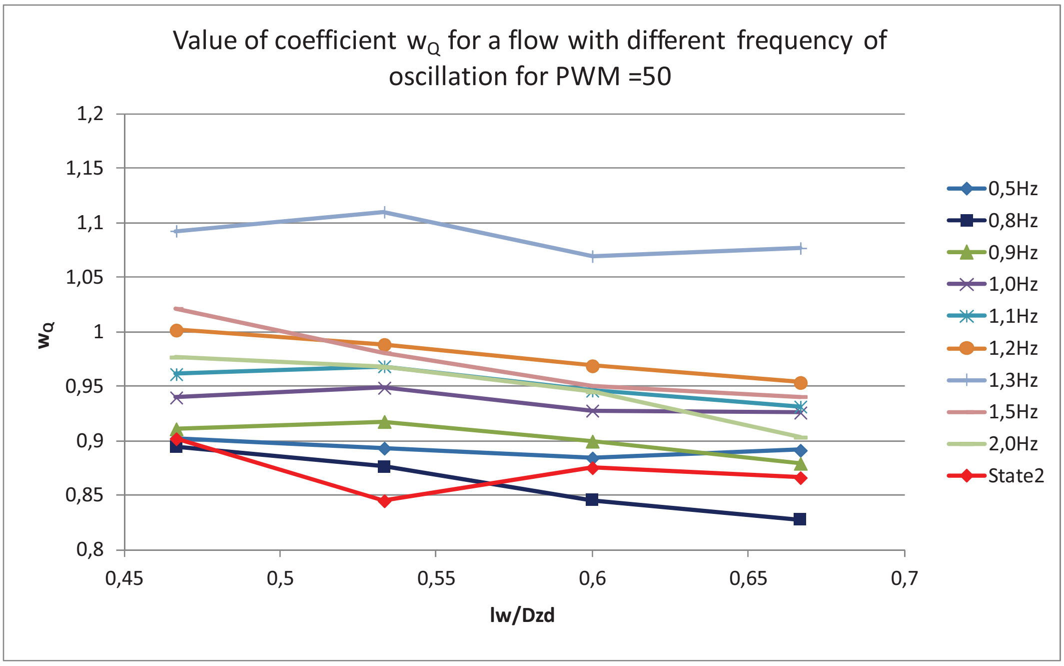


*Fig. 7. Value of indicator $w_Q$, for PWM =50, for different values of frequencies of the control signal in function $l_w/D_{zd}$*

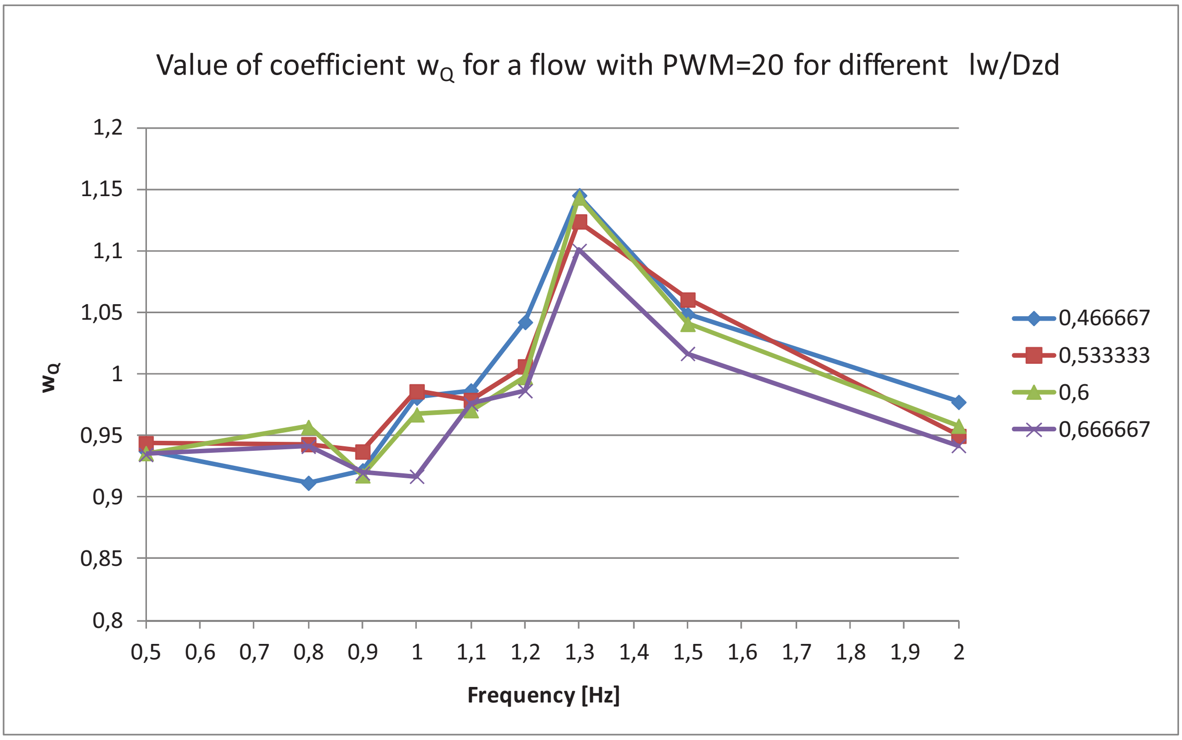


*Fig. 8. Values of coefficient $w_Q$ for $l_w/D_{zd}$ in function of frequencies of the control signal fc*

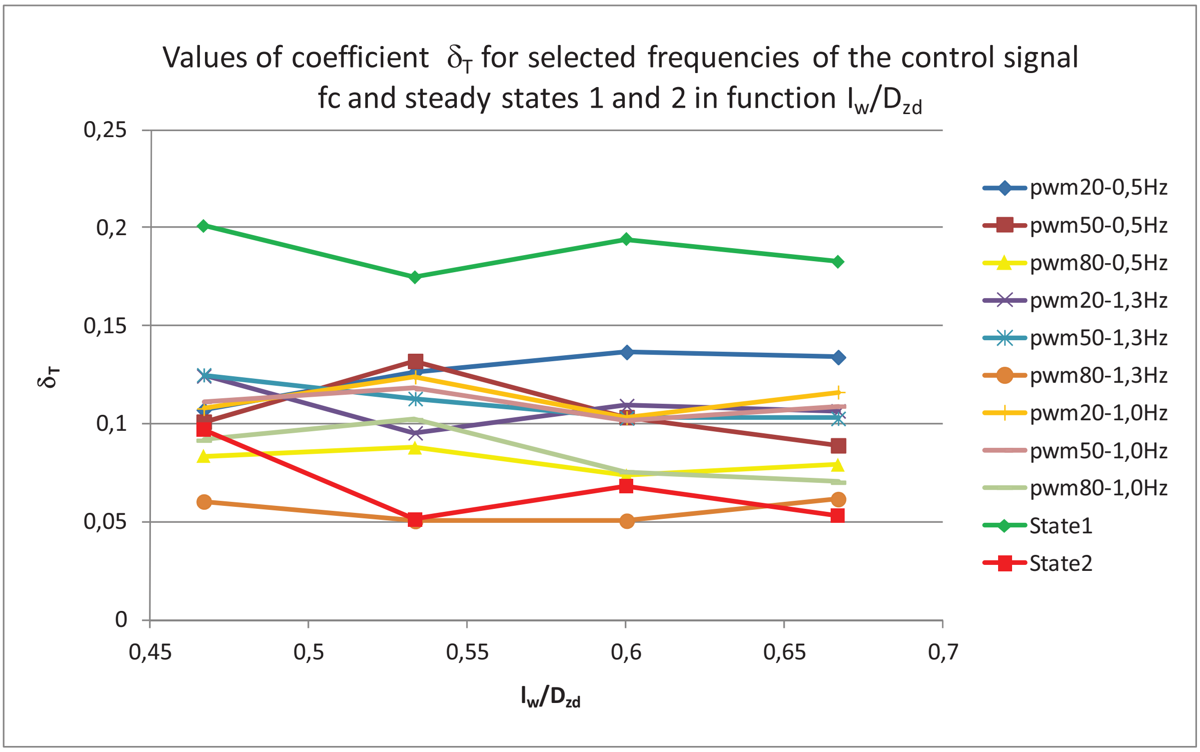


*Fig. 9. Values of coefficient $\delta_T$ for selected frequencies of the control signal fc and steady states 1 and 2 in function $l_w/D_{zd}$*

## 5. Discussion and conclusion

In effect of changing parameters of the air stream flowing out of a nozzle there have been obtained different values of indexes describing the heat exchange process.

Form the point of view of the heat exchange process intensification (heating), the most important parameter affecting the process course is the frequency of change of the flowing out air stream steady state (parameter fc). For the accepted range of low frequencies the obtained results definitely indicate that the frequency with value fc = 1.3Hz increases the amount of heat taken over by the wall from the air flowing around it. For the remaining six out of nine values of the control stream frequency there have been obtained values of index wq smaller than 1, which indicates a reduction of the heat amount taken over by the wall. The influence of fc frequency is particularly well seen in figure 8.

From the point of view the temperature distribution on the examined element the most important thing is the filling space of PWM signal (fig.9). On the basis of conducted tests it can be found that the most uniform temperature distributions on the heated element can be obtained for high values of PWM. The highest value of the temperature non-uniformity coefficient was reached for the flow in the first steady state. However, the highest values of the heated wall have been reached for this state.

Application of a controlled stream element and an appropriate match of the air stream outflow parameters enables enhancing the heat exchange process and shaping the temperature distribution on the heated element (flat wall).

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