Assessment of energy efficiency of channel with nozzles

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Abstract. An algorithm for calculating the energy coefficient has been obtained, which makes it possible to estimate the efficiency of channel with various heat exchange intensifiers in the form of chaotic nozzle elements. The numerical study results are presented in the form of relationship between the energy coefficient $E_d$ and the Reynolds number $Re_e$. This made it possible to assess these heat exchange intensifiers from the point of view of energy efficiency and to determine the most optimal ones.

1. Introduction
Heat exchangers account for up to 70% of material and energy intensity of power and petrochemical production. The utilized heat exchange equipment is characterized by extreme diversity. Many enterprises pose a task of increasing thermal and hydrodynamic efficiency of heat exchange equipment.

The most acute problem is intensification of heat transfer in heat exchangers, where viscous media are used as a working medium, since due to low flow rates ($Re<500$), such heat exchangers are characterized by low intensity of heat exchange.

To increase efficiency of heat exchange processes, various methods of intensification are used. The choice of one or another method of heat exchange intensification is carried out taking into account a variety of factors, since the composition, thermal physical properties of working media, and operating modes of devices vary in wide ranges.

Basing on research analysis on the use of various types of intensifiers [1-4], it can be concluded that application of intensification methods using chaotic nozzle elements is very effective both for upgrading the existing equipment and for newly designed ones.

The conducted analysis [5, 6] shows that usage of chaotic nozzle elements in channels improves the efficiency of heat transfer. This is achieved as a result of increased flow turbulence, which leads to a decrease in thermal resistance to convective heat transfer exerted by the boundary layer, or to direct destruction and turbulization of the boundary layer itself. But at the same time, the use of chaotic nozzle elements, as well as other methods of intensification of heat exchange processes, leads, as a rule, to an increase in thermodynamic indices of the systems under consideration, which in some cases increases much faster than the heat transfer coefficient. However, with a rational approach to choice of heat transfer intensifier, it is possible to significantly intensify heat transfer and reduce the overall dimensions and weight of the apparatus. Therefore, the task of choosing an intensifier is steel on the top of its relevancy.

There are various ways to assess the energy efficiency of application of various intensifiers [7, 8]. However it is important to note that parameters characterizing the perfection of heat exchange
equipment are interconnected, so while improving one of the qualities, the other one deteriorates. Therefore, the assessment of energy efficiency of heat transfer intensifier application is a relevant topic.

This article is devoted to assessing the effectiveness of application of an intensifier of heat exchange in the form of various nozzle elements. The other task is to assess the influence of its geometrical parameters on the heat-hydraulic performance of a heat exchanger.

2. Energy coefficient

To select energy-efficient and energy-saving intensifiers, we consider the method proposed by M.V. Kirpichev and V.M. Antufiev. This method is based on determination of energy coefficient $E_d$, which characterizes the heat-hydraulic perfection of heat exchange process around a certain surface [9].

According to expression of V.M. Antufiev the energy coefficient has a known form [9]

$$E_d = \frac{\alpha \cdot F}{N},$$

(1)

where $\alpha$ is heat transfer coefficient, $W/(m^2 \cdot K)$; $F$ is surface area of heat exchange, $m^2$; $N$ is supplied power, $W$.

Surface area of heat exchange for a channel with nozzle we determine as [10,11]:

$$F = S \cdot H \cdot a_v,$$

(2)

where $S$ is cross section area of channel with nozzle, $m^2$; $H$ is nozzle layer length, m; $a_v$ is specific surface of nozzle, $m^2/m^3$.

Power supplied for pumping of medium is [12]:

$$N = u_0 \cdot S \cdot \Delta P,$$

(3)

where $u_0$ is medium velocity in a channel with nozzle, $m/s$; $\Delta P$ is pressure difference, Pa.

Thus, taking into account expressions (2) and (3), we write the energy coefficient in the following form

$$E_d = \frac{\alpha \cdot H \cdot a_v}{u_0 \cdot \Delta P},$$

(4)

Pressure difference in a channel with nozzle is [13]

$$\Delta P = \frac{\xi \cdot H \cdot \rho \cdot u_0^2}{2 \cdot \varepsilon_{void}} d_e,$$

(5)

where $\xi$ is friction resistance coefficient; $d_e = 4 \cdot \varepsilon_{void}/a_v$ is equivalent diameter of nozzle, m; $\rho$ is medium density, $kg/m^3$; $\varepsilon_{void}$ is specific void space of nozzle, $m^3/m^3$.

Taking into account the expression (5) the energy coefficient takes the following form:

$$E_d = \frac{\alpha \cdot H \cdot a_v \cdot 2 \cdot \varepsilon_{void}^2 \cdot d_e}{u_0^3 \cdot \varepsilon \cdot H \cdot \rho} = \frac{8 \cdot \alpha}{u_{av}^3 \cdot \varepsilon \cdot \rho},$$

(6)

where $u_{av}$ is average velocity of medium in nozzle, m/s.

By expressing the heat transfer coefficient through the dimensionless Nusselt complex $\frac{\varepsilon_{void}}{\varepsilon}$, the expression (6) is written as

$$E_d = \frac{8 \cdot \frac{\varepsilon_{void}}{\varepsilon} \cdot \lambda}{u_{av}^3 \cdot \varepsilon \cdot \rho \cdot d_e},$$

(7)

where $\lambda$ is thermal conductivity coefficient, $W/(m \cdot K)$. 

An expression for determining the average heat transfer coefficient in a channel filled with chaotic nozzle elements was obtained in [14] using the Owen boundary layer model with a turbulent viscosity function taking into account pulsations damping in a viscous sublayer, which has the form

$$\text{Nu}_e = \frac{1.85 \cdot \text{Re}_e^{0.75} \cdot \text{Pr}^{0.333} \cdot (\frac{\xi}{2})^{0.25}}{1.48 \cdot \text{Re}_e^{0.125} / \xi^{0.25} + 2.5 \ln \left(4 \cdot \text{Re}_e^{0.125} \cdot \xi^{0.5}\right)},$$

where \( \text{Re}_e = u_{av} \cdot d_e / \nu \) is equivalent Reynolds number; \( \text{Pr} \) is Prandtl number.

Also, the heat transfer coefficient can be expressed in terms of the average thermal number of Stanton \( \text{St}_{T} \), and then the expression for energy coefficient will take the form

$$E_d = \frac{8 \cdot \text{St}_T \cdot c_p}{u_{av} \cdot \xi},$$

where \( c_p \) is heat capacity at constant pressure, J/(kg·K).

The average thermal number of Stanton \( \text{St}_T \) we find using expression (8) [15]

$$\text{St}_T = \frac{1.85 \cdot (\frac{\xi}{2})^{0.25}}{\text{Re}_e^{0.25} \cdot \text{Pr}^{0.667} \left[1.48 \cdot \text{Re}_e^{0.125} / \xi^{0.25} + 2.5 \ln \left(4 \cdot \text{Re}_e^{0.125} \cdot \xi^{0.5}\right)\right]}$$

Thus, the greater is the energy coefficient \( E_d \), the more efficient from an energetic point of view is the channel (apparatus) with intensification elements in the form of chaotic nozzle elements.

3. Results and discussions

As an example, we consider the following problem: it is necessary to determine the most energy-efficient intensifier in a form of chaotic nozzle elements, during the heat exchange process.

A smooth pipe was considered as a basic thermal element, and the following nozzles were considered as intensifiers:

1) Ceramic Berl saddles (size is 25 mm) with technical characteristics: \( d_e = 0.011 \) m, \( a_v = 260 \) m\(^2\)/m\(^3\), \( \varepsilon_{\text{void}} = 0.69 \) m\(^3\)/m\(^3\).

2) Ceramic Pall rings (size is 25 mm) with technical characteristics: \( d_e = 0.012 \) m, \( a_v = 250 \) m\(^2\)/m\(^3\), \( \varepsilon_{\text{void}} = 0.74 \) m\(^3\)/m\(^3\).

3) Ceramic Racshig rings (size is 25 mm) with technical characteristics: \( d_e = 0.015 \) m, \( a_v = 200 \) m\(^2\)/m\(^3\), \( \varepsilon_{\text{void}} = 0.74 \) m\(^3\)/m\(^3\).

Initial data is the following:

- Medium is MS-20 oil;
- Coefficient of oil kinematic viscosity \( \nu = 2.68 \cdot 10^{-4} \) m\(^2\)/s;
- Oil thermal conductivity coefficient \( \lambda = 0.131 \) W/(m·K);
- Medium density \( \rho = 881 \) kg/m\(^3\);
- Prandtl number \( \text{Pr} = 3780 \);
- The average oil velocity \( u_{av} \) varied in the range 1.25–2.25 m/s.

We apply the obtained expressions for determining the energy coefficient for solving the posed problem.

Basing on the calculations, we plot the relationship between energy coefficient \( E_d \) and the Reynolds number \( \text{Re}_e \). Figure 1 shows the obtained relationships for intensifiers under consideration.
The calculated data show that application of chaotic nozzle elements consisting of Berl ceramic saddles as heat transfer intensifier is the most beneficial from energetic point of view. For all three intensifiers, we see that with an increase in the Reynolds number $Re_e$, the power supplied for medium pumping rapidly increases in proportion to the increase in the average velocity $u_{av3}$, thereby the value of the energy coefficient decreases.

4. Conclusions
This method for assessing energy efficiency allows performing comparison of intensifiers of various shapes and sizes, which is convenient when choosing the most energy-efficient and energy-saving intensifier. Also it allows obtaining technical solutions for the optimal energy-saving intensifier both at the equipment design stages and during industrial tests.

References
[1] Chennakesavan B A I 1960 Ch.E Journal 6(2) 246-50
[2] Koch R 1958 VDL Forschung-Heft 469 Dusseldorf
[3] Laptev A G, Farakhov T M, Lapteva E A 2015 Models of transport phenomena in disordered nozzle and granular layers Teoreticheskie osnovy himicheskoj tehnologii 49(4) 404-14
[4] Laptev A G, Basharov M M 2016 Efficiency of heat and mass transfer and separation of heterogeneous media in petrochemical apparatus Kazan: Center of innovation technology 344
[5] Laptev A G, Dudarovskaya O G, Farakhov T M 2016 Intensification of heat transfer in channels under laminar mode. Energetika Tatarstana 1 33-35
[6] Alekseev K A 2016 Flow hydrodynamics in static mixers of nozzle type: PhD thesis. Kazan: KNITU 170
[7] Demenok S L, Sivukha S M, Medvedev V V 2015 Hydrodynamics and heat exchange in ball laying Strata: St. Petersburg 192
[8] Laptev A G, Dudarovskaya O G, Farakhov T M 2016 Evaluation of energy efficiency of methods for heat transfer intensification in viscous media. Vestnik Kazanskogo tehnologicheskogo universiteta 19(6) 59-63
[9] Gortyshov Yu F, Olimpiiev V V, Baigaliev B E 2004 Heat-hydraulic calculation and design of equipment with intensified heat exchange Kazan: Publishing house of Kazan State Technical University 432
[10] Laptev A G, Farakhov T M, Dudarovskaya O G 2015 Mathematical model of mixing of liquids with dispersed phase under laminar and turbulent regimes in nozzle mixers Teoreticheskie osnovy himicheskoj tehnologii 49(1) 23-32
[11] Laptev A G, Farakhov T M, Lapteva E A 2015 Mathematical model of heat transfer in channels with nozzles and granular layers Power Engineering 177-80
[12] Farakhov M I, Laptev A G, Basharov M M 2015 Modernization of mass transfer apparatus by new nozzles in chemical technology Teoreticheskie osnovy himicheskoj tehnologii 49(3) 247-252
[13] Kagan A M, Laptev A G, Pushnov A S, Farakhov M I 2013 Contact tips of industrial heat and mass transfer apparatus Kazan: Fatherland 454
[14] Dudarovskaya O G 2016 Models of intensified heat mass transfer and mixing of media in channels with chaotic nozzle layers: PhD thesis Kazan 202
[15] Laptev A G, Farakhov T M, Dudarovskaya O G 2016 Efficiency of transport phenomena in channels with chaotic nozzle layers Strata: St. Petersburg 202