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Features of Calculating the Characteristics of Energy Complexes Using Low-Grade Energy

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ABSTRACT

The development of stationary energy seems to be an important aspect of introduction of energy-saving technologies in transportation sector. In Russia, it is conditioned by the main provisions of the Energy Strategy of the Russian Federation until 2030. In this regard, the problem of efficient use of low-grade heat based on the organic Rankine cycle (ORC) in stationary heat energy supply units in the transport industry is urgent. In particular, this task is typical for boiler houses converted from heavy fuel oil to gas fuel. In this case, the efficiency of ORC application will primarily be determined by the efficiency of the used heat exchangers (HE) with a phase transition, as a result of which, both technically and theoretically, the problem of designing and calculating the optimal characteristics of these HE will be of great interest.

The article presents a theoretical and computational model of heat transfer during phase transitions in turbulent flows based on the relations obtained by the stochastic theory of hydrodynamics and heat transfer. The modelling of the effect of turbulence during the phase transition with undeveloped boiling of the bubble mode is considered. The comparison results show satisfactory conformity of the values obtained according to the formula based on stochastic equations with the values calculated according to the empirical formula for the flow in a pipe, used in the engineering method of designing heat exchangers. The results obtained open the prospect for studying the processes of heat transfer during phase transitions in turbulent flows of HE to reduce their overall and mass characteristics, as well as to increase the energy efficiency of both the devices themselves and the efficiency of the entire energy complex.

Keywords: *transport, energy complex, heat transfer, undeveloped boiling, Rankine cycle, stochastic equations, bubble mode.*

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Background.

The importance of introducing energy-saving technologies in transport determines the vector of development of stationary energy in this sector. In particular, efficient use of low-grade heat in stationary transport energy units based on the organic Rankine cycle (ORC) is quite relevant. This task is typical of boiler houses of stationary power engineering units of transport, the efficiency of which is largely determined by heat exchangers that ensure functioning of the energy complex.

The creation of new compact heat exchangers, as it is known, is focused not only on the search for various engineering solutions [1; 2] to increase their efficiency, but also on the new ways of developing the theory of turbulence, various ideas of description of its use being presented in [3–20]. In this regard, modernization of stationary energy facilities, e.g., in Russia, basically, but not completely, corresponds to the main guidelines of the energy system, which must meet the requirements of the energy strategy of the Russian Federation until 2030: energy security; energy efficiency of the economy; energy budget efficiency; environmental safety of the energy sector [21; 22]. Namely, the area of environmental safety and energy efficiency does not fully use the innovation capacity of existing possibilities regarding utilizing the energy of exhaust gases from a boiler house with subsequent formation of a closed energy cycle.

Attention is paid to this problem in other countries as well [23; 24], where schematic diagrams of energy complexes based on the organic Rankine cycle are considered.

In this regard, the methods of theoretical and computational study of the heat transfer process during phase transitions remain in the focus of attention when designing compact heat exchangers utilizing low-grade energy, and with regard to the problem of considering multi-parametric processes and their mutual influence. Despite the numerical methodologies based on RANS, LES and DNS statistical methods [25; 26], engineering methodologies based on empirical and semi-empirical relationships remain important. This is especially significant in view of the results obtained based on the stochastic theory of turbulence. The theory of stochastic turbulence [27–47], based on stochastic equations and the equivalent circuit theory, makes it possible to obtain analytical dependences for the first and second critical Reynolds numbers [27–31], profiles of averaged fields of velocity and temperature [32–34], friction and heat transfer coefficients [35–38], second order correlations, [39–41], correlation dimension of attractors [42; 43], spectral functions [46; 47]. Such results allow us to study the problem of considering the influence of turbulence parameters on the process of heat transfer in the flow in the presence of phase transformations [44; 45]. We emphasize that the modelling of hydraulic losses in the bubble flow mode, considering the characteristics of the flow turbulence, was studied in [46; 47].

The *objective* of the article is to present a theoretical and computational model of heat transfer during phase transitions in turbulent flows based on the relations obtained within the stochastic theory of hydrodynamics and heat transfer. The modelling of the effect of turbulence during the phase transition with undeveloped boiling of the bubble mode is considered.

Results

1. Heat transfer in an undeveloped boiling regime

In engineering practices, modelling heat transfer during phase transitions in the bubble mode is described by the heat transfer coefficient [25; 26]. As it is known, in the economiser area there are: the area of convective heat transfer; area of undeveloped surface boiling; area of developed surface boiling. In the evaporation area, there are: area of developed boiling; area of poor heat transfer. In the steam superheating area, there is a single calculation section of convective heat transfer. Here we will consider the motion in a vertical pipe in the economiser section in the area of undeveloped surface boiling. For the beginning of the area of undeveloped surface boiling, one should take the cross section in which $t_{st} = t_s$. The heat transfer coefficient in the undeveloped boiling area can be calculated by the formula:

$$\alpha_{\text{n.k.}} = \alpha_k + \left[\frac{q}{\dfrac{q}{\alpha_{\text{r.k.}}} - \dfrac{x_{\text{r.k.}} r}{\alpha_0}} - \alpha_k \right] \left[\frac{x - x_{\text{n.k.}}}{x_{\text{r.k.}} - x_{\text{n.k.}}} \right], \qquad (1)$$

where α_k is heat transfer coefficient for a single-phase flow in a pipe;

α_0 is coefficient of heat transfer during boiling in a large volume;

Table 1

Calculation of Nusselt numbers for the characteristic parameters of turbulent heat transfer from the wall of a circular pipe to water (authors' calculations)

Re	$Re^{0,8}$	$Re^{7/8}$	Nu_d, equation (5)	Nu_d, equation (6)
10^4	1585	3163	57	76,95
$5 \cdot 10^4$	5743	12930	228	279
10^5	10000	23717	420	485
$5 \cdot 10^5$	36239	96961	1716	1757
10^6	63095	177827	3152	3063

Table 2

Calculation of Nusselt numbers for the characteristic parameters of turbulent heat transfer from water to the pipe wall (authors' calculations)

Re	$Re^{0,8}$	$Re^{7/8}$	Nu_d, equation (6)	Nu_d, equation (5)
10^4	1585	3163	32	43
$5 \cdot 10^4$	5743	12930	130	156
$3 \cdot 10^5$	24082	62012	620	655
10^6	63095	177827	1778	1715
$5 \cdot 10^6$	228652	727107	7271	6219

$\alpha_{r.k.}$ is coefficient of heat transfer in the area of developed boiling;

q is heat flux density;

r is specific heat of vaporization;

x is current value of the relative enthalpy of the working fluid;

$x_{n.k}$ is relative enthalpy of the working fluid, at which undeveloped boiling begins;

$x_{r.k}$ is relative enthalpy of the working fluid, corresponding to the beginning of the developed surface boiling.

The value of the relative enthalpy of the flow in this section is determined for the longitudinal internal and external flow around the heat exchange tubes:

$$x_{\text{n.k.}} = -\frac{qc_r}{\alpha_k r}. \quad (2)$$

For the flow inside the pipe and inside the annular channels in the range of operating parameters: $p = 2,9 \div 19,6$ MPa; $\rho w = 1000 \div 5500$ kg/(m$^2 \cdot$ s); $q = 0,7 \div 1,7$ MW/m^2.

$$x_{\text{r.k.}} = -140\left(\frac{q}{r(\rho w)_{sm}}\right)^{1,1}\left(\frac{(\rho w)_{sm} d}{\mu_1}\right)^{0,2}\left(\frac{\rho_1}{\rho_2}\right)^{-0,2}. \quad (3)$$

Indices 1 and 2 – respectively, refer to liquid, steam;

ρ is density;

w_{sm} is two-phase flow speed.

2. Heat transfer during the flow of a single-phase liquid

Let us first write down the expression for α_0, heat transfer coefficient during boiling in a large volume (p is for pressure). For water, this is $\alpha_0 = 4,34\, q^{0,7} \cdot (p^{0,14} + 1,37 \cdot 10^{-2} p^2)$ [29]. With undeveloped boiling and forced turbulent flow near the pipe wall, it, as well as the heat transfer coefficient at developed boiling $\alpha_{r.k.}$, as it is known [28; 29], plays an insignificant role in comparison with the value of the heat transfer coefficient for the forced flow of a single-phase flow in the pipe α_k. It is known [5; 6] that α_k for a single-phase liquid in a turbulent regime in the ranges $0,6 < \mathrm{Pr} < 200$, $10^4 < \mathrm{Re_d} < 5 \cdot 10^6$ is determined by the dependence:

$$\alpha_\kappa = \frac{\lambda Nu}{d}, \quad (4)$$

$$Nu = 0,021 \mathrm{Pr}_L^{0,43} \mathrm{Re}_d^{0,8} (\mathrm{Pr}_L / \mathrm{Pr}_W)^{0,25}, \quad (5)$$

where Nu, Pr, Re are Nusselt, Prandtl and Reynolds numbers, L, W indices refer to the flow core and that on the wall;

d – pipe diameter;

λ – thermal conductivity.

As follows from the comparison [12–15], the deviation of the calculation results using dependence (5) and other dependences for Nusselt number from experimental distributions can be of 25 %. As noted in [3–16], such a spread can be explained primarily by the influence of the degree of turbulence and its scale, according to the dependence:

$$Nu_d = 0,2\left[\left(\frac{\sqrt{E_{st}/\rho}}{U_0}\right)\mathrm{Re}_d\right]^{(7/8)}\left[(\mathrm{Pr})^{7/12}\right]. \quad (6)$$

3. Calculation results

Comparison of the results of calculating Nusselt numbers for the characteristic parameters of turbulent heat transfer from the wall of a circular pipe to water is given in Table 1.

Comparison of the results of calculating Nusselt numbers for the characteristic parameters of turbulent heat transfer from water to the pipe wall is presented in Table 2.

Thus, considering the turbulence parameters according to formula (6) makes it possible to calculate according to formulas (1), (2) with high reliability the heat transfer during the phase transition in the bubble mode.

Conclusion.

A modernised model of undeveloped boiling in tubes of heat exchangers designed to use low-grade heat based on the organic Rankine cycle for already modernised boiler houses converted from fuel oil to gas is so presented. The comparison results show satisfactory conformity of the values obtained according to formula (6) based on stochastic equations, with the values calculated according to the empirical formula (5) for the flow in a pipe, used in the engineering method of designing heat exchangers. The results obtained are promising for studying heat transfer processes during phase transitions in turbulent flows according to formulas (1), (2).

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