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On the mathematic simulation of the energy efficiency for heat exchangers with the systems of impingement plane-parallel jets

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Abstract. The article gives the analytical generalization of the data on the energy efficiency for heat exchangers with the flat heat exchange surface to which systems of impact plane parallel jets are sent. Functional relations of specific power consumption (per unit of area), which were obtained for the first time using the techniques of the similarity law, for moving a heat carrier are shown with regard to design and operation factors. The regression equations representing a mathematical model of the process enable to carry out an analysis of various factors impact on the parameter to be determined. The obtained results can be used to optimize or to create the calculation techniques for new highly-efficient heat exchange devices with jet plane -parallel impingement systems and also to reduce power consumption for moving a heat carrier.

1 Introduction

The upgrading of energy efficiency for a heat exchange device can be achieved by way of intensification of the heat transfer operation. This is made possible by moving a heat carrier to the heat exchange surface as various systems of impact jets. The application of this impinging jets technology ensures the upgrading of heat exchange devices efficiency (they can be used in very different industrial branches for cooling, heating, drying etc. heat exchange surfaces), enables to use less alloyed and thus cheaper steel sorts, and to make a heat exchange device more compact [1-13].

The issue of assessment and criteria of the efficiency for the newly designed heat exchangers is very important. In accordance with the Manual for the preparation of industrial feasibility studies from the UNIDO (United Nations Industrial Development Organization) [14], when creating a new project one should distinguish pre-investment, investment phases and the stage of the direct operation. These phases (apart from a direct operational one) carry out the monitoring of the efficiency of the newly offered design. At that, a profound analysis of possible versions of solution is carried out to implement the project with the least risk of making an inefficient or even a wrong decision.

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2 Methods and Results

When the proposed structure is new and there are no necessary statistic data for the practical use, it makes sense to perform an evaluation of the newly proposed structure using various criteria.

For a comparative assessment of various structures, some coefficients are needed that are equally right for different forms of convective surfaces and for any method of their heat carrier flow.

For instance, to assess the efficiency of a heat exchange unit one can use an energy efficiency factor (from V.M. Antuf'ev's work), presenting a relation of the amount of the heat transfer to the energy consumed to overcome the resistance. To exclude the temperature drop, the comparison with the energy efficiency factor should be done at ΔT= = 1 K.

If the energy consumption to overcome the aerodynamic resistance is assigned to the heat exchange surface area, then the energy efficiency factor looks as follows.

$$E = \frac{\alpha}{N_0},$$

where α - the heat transfer coefficient average over the surface, Wt/ (m^2 K);

$N_0 = \frac{N}{F}$ – the power consumption expenses for a unit of the heat exchange surface, Wt/(m^2); F - the area of the heat exchange surface, m^2.

The power consumption necessary to move a heat carrier is in proportion to the product of the expense to the aerodynamic drag (from M.A. Mikheev's work):

$$N = \frac{V\Delta P}{3600\eta},$$

where ΔP_b - the aerodynamic drag, Pa;

V - the consumption of the heat carrier, m^3/h;

η - the fan performance.

For the metal heat exchangers

$$E = \frac{K}{N_{01} + N_{02}},$$

where K - heat transfer coefficient, Wt/(m^2 K);

N_{01}, N_{02} - specific power consumption for moving a cold and hot heat carriers, Wt/(m^2 K).

It is obvious that the higher energy efficiency factor the better the heat exchange surface with all else being equal. However, the absolute value (E) cannot serve as a measure of the thermal and hydrodynamic efficiency because the energy efficiency factor value decreases with the growth of heat carrier speed resulted from the fact that the power consumption increases considerably faster than the amount of the exchanged heat.

The increase of power consumption for moving a heat carrier will result in the increase of the rate of heat exchange. This indicates greater flow turbulence in the carrier as a result of a faster speed out of the nozzles. Moreover, as was indicated in the papers of the Gas Institute from the Ukrainian Academy of Sciences and in the work which refers to these proceedings [3], the optimum value at the jets impingement can be considered a size of order 100 Wt/ m^2. Under the subsequent increase of energy loss, the heat exchange increases insignificantly, and the value of energy efficiency (in particular, the energy factor) decreases approximately by 40% (from 1.7 to 2.5 times).

But there are very few data on the impact of the change in the performance and geometric characteristics of the jet systems on the power consumption for moving a heat carrier (and thus, on the energy efficiency) in the devices with the systems of plane-parallel impact jets [15]. The given article is devoted to this issue.

The present work can be of interest for solving questions arising in the industry and science in different lands in the world. In particular, to solve problems put in the « Power Strategy of Russia till the year 2020».

The application of the obtained results will ensure the competitive advantages for specialists using them [16].

Using the techniques of the theory of similarity, one can obtain empirical dependencies to determine the specific power consumption for moving the heat carrier under the conditions of the plane-parallel jet impingement on the flat heat exchange surface [17-19]. This works show the methods of implementing experimental research in a specially designed plant. A number of tests have been carried out and part of their results is given in this article. In particular, a complete factorial experiment has been carried out of the form of 2^3.

At that, a dependency (parameter) N/F of specific power consumption was defined from the following factors: *Re* — Reynolds's number; non-dimensional ratio S/b of the distance between the jet axes S to the width of the slot-hole nozzle b — as well as a non-dimensional ratio h/b of the distance from a nozzle cut to the heat exchange surface h - to the width of a slot-hole nozzle b. When calculating a Reynolds's number, the width of a slot-hole nozzle b was taken for the characteristic dimension:

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

where ω — the heat carrier speed at an exit of a slot-hole nozzle, m/s;

ν — coefficient of kinematic viscosity, m^2/s .

The speed of the expiration of air jets was determined by:

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

where n — the quantity of slot-hole nozzles;

L — the length of a slot-hole nozzle, m.

Therefore, the dependence of the required parameter $\mathrm{N/F}$ was determined from the following factors:

$$X_1 = \mathrm{Re},\ X_2 = \frac{S}{b},\ X_3 = \frac{h}{b}.$$

The work [17] presents the levels and intervals of factor variation and the planning matrix in the ordinary and logarithmic coordinate space. Air temperature at an exit of the nozzle was taken as the defining temperature.

The regression equations in the ordinary and logarithmic coordinate space were obtained (after the checking of the importance of the coefficients). The given equations are mathematical models of the process under study.

$$\mathrm{N/F} = 29.1992 + 25.6815X_1 + 16.1747X_2 + 14.1844X_1X_2 \tag{1}$$

$$\mathrm{N/F} = 2.489\cdot 10^{-9}\cdot \mathrm{Re}^{2.5038}\cdot\left(\frac{S}{b}\right)^{1.153} \tag{2}$$

In the latter two dependences (1) and (2), the value of the *Re* number was changing from 715 to 2150, $\frac{S}{b}$ - from 26.67 to 80 , $\frac{h}{b}$ correspondingly from 2 to 8, S = 0.08 м.

$$\mathrm{N/F} = 28.7799 + 25.3825X_1 + 16.1191X_2 + 14.0917X_1X_2 \tag{3}$$

$$\mathrm{N/F} = 0.12478\cdot\left(\frac{\mathrm{Re}}{1240.165}\right)^{2.9053-0.09256\cdot\ln\left(\frac{S}{b}\right)}\cdot\left(\frac{S}{b}\right)^{1.1989}\cdot\left(\frac{h}{b}\right)^{-0.0419} \tag{4}$$

For formulas (3) and (4), the value of the *Re* number was changing within 715 and 2150, and the values $\frac{S}{b}$ from 26.67 to 80, $\frac{h}{b}$ from10 to 20, S = 0.08 м.

$$\mathrm{N/F} = 10.885 + 9.297X_1 + 8.041X_2 + 7.87X_1X_2 \tag{5}$$

$$\mathrm{N/F} = 0.1546\cdot\left(\frac{\mathrm{Re}}{620.794}\right)^{1.5991\ln\left(\frac{S}{b}\right)-3.1317}\cdot\left(\frac{S}{b}\right)^{1.0675} \tag{6}$$

For formulas (5) and (6), the *Re* number value was changing from 360 to1070, $\frac{S}{b}$ from 13.33 to 40, $\frac{h}{b}$ from 2 to 8, S = 0.04 м.

$$\mathrm{N/F} = 10.345 + 8.9931X_1 + 7.8876X_2 - 0.1358X_3 + 7.5808X_1X_2 \tag{7}$$

$$\mathrm{N/F} = 0.088116\cdot\left(\frac{\mathrm{Re}}{620.794}\right)^{1.4479\cdot\ln\left(\frac{S}{b}\right)-2.5503}\cdot\left(\frac{S}{b}\right)^{1.2078} \tag{8}$$

In the latter two formulas, the Re number value was changing from 360 to 1070, $\frac{S}{b}$ - from 13.33 to 40 , $\frac{h}{b}$ - from 10 to 20, S = 0.04 м.

The check by the tabular value of Fischer's criterion (F_T – criterion) showed that all the received equations described the experimental data adequately.

3 Discussions

The formulas' analysis enables to make a conclusion that the distance from the nozzle cut to the heat exchange surface does not influence the power consumption per a heat exchange surface unit for $\frac{h}{b}$, changing from 2 to 8 (equations (1), (2), (5),(6)), and for $\frac{h}{b}$, changing from 10 to 20 – has a very insignificant impact, with the increase of factor *X3=h/b* leads to the decrease of N/F.

Fig. 1 shows the variation of the Nusselt number from the specific (per surface unit) power consumption for the air moving at the non-dimensional distance *h/b*=10. The power consumption increase has a significant impact on the heat exchange rate and is the greater, the less the open surface and the width of the slot-hole nozzle are. Thus, when increasing *N/F* from 10 to 70 Wt/ m^2 at *s/b*=80, *b*=0.001 m the Nusselt number increases from 3.5 to 6 (by 1.7 times), and at *s/b*=13.3, *b*= 0.003m – from 15.5 to 23.5 (that is by 1.5 times).

At the same width of the slot, the increase of *s/b* by 2 times results in the increase of the heat exchange rate approximately by 15% at the constant value of *N/F*. With that, the increase of the slot width by 2 times at the constant s/b and *N/F*, does not have a practical impact on the heat transfer factor value α. At preset values of *N* and *F*, the increase of the jet number results in the heat exchange enhancement which is confirmed in Fig.1.

4 Conclusion

The author of the given article received (along with co-authors) a number of copyright certificates and a patent mentioned in the work [20]. Their introduction in Ukraine at the Lozovsky Forging and Mechanical Plant at Kharkov Tractor Plant and in the Russian Federation at Volgograd Steel Works "Red October" enabled to eliminate the consumption of industrial water and the reduction of the natural gas consumption to 30 percent. The obtained results were confirmed by the acts of implementation. The research results given in the article have a potential for the development or optimization of designs of new heat exchangers with plane-parallel jet impingement as well they can be useful to develop their calculation procedure.

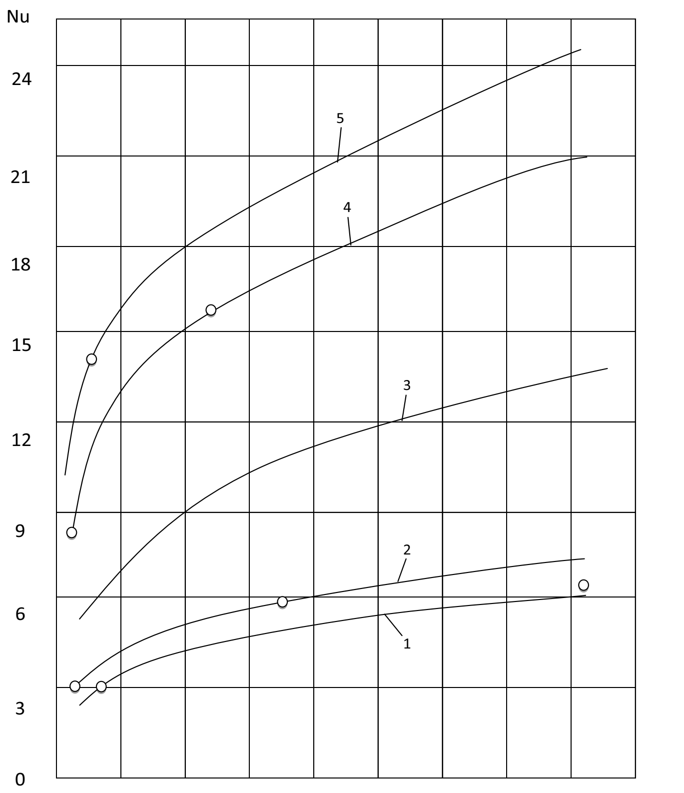

Fig.1. The dependence of the number *Nu* on the specific power consumption at *h/b* = 10
1 – *b* = 0.001 m; *S /b*=80; 2 – *b* = 0.001 m; *S /b*=40; 3 – *b* = 0.002 m; *S /b*=40;
4 – *b* = 0.003 m; *S /b*=26.67;5 – *b* = 0.003 m; *S /b*=13.3.
-------- - formula evaluation; ○ - the test data.

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