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Research of Hydraulic Resistance and Heat Transfer in Elements of Pipe Columns with Alternate Arrangement Located in Gas Pipes behind the Screen of Hot-Water Boiler

Rakhimzhan K. Orumbayev*, Andrey A. Kibarin*, Maxim S. Korobkov*[1], and Tatyana V. Khodanova*

Abstract –*In modern designs of hot-water boilers, depending on design layout and arrangement of external screens with furnace cage presented by membrane panels, there appears a channel with longitudinal and cross runaround in cross-section of gas pass. Whereas cross-section of such channel differs from traditional forms, thoroughly researched and presented in academic publications. In this paper there are presented results of experimental researches on determination of hydraulic resistance and coefficient of heat transfer for particular convective elements of boilers with new configuration – membrane type furnace screens and swirler device at gas pass located behind the screens. It is shown that in gas pass with swirler device located behind the screens, in case of cross runaround of tubes and high temperature of gases (870÷970)°K, one can expect the increase of heat transfer coefficient in comparison with classic alternate arrangement of tube columns with large amount of tubes in cross row.*

Keywords – alternate arrangement of tubes column, convective heat transfer, hot-water boiler, hydraulic resistance. membrane type furnace screens.

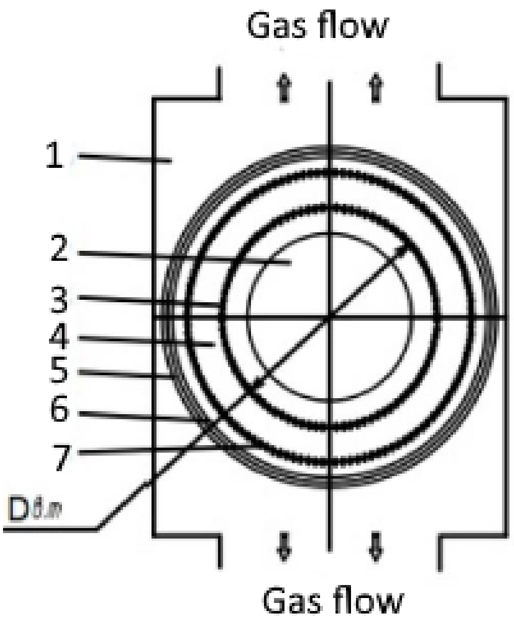
1. INTRODUCTION

Despite the sufficient industrial reserves of raw hydrocarbon deposits in Kazakhstan [1]-[3], further use of hydrocarbons in energetics, and in heat supply accordingly, would be held back by circumstances connected with decrease of greenhouse gases (CO_2 gases) according to Kyoto protocol, ratified by Kazakhstan on March 26, 2009 [4], and the Law of Republic of Kazakhstan "About energy saving and increase of energy efficiency" [5]. That's why nowadays search of ways for modernization, substitution of constructively and physically outdated hot-water boilers of central heating systems in Republic of Kazakhstan with purpose of fuel resources economy (natural gas, fuel oil), decrease of operational and repair costs, and sufficient decrease of polluting emissions and greenhouse gases emissions in the atmosphere.

2. RESEARCH OBJECTIVES

Over the last several years there are membrane all-welded tube panels widely used as furnace screens in designs of hot-water boilers, which decreases consumption of expensive heat isolation materials and metal [6], [7]. However, backside surface of these membrane panels in furnace of hot-water boilers with low and medium heating capacity is used not efficiently enough. 100% use of backside surface of membrane panels in furnace screens during the active heat transfer may in some designs additionally decrease consumption of metal operated under pressure by 20% of all weigh of a boiler. Secondly, in case of using the backside surface of membrane panels, the increase of heat transfer is achieved by the gas flow itself, which travels to thermal boundary layer of convective surfaces, where up to 85% of the whole amount of heating resistance of the flow is concentrated.

Depending on design layout and arrangement of external screens with furnace cage presented by membrane panels, there appears a channel with longitudinal and cross runaround in cross-section of gas pass. As an example on Figure 1 is shown the view from the top section of hot-water boiler



1 – exhaust gases duct, 2 – furnace, 3 – internal cylindrical membrane type furnace screen, 4 – behind-the-screen gas pass, 5 – external heat insulated panels, 6 – heat reflecting panels, 7 – coaxial external furnace screen

Fig. 1. Cross-section view of hot-water boiler.

*Non-Commercial JSC Almaty University of Power Engineering and Telecommunications. 126 Baytursynov Street, Almaty City, 050013, Kazakhstan.

[1]Corresponding author;
Tel: + 7 727 292 90 92
E-mail: korobkovmax@gmail.com.

Whereas the cross-section of such channel differs from traditional forms, thoroughly researched and presented in bibliography [8]-[10]. Calculation of hydrodynamic and heating characteristics of channels on new convective surfaces, including those with swirler devices located at behind-the-screen gas pass, in case of longitudinal and cross runaround and using already known formulas may cause serious mistakes and miscalculations [8]-[11]. That's why it can be useful for calculations to refine these formulas in order to define resistance and heat transfer coefficients for particular convective elements of boilers with new configuration.

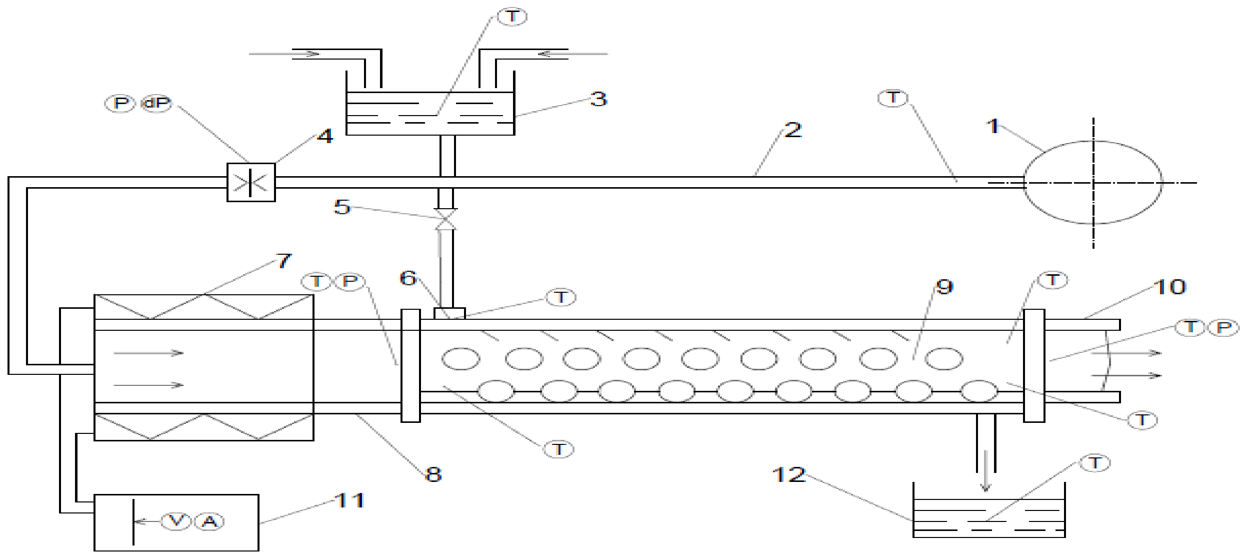
Analysis of literature allows to make a conclusion that number of experimental, calculated and theoretical works on research of hydrodynamics and heat transfer in rectangular channels having sophisticated forms in cross-section with longitudinal ribbing – is limited.

That's why authors of this work have performed experimental researches on definition of hydraulic resistance and heat transfer coefficient, which are generalized and presented in the form of criteria dependencies.

3. EXPERIMENT STAND DESCRIPTION

The research of hydrodynamic and heat exchange in the straight channel of gas pass, which is located behind the screen and has transverse flow around of checkered-pattern elements of the column, was performed on experimental stand that is shown on the Figure 2.

Centrifugal air blower 1 supplies air into the stabilization area 2, where the orifice flow meter 4 is installed. Length of stabilization area till the orifice is 37, 6 gages. Orifice flow meter is made of Cr11NiTi9Ti type stainless steel. During the research the air consumption was changing from 40 to 500 normal m^3/hour. Temperature of the air was measured by using the chromel-copel thermocouple. After the orifice there is an output stabilizing area, which length is equal to 20 gages.



T – point of temperature measurement, P – point of pressure measurement, dP – point of pressure differential measurement, V – point of voltage measurement, A – point of electric current measurement, 1 – centrifugal air blower, 2 – stabilization area, 3 – container with constant level, 4 – orifice flow meter, 5 – valve, 6 - special column with thermocouple installed, 7 – electric heater, 8 - input stabilizing area, 9 - experimental area of gas duct located behind the furnace screen, 10 - outlet stabilizing area, 11 - voltage control unit, 12 - calibrated flow-measuring container.

Fig. 2. Main scheme of the experimental stand.

After the flow turns 180° in other direction, the air is then directed into the electric heater 7 with voltage control units 11 of 40 kW total. Input stabilizing area 8 gives opportunity to change the cross-section of channel gradually from circular to any other desired. Moreover, designs of input stabilizing area and experimental area of gas pass located behind the furnace screen 9, allows changing the channel's height and cross-section shape of operating area. In order to perform research of the heat exchange in the input stabilizing insulated area, there were six thermocouples installed on both sides, on the upper surface and along the stabilizing area. Holes were made on all four sides of stabilizing area in order to measure the static inlet pressure. Length of the area is 25-30 equivalent diameters of gas duct channel located behind the screen. After the adjustable experimental area the hot air was going into the outlet stabilizing area 10 that is 20 – 25 gages long, and where the thermal compensation unit is installed, then air was released in the atmosphere. Adjustable experimental area of gas pass located behind the screen is cooled with water supplied from container with constant level 3. Water consumption is controlled by valve 5. Immediately on the inlet of experimental area, there was thermocouple installed into special column 6, opposite side of which served as the collector for lower pipe panel. Warm water was supplied to lower pipe panel form the side of hot air inlet. After consequent run-through the pipe column the water from outlet collector was dumped into the calibrated in advance flow-measuring container 12 using the flexible hose.

4. DEFINING THE HYDRAULIC RESISTANCE COEFFICIENT IN ELEMENTS OF TUBE COLUMNS WITH ALTERNATE ARRANGEMENT

Hydraulic resistance in tube columns is defined by nature of liquid flow in shell side. Periodical speed-ups and slowdowns of the flow, specific for cross runaround of tube columns, generate eddy zones of the flow, which lead to loss of kinetic energy of the flow. For small amount of rows of tubes, total hydraulic resistance is affected by additional loss of kinetic energy in the first row, as well as losses of pressure when the flow exits the tube columns. In case of columns with small amount of rows this factor may play quite a significant role.

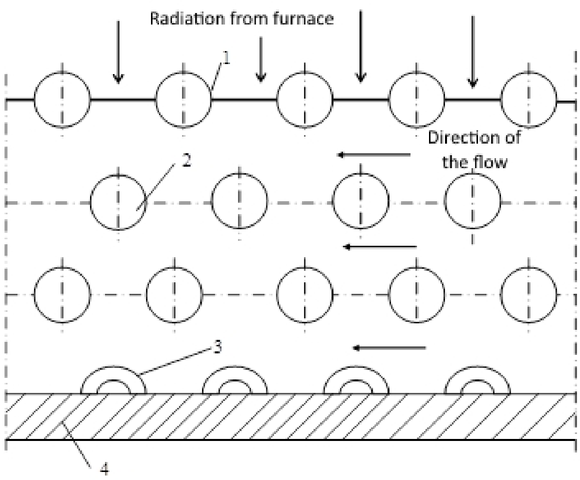
Generally, considering physical parameters of heat transferring medium, functional dependency of pressure change is defined in nondimensional form according to formula:

$$Eu = f\left(\mathrm{Re}, \frac{s_1}{d}, \frac{s_2}{d}, z\right) \qquad (1)$$

Power form of dependency is widely used in practical calculations in case of generalization of experimental data:

$$Eu = k\,\mathrm{Re}^n\, z \qquad (2)$$

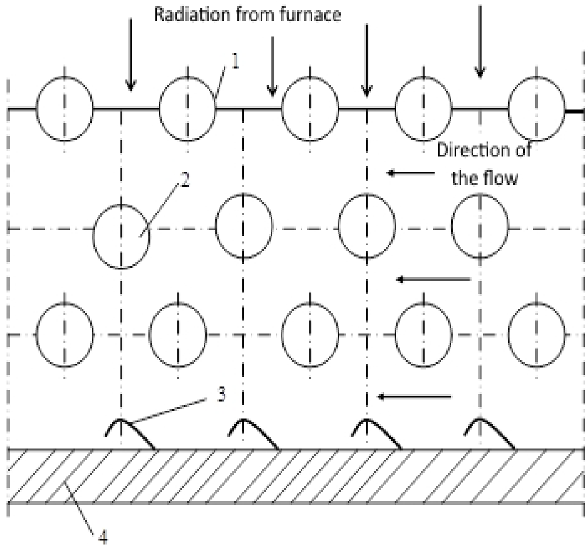
Research of static pressure field was performed in specific cross-section of the channel on behind-the-screen gas passes with swirler device models, which layouts are presented on Figures 3-5. Cross sections for measurements were – inlet stabilizing sector; outlet stabilizing sector; experimental sector itself.



1 – all-welded membrane panel, 2 – tube column with alternate arrangement, 3 – swirler devices in the form of half tubes, 4 – portable heat isolated panel.

Fig. 3. Longitudinal cross-section of model's channel № 8 with swirler device in the form of half cylinder.

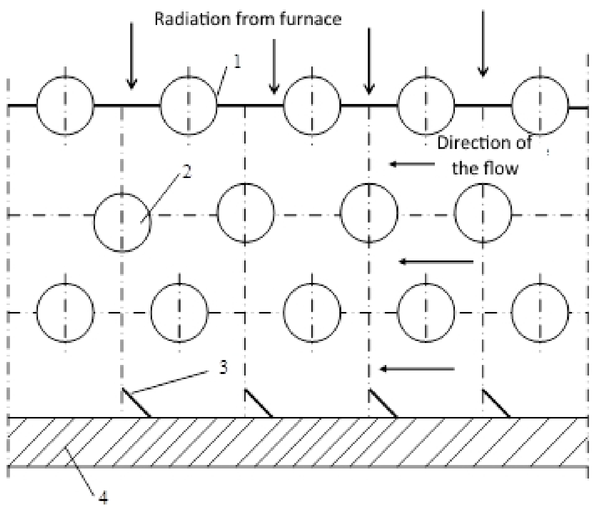
There are swirler devices in cross arrangement shown on the lower wall of the channel, in form of half cylinders (model № 8), panels located under 45° angle with bent edge (model № 9) and panels located under 45° angle (model № 10). Swirler devices are installed with longitudinal spacing equal to longitudinal spacing of tubes' column.



1 – all-welded membrane panel, 2 – tube column with alternate arrangement, 3 – Γ-shaped panels, 4 – portable heat isolated panel.

Fig. 4. Longitudinal cross-section of channel № 10 with swirler device in the form of Γ-shaped panels.

(7)



1 – all-welded membrane panel, 2 – tube column with alternate arrangement, 3 – bent panels, 4 – portable heat isolated panel.

Fig. 5. Longitudinal cross-section of channel № 9 with swirler device in the form of bent panels.

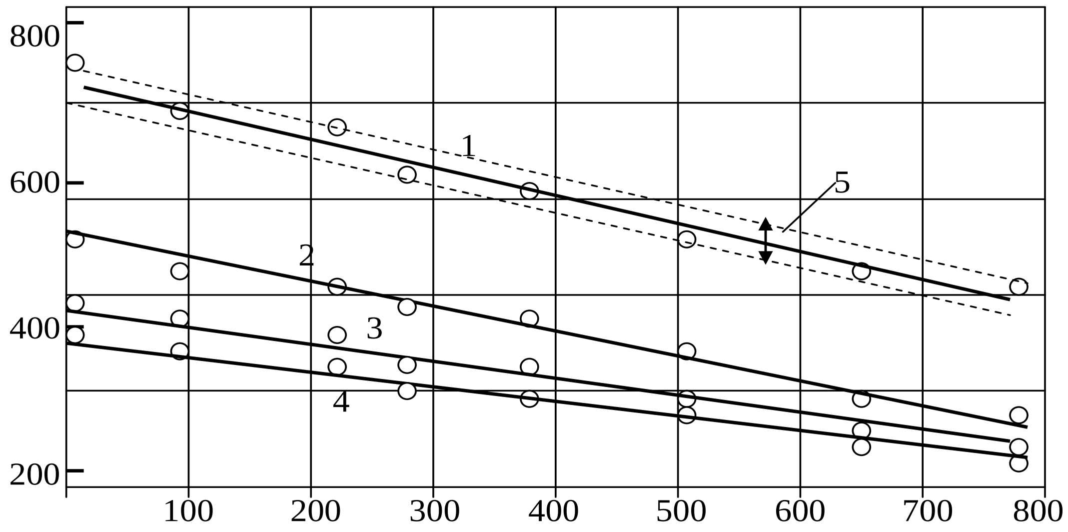
Lower wall with different types of panel edges together with tubes column forms a curved channel, with periodically longwise changing width.

Geometrical parameters of tubes column with alternate arrangement are represented in Table 1.

Figure 6 shows change of static pressure lengthwise in relation to experimental section of model № 8 in case of different Reynolds number.

Table 1. Geometrical parameters of model of tubes column with alternate arrangement.

Model	Equivalent diameter, m	Transverse tube spacing	Longitudinal tube spacing	Type of swirler device	Angle of swirler device bend, degrees
№8	0,038	1,84	1,4÷3, 0	Half cylinder	-
№9	0,038	1,84	1,4÷3, 0	panel	45
№10	0,038	1,84	1,4÷3, 0	Panel with bend edge	45

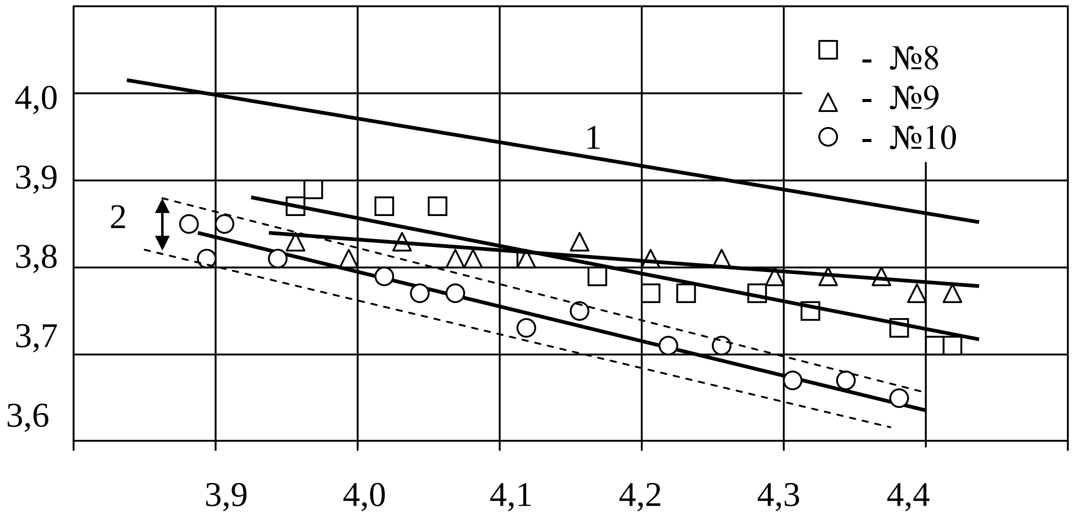


X axis – length of a channel, mm; Y axis – static pressure, Pa. Legend: 1 – Re number = 21500; 2 –Re number = 17000; 3 – Re number = 15500; 4 –Re number = 14000; 5 – experimental inaccuracy.

Fig. 6. Spread of static pressure along the tube columns with alternate arrangement.

As it is seen on Figure 6 the static pressure difference for large Re numbers is growing significantly, and as the flow speed in tube columns with alternate arrangement increases the hydraulic resistance of the flow grows as well. Whereas, it was noticed experimentally in case of all models that periodic change (increase and decrease) of static pressure along longitudinal row of cross-flowed tubes, this effect was achieved in other analogous experimental works [15].

Figure 7 shows the dependence of the hydraulic resistance coefficient on Re criteria for channel models № 8-10. Results obtained on models 8-10 were compared with hydraulic resistance of standard tubes column with alternate arrangement and the same geometrical parameters. Hydraulic resistance of so called normative column with alternate arrangement was defined by formulas [9].



X axis – Artificial number of Reynolds number; Y axis – artificial number of (1000ξ). Legend: 1 – normative tube column with alternate arrangement, 2 – precision of generalization; №8 – with half cylindrical rails; №9 – with panel rails; №10 – panel with bent edge.

Fig. 7. Dependency of lg(1000ξ) on lgRe.

Analysis of the Figure 7 shows that within researched range of Reynolds numbers the value of resistance coefficient for model №9 with panel straight swirler devices is higher than for model №8 with half-cylindrical sidewalls. In case of isometric flow with increase of Re number, coefficient of hydraulic resistance for model №9 increases in relation to hydraulic resistance coefficient for model №8.

Having an Re number values from 6 × 10^3 to 12 × 10^3 the coefficient of hydraulic resistance for models №8, №9 and №10 is almost not changing. Increase of hydraulic resistance coefficient for model №9, as the Re number grows (as the speed grows) is determined by the fact that the panel stimulates transfer of the most part of the flow onto the tube. Space behind the panel is filled with additional swirls, requiring consumption of kinetic energy of the flow.

For model №8, as the Re number increases (speed of the flow) the hydraulic resistance coefficient changes parallel to normative tube column resistance coefficient.

Hydraulic resistance coefficient for model №10 is less than for models №8 and №9. In case of this model the smoothly bend edge of swirler device “ennobles” the flow image and the point of vertexes detachment shifts down along with the flow. Then the increase of speed begins and as in the case of flow for model №8 there is no additional space for swirls. This diagram shows dependence of hydraulic resistance of tube column with the same accuracy, the two stations, Wonderboom and geometric characteristics. Hydraulic resistance coefficient of three models, which are №8, №9 and №10, is less than hydraulic resistance of normative tube column. This has result from the fact that the flow in these three models differs from the flow in tube column. Flow in models №8, №9 and №10 may be observed as flow in the channel with periodical cross runaround of the tube. Whereas walls of the channel are substituted by membrane panels with cross-sectional runaround. Having such a flow, the swirl zones on two walls behind the half-cylinder are somewhat smaller than behind the tubes in tube column. Researches on determination of hydraulic resistance were performed under isometric and non-isometric conditions.

Generalization of experimental data allows to recommend the dependency for calculation of hydraulic resistance coefficient in elements of tubes with alternate arrangement and cross-paneled swirler devices under isometric conditions.

$$\xi = 6{,}96\,\mathrm{Re}^{-0{,}32} \tag{3}$$

In case of non-isometric flow, calculations of hydraulic resistance coefficient may be performed using the generalized formula:

$$\xi = 29{,}9\,\mathrm{Re}^{-0{,}17} \tag{4}$$

or with consideration of relative tube spacing in tube column σ1 = s1/d, σ2 = s2/d, using this formula:

$$\xi = 27{,}26 \times (\sigma_1 - 1)^{-0{,}26} \times (\sigma_2 - 1)^{-0{,}27} \times \mathrm{Re}^{-0{,}16} \tag{5}$$

Performed researches on hydrodynamics in elements of tube column with alternate arrangement and membrane and cross-sectional swirler devices showed that flow image in such elements is sophisticated and depends on form of guiding rails on of the sides.

Researched range using Reynolds number within the range of (6 ÷ 30)10^3 matches the quadratic dependence during operation [12] within the same range of Reynolds numbers. As it is known, resistance in tube column with alternate arrangement mainly depends on relative cross-sectional spacing σ_1 and it noticeably increases when resistance decreases. As for the longitudinal relative spacing σ_2, when it increases the amount of space for swirl areas also increases, and as it was shown, in some cases it may affect resistance of tube column with alternate arrangement.

For calculation of hydraulic resistance within larger range of researched or similar elements of tube columns with alternate arrangement one should consider the adjustments given in [9], [12].

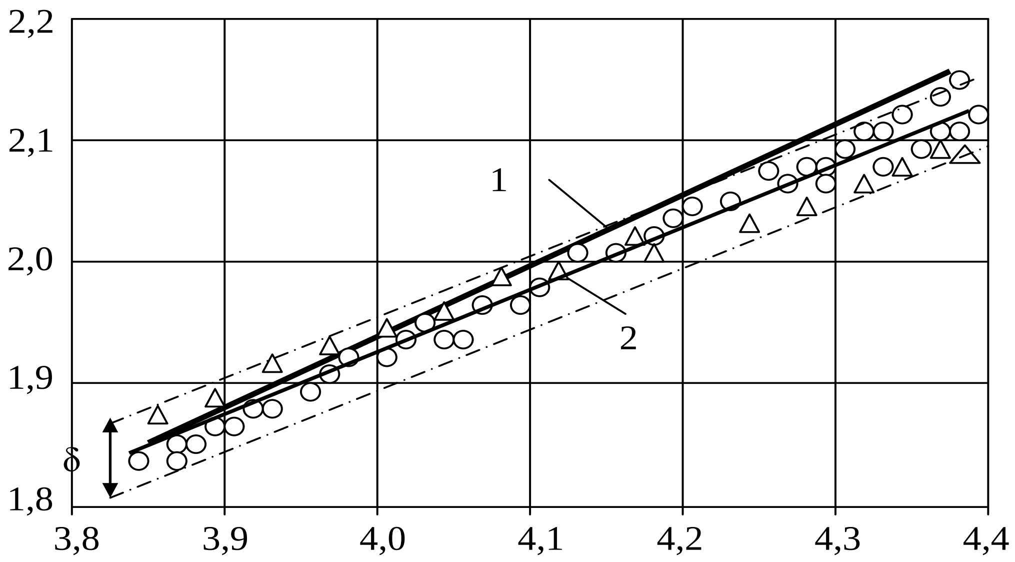
5. DETERMINATION OF HEAT TRANSFER COEFFICIENT IN ELEMENTS OF TUBE COLUMNS WITH ALTERNATE ARRANGEMENT

Along with development of boiler units, more detailed research of heat transfer in cross-sectional run-around tube columns with alternate and in-line arrangement in gas flow should be performed, and these surfaces should be considered as the most effective convective heating surfaces. Works, performed in large research centers, allowed to obtain reliable formulas for calculation of tube columns heat transfer in gas flow.

In the most general case, equations for heat transfer in cross-sectional washed tube columns with alternate arrangement under conditions of forced stationary flow of gases are presented in form of criteria in [9, 10, 13, 14]

Assuming that physical properties of airflow remain unchanged, generalization of experimental data on models simplifies a bit. During the research of heat transfer in three researched models of channels, experimental data were gathered when unit was achieving stationary heating mode.

Figure 8 shows dependencies of lgNu on lgRe for models №8, №9 and №10. For comparison purposes there is given a dependency for classic tube column with alternate arrangement.



X axis – logarithm of Reynolds number; Y axis – logarithm of Nusselt number. Legend: 1 – tube column classic alternate arrangement Nu = 0,35 × Re ^{0,6} [12], 2 – dependency obtained experimentally with three types of swirler devices (6), δ - inaccuracy.

Fig. 8. Generalization of experimental data on heat transfer in elements of tube column with alternate arrangement and swirler devices of different shape.

All experimental points are generalized by dependency as given below:

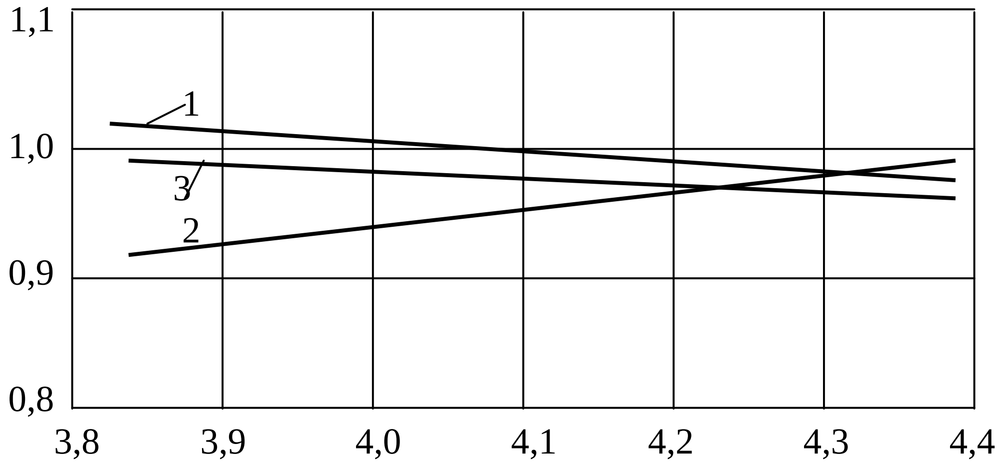
$$Nu = 0,72 \times \mathrm{Re}^{0,53} \times \mathrm{Pr}^{0,4} \quad (6)$$

Generalized formula for engineering calculations of heat transfer obtained for elements of tube column with alternate arrangement, with small amount of tube in transverse row and relative spacing σ_1 = 1,26, and σ_2 = 1,5, within the range of Reynolds numbers.

Diameter of tubes of tube column elements was considered as typical size. During determination of Reynolds criteria the speed was calculated at the most narrow pass-through section of tube column. Heat transfer coefficient α is related to total surface of heat transfer from the side of air. Complete surface comprises of tube surface, membrane surface, surface of the upper panel with transverse swirler devices and outer isolation.

Within the Re numbers = 6000 ÷ 18000 (within this range convective heating surfaces of boiler units are operating) for model №9, which are shown on the Figure 9, the biggest amount of heat transfer was received in comparison with models №8 and №10. This has result from the fact that in case of small speed values the panel swirler device of model №9 directs the flow onto the side surface of the tube. Therefore, increases the tube's perimeter, operated with higher heat transfer coefficient within the range of about 90° degrees, whereas in case of ordinary tube columns with alternate arrangement the heat transfer coefficient is minimal. Hydraulic resistance within this range of Re number remains the same as in models №8 and №10 (Figure 7). As the Re number increases up to 18000, heat transfer rate of model №9 becomes less than in models №8 and №10. However, in this case the hydraulic resistance of model №9 growth significantly. This has result from the fact of presence of serious swirl areas behind paneled swirler devices, which have a negative impact on the heat transfer rate as well. Heat transfer rate of model №8 increases as the Reynolds number goes over 18000. The flow mode analogous to the cylinder runaround in curved channel becomes specific for the model №8. Heat transfer for the model №10, with swirler device in form of panels with bent edge lays in the range between heat transfer rates of model №8 and №9.

Within the whole researched range of speeds the relation of heat transfer to classic tube column with alternate arrangement on these three models is less than 1, except the model №9 (Figure 9). Within the range of Reynolds number from 6000 to 18000 relation of Nu9/ Nu is more than 1.



X axis – logarithm of Reynolds number; Y axis – relation of Nui/ Nu. Legend: 1 – with panel – halves of tubes, 3 – Γ – shaped panels.

Fig. 9. Comparison of heat transfer in elements of tube column with alternate and classic alternate arrangement.

Experimentally it was shown that for the tube columns with alternate arrangement and small amount of tubes in a transverse row, the best thermal engineering parameters have transverse swirler devices (model №9), in comparison with half tubes (model №8) or Γ – shaped panels (model №10). Maximal heat transfer is possible if panel width equal to $[(2)^{0,5}/2] \times d_{tube}$ and its arrangement under 45° angle in relation to ceiling. Whereas the edge of the panel that is extended and exposed to the flow, matches the edge forming the half tube of the ordinary tube column with alternate arrangement.

Thus, having swirler devices mounted on the wall of the gas pass located behind the screen, and in case of cross runaround of tubes along with high temperature of gases (870 ÷ 970)°K, one may expect the increase of heat transfer rates as in the tube column with classic alternate arrangement due to additional radiant heat coming from the wall. Researched tube column with alternate arrangement with paneled swirler device is suggested for implementation on convective surface of steel hot-water boilers operated on natural gas and diesel fuel.

6. CONCLUSION

Basing on performed experiments it is possible to make a conclusion that: in the gas pass with swirler devices located behind screens, and in case of cross runaround of tube along with high temperature of gases (870 ÷ 970) °K, one may expect the increase of heat transfer rates which would be higher than those in the tube column with classic alternate arrangement and large amount of tubes in transverse row.

It was shown that for tube column with classic alternate arrangement and small amount of tubes in transverse row, the best heat-engineering characteristics are provided by transverse swirler devices. Maximal heat transfer may be achieved if panel width would be equal to [(2)0,5/2] ×dtube and its arrangement under 45° angle in relation to ceiling. Whereas the cross-section determined by extended part of the panel's edge and exposed to the flow, matches the cross-section of each next row of tubes forming elements of tube column with alternate arrangement.

There were obtained generalized formulas for engineering calculations of heat transfer in elements of tube column with alternate arrangement and small amount of tubes in transverse row and relative spacing $\sigma_1 = 1{,}26$, and $\sigma_2 = 1{,}5$, within the range of Reynolds numbers $(5 \div 28) \times 10^3$.

Advantages of the proposed construction of the boiler are in increase the heat removal by using 100% surface of the furnace screen tubes in the active heat transfer and optimize the relative size of the flue off-screen.

Research results and designs of convective pack suggested for implementation in convective surface of steel hot-water boilers produced in Republic of Kazakhstan and operated on natural gas and diesel fuel.

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