About mathematical modeling of aerodynamic characteristics in devices with a leakage of the impact systems of plane-parallel streams on the heat exchange surface

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Abstract. The article is devoted to the development of the general aerodynamic theory in case of a leakage by the systems of plane-parallel impact jets on the plane heat exchange surface [1-2]. An analytical generalization of data on aerodynamic resistance with the blowout of flat surface by the system of the plane-parallel impact jets was implemented. These data were obtained as a result of the application of mathematical theory of planning an experiment. The equations of regression are the mathematical model of process. Functional dependences between the constructive factors and the regime parameters of these first obtained experimental dependences on aerodynamic resistance in the jet heat exchangers with the leakage of air in the form of the system of plane-parallel jets were established. Results of work can be used in developing of different methods of calculation for various new designs of highly effective heat exchangers or their optimization for various branches.

1 Introduction

The problem of development of ways of an intensification of heat exchange, economic on energy consumption, in devices with the jet streams creating in them turbulent structures which define a heat mass exchange is very actual [1-29].

Delivery of the heat carrier in case of impact stream system accumulating on a heat exchange surface perpendicularly to her is used for inlet or outlet of thermal streams with big density and allows to increase considerably intensity of heat exchange in the devices which are used in energetic for cooling of shovels of turbines, in aircraft technical, in metallurgical industry, in heat treatment and drying of various materials, in heat exchangers for various branches of equipment. In recent years impact streams are used in cooling systems of the central processors and graphic chips of the electronic-computing equipment, bipolar transistors in converters of electric current, chips and power modules of the telecommunication equipment [3].

Although the questions of heat exchange are studied rather in detail, there are obviously not enough results of research of the aerodynamic characteristics and their analytical

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generalizations suitable for practical application in engineering practice.

There were recently some works which were devoted to studying of mechanism of influencing of hydrodynamic structures on convective heat transfer in turbulent flows of heat carrier. In the work which was performed at the Ural state technical university (The Ural polytechnic institute) [4] an author investigated structural and hydrodynamic conditions of increase in a heat transfer in the impact streams, including structural and dynamic factors of the heat exchange in an axisymmetric stream, influence on hydrodynamics and heat exchange with a barrier to a twist of an impact stream, influence of changing of a form in cross section of the channel which was forming a spray on a current and a heat transfer, and also an interaction hydromechanics in case of combination of impact streams in to complexes. Particularly it was shown in this work that significant increase of heat transfer (in 1.8 times) can be provided with an application of the channel which was forming a spray with a form of the cross section which isn't possessing full symmetry (for example, a triangle, a square). Increase in intensity of heat exchange is explained by increase in tangential and radial gradients of the field of pressure a barrier (i.e. complication of topography) in comparison with an axisymmetric stream that leads to creation of additional turbulent overflows. But this question was investigated only for single impact streams.

An effect of changing of a configuration in a secondary fan stream consisting in a surface of a barrier had a hydrodynamic form which repeats a form of the spray forming channel was revealed in the work [5] which is logical development of the previous one.

Some works had appeared on hydrodynamics in the pulsing and twirled impact streams [6- 8]. For example the numerical analysis of hydrodynamic and thermal processes which took place in the pulsing impact streams was made in work [8]. Influence of a tilt angle, amplitude and frequency of pulsations of speed of a stream on hydrodynamic characteristics was shown. Topological features of the twirled impact currents were studied at National Research Nuclear University "MIFI" [6]. Different ways of visualization of vortex structure of a stream and an acoustic method were used. The obtained experimental data showed that an emergence of a sound resonance corresponded to forming of three-dimensional steady large-scale vortex structures in the form of toroidal spiral whirlwinds in the area before a barrier. But there is no generalization of the obtained experimental data in the form of analytical dependences in this work.

For the case of interaction of an internal boundary layer with an external layer (stream) existence of special coherent structures by practical consideration in thin wall streams was revealed in work [4]. The intensification of heat exchange occurred owing to destruction of an internal interface because the main bearing hydrodynamic structure transported the system of micro whirlwinds to a heat exchange surface.

At the same time the following situation moved forward (it was quoted from [4]): "Extensive material on the discussed subject was saved up and an impression was made apparently that further progress in studying of turbulence should be expected in the direction of theoretical judgment. Great success in the field of computer facilities had led to the overestimated assessment of opportunities of computer modeling in processes of transfer. However the break in understanding of the nature of a whirl hadn't occurred in this discussed direction. The theory substantially begins to become isolated on itself, productive dialogue with experiment weakens. The proof to that is lack of an answer to a question: Which experience or a complex of experiments should be put to receive necessary data for creation of a new impulse in understanding of a physical essence of turbulence of processes of heat exchange at such movement? Even a little developed list of identification signs of existence of various coherent structures and their roles in transfer processes wasn't made. There was no theoretical generalization of results of the ordered structures in heat transfer actually on this background. There are only separate data. Including all circumstances it will be rational to return back to active accumulation of fund of experimental data with coordinating for this effort of scientists from various specialties".

The type of a barrier is exerted the great influence on aerodynamic characteristics of a stream with impact leakage of the flow system. For example this heat exchange surface may have spherical cavities on it. It is possible to use different types of nozzle openings from which streams expire (plane-parallel, axisymmetric and asymmetrical). The scheme of withdrawal of the fulfilled stream, unevenness of a profile of speed and level of turbulence in the initial section of a stream, passive and active turbulizers are also exerted the considerable impact on the process [1, 2, 9].

2 Methods

It is necessary to know all aerodynamic characteristics of a stream which define the heat transfer intensity from a heat exchange surface for the analytical solution of problems of the interfaced heat exchange which need to be solved in calculating of new designs with an impact leakage of streams. Analytical decisions for the differential equations with private derivatives which describe a current of gaseous environments with difficult hydrodynamics and also systems of the differential equations for cases of difficult hydrodynamics are received only in very limited number of cases.

The received results are very often have insufficient reliability because of a large number of assumptions. Therefore analytical research of a current of gaseous environments is often limited to linear mathematical models, a priory model decisions and different approximate methods (especially in multidimensional cases) [10].

Bases of experimental and settlement data which are available for consideration are very limited. For example it wasn't possible to find such results of investigation of aerodynamic characteristics in special case of systems of the plane-parallel streams with rectangle form of the cross section of the channel which was forming a spray especially at small values of Reynold's numbers Re [1- 2].

Calculations of processes of heat exchange and aerodynamics on a heat exchange surface (barrier) under difficult conditions in which systems of streams leaked this surface can be executed rather precisely in case of using of empirical dependences which are received with use of methods of the theory of similarity [1, 2, 11].

An expense of the heat carrier is much more in system of plane-parallel impact streams than in multirow system of axisymmetric streams at identical regime and constructive factors (expiration speed, distances s on axes of streams, width of b of a slot-hole nozzle equal to diameter). Therefore use of systems with a big relative step of s/b and therefore bigger size s is advisable.

At the same time it is necessary to provide small difference of temperatures [12-14] along a heat exchange wall in the direction, perpendicular to streams for an exception of temperature straining and ensuring durability of a design of the heat exchange device. But this difference depends not only on dimensionless distance of s/b, but also on an absolute value s of distance between axes of streams and distance h from a nozzle cut to a surface of heat exchange.

Therefore the decision to find dependence of parameters on the following factors has been made: s; s/b; h/b; Re.

The description of experimental installation, technique of carrying out experiment, designation and some results were provided in works [11,16]. Complete factorial experiment of type 2^4 was used. The matrix of planning was given in [15]. Series A in this article conforms to series 5 and series B conforms to series 6 in [16]. Levels and intervals of a variation of factors in A and B series of experiments are given in standard and logarithmic space of coordinates in the tables 1 and 2.

Table 1. Levels and intervals of a variation of factors in A and B series of experiments in standard space of coordinates.

Factors	Centre of the plan	Interval of variation	High level	Low level
Series A				
$x_1 = s$	0.06	0.02	0.08	0.04
$x_2 = s/b$	33.335	6.665	40	26.67
$x_3 = h/b$	5	3	8	2
$x_4 =$ Re	892.5	177.5	1070	715
Series B				
$x_1 = s$	0.06	0.02	0.08	0.04
$x_2 = s/b$	33.335	6.665	40	26.67
$x_3 = h/b$	15	5	20	10
$x_4 =$ Re	892.5	177.5	1070	715

Table 1. Levels and intervals of a variation of factors in A and B series of experiments in logarithmic space of coordinates.

Factors	Centre of the plan	Interval of variation	High level	Low level
Series A				
$x_1 = \ln s$	56.571	0.3465	4.382	3.689
$x_2 = \ln s/b$	32.671	0.2025	3.689	3.284
$x_3 = \ln h/b$	3.999	0.693	2.079	0.693
$x_4 = \ln$ Re	874.36	0.2015	6.975	6.572
Series B				
$x_1 = \ln s$	56.571	0.3465	4.382	3.689
$x_2 = \ln s/b$	32.671	0.2025	3.689	3.284
$x_3 = \ln h/b$	14.154	0.3465	2.996	2.303
$x_4 = \ln$ Re	874.36	0.2015	6.975	6.572

3 Results, discussion

Average values of aerodynamic resistance are presented in table 3.

Table 3. Average values of aerodynamic resistance, Pa.

Number of experiment	Series A	Series B
1	46.4	44.3
2	24.0	22.4
3	102.7	99
4	38.2	36.9
5	47.86	44.7
6	24.8	23.0
7	104.25	101.5
8	39.6	37.0
9	29.6	27.4
10	12.5	11.5
11	50.2	48.76
12	12	19.66
13	13	28.0
14	14	12.2
15	15	49.0
16	21.6	19.69

The regression equations (in logarithmic space of coordinates) which are mathematical models of process have been received after checking of the importance of coefficients and a number of transformations:
Series A

$$\Delta P_b = 1.2 \cdot 10^{-5}\,\mathrm{Re}^{1,4743}\left(\frac{s}{b}\right)^{1.4049}\left(\frac{s}{0.05657}\right)^{1.0652-0.6528\ln\left(\frac{s}{b}\right)} \quad (1)$$

This equation can be replaced with relatively rather simpler:

$$\Delta P_b = 3.7 \cdot 10^{-7}\,\mathrm{Re}^{1.4743}\left(\frac{s}{b}\right)^{1.4049}(s)^{-1.2107}, \quad (2)$$

$$\Delta P_b = 3.7 \cdot 10^{-7}\,\mathrm{Re}^{1.4743}\left(\frac{s}{b}\right)^{0.1942}(b)^{-1.2107}. \quad (3)$$

The results of calculations which were executed on these three equations are differing no more than for 6%.
Series B

$$\Delta P_b = 6.04 \cdot 10^{-6}\,\mathrm{Re}^{1.531}\left(\frac{s}{b}\right)^{1.4686}\left(\frac{s}{0.05657}\right)^{1.1241-0.6771\ln\left(\frac{s}{b}\right)}. \quad (4)$$

We will replace the equation to simpler (results of calculations will differ no more than for 4%):

$$\Delta P_b = 1.8 \cdot 10^{-7}\,\mathrm{Re}^{1.531}\left(\frac{s}{b}\right)^{1.4686}(s)^{-1.2364}, \quad (5)$$

$$\Delta P_b = 1.8 \cdot 10^{-7}\,\mathrm{Re}^{1.531}\left(\frac{s}{b}\right)^{0.2322}(b)^{-1.2364}. \quad (6)$$

Check on F_T – criterion (tabular value of Fischer's criterion) showed that all received equations adequately described the experimental data. Width of a slot-hole nozzle through which air moved on a heat exchange surface in the form of system of plane-parallel streams was taken like defining size for calculation of Reynold's number. Air temperature on a nozzle cut was taken like the defining temperature:

$$\mathrm{Re} = \frac{b\,\omega}{\nu},$$

speed of the expiration of air jets was determined by a formula:

$$\omega = \frac{V}{3600 nLb},$$

where n – quantity of slot-hole nozzles;
L – length of a slot-hole nozzle, m.

Dependence of aerodynamic resistance from the distance between a nozzle and a heat exchange surface at various expenses of air from 416.7 to 1250 $m^3/(h\ m^2)$, width of a slot-hole nozzle and distances between them were presented on the Fig.1.

It was followed from the schedule that the dimensionless distance of h/b had little effect on aerodynamic resistance in the studied range. If h/b was growing, then aerodynamic resistance was decreasing a little. Much stronger impact was exerted by the change of width of a slot-hole nozzle (at constant distances on axes of streams), change of the distance between the slot-hole nozzles with their constant width and of course changes of a consumption of air. It was confirmed by the equations of regression (1-9) [1], (1-6) and also data which were provided in the table. It was followed from them that in all range of change for *h/b* from 2 to the 20th distance from a nozzle cut to a heat exchange surface practically didn't exert impact on aerodynamic resistance. Aerodynamic resistance increased with growth of Re, *s/b* and with reduction of width of a slot-hole nozzle of *b*.

In the table 2 levels and intervals for variation factors of distance *s* on axes of streams and width of a slot-hole nozzle *b* in logarithmic space of coordinates were calculated for the case of *s* and *b* have dimension of millimeters. Further equations of regression which were received were transformed for dimension of meters.

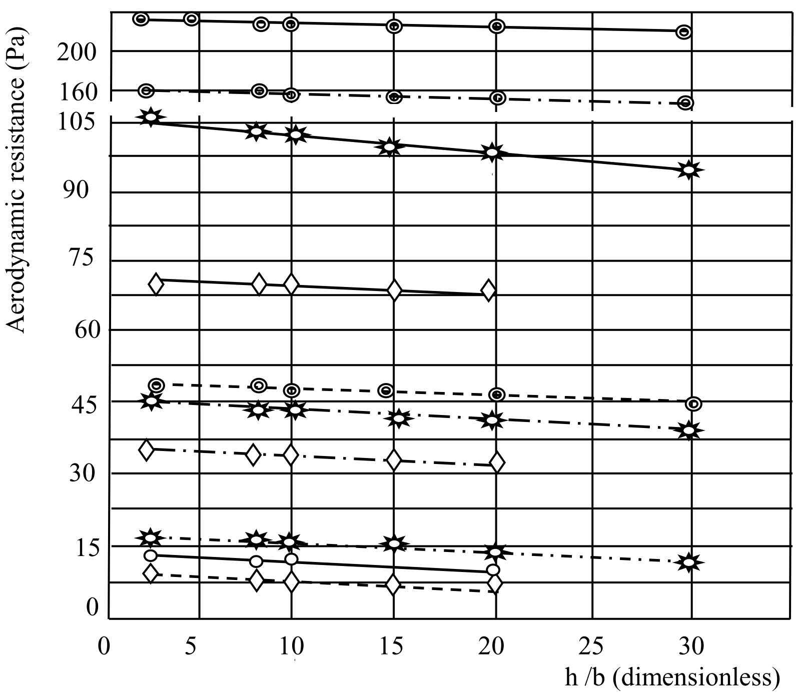

Fig. 1. Dependence of aerodynamic resistance on distance from the heat exchange surface to a nozzle cut at various constructive characteristics and expenses of air:

———— V = 165 m³/h (ϑ -1250 m³/(h m²)),

– · – · – · – V = 110 m³/h (ϑ -833.3 m³/(h m²)),

– – – – – – – V = 55 m³/h (ϑ - 416.7 m³/(h m²)).

◎ – *s* = 0.08 m; *b* = 0.001m,

✹ – *s* = 0.04 m; *b* = 0.001m,

◇ – *s* = 0.08 m; *b* = 0.003m,

○ – *s* = 0.04 m; *b* = 0.003m.

4 Conclusion

Copyright certificates and the patents which were obtained by the author of the present article (in a co-authorship) and listed in [25] are quite successfully introduced in industrial production (on Volgograd Steel Works "Red October", Lozovsky Forging-Mechanical Plant Kharkov Tractor Plant). Their use has allowed to cut fuel consumption to 30% and to exclude a consumption of technical water that is confirmed by Acts of industrial introduction. Results of researches the part of which was given in this article can be used in developing methods for calculation of various new designs of highly effective heat exchangers or their optimization [19-23], [25-29] for various branches including recuperators with a heat carrier leakage in the form of systems of impact plane-parallel streams for heating of air due to heat of the leaving products of combustion of fuel for his economy and improvement of an ecological state. Obtained results will be useful in engineering practice for increasing of competitive advantages of specialists [30]. Work is very perspective as for implementation of the plans provided by "Power strategy of Russia till 2020" and the solution of the questions existing in world science and the industry.

Designations:

Re — Reynolds number;
b — width of a slot-hole nozzle, m;
h — distance from a nozzle cut to a surface of heat exchange, m;
s — distance on axes of streams, m;
V — expense of the heat carrier, m^3/h;
ω — heat carrier speed on a cut of a slot-hole nozzle, m/s;
ϑ — expense of the heat carrier specific (per unit area), m^3 / (h m^2);
ν — coefficient of kinematic viscosity, m^2/s;
F — surface area of heat exchange, m^2;
n — quantity of slot-hole nozzles;
L — length of a slot-hole nozzle, m;
ΔP_b — aerodynamic resistance, Pa;
F_T — tabular value of Fischer's criterion.

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