Heat exchange, resistance and energy efficiency heat-transfer gases with variable physical properties

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Abstract. The new equations of heat exchange and resistance are offered for turbulent flow in the channels, which have structural parameters for the account of influence of variability of individual physical properties of heat-transfer gases. Energy efficiency of heat exchange of gases of different atomicity is analyzed for their heat and cooling.

1. Introduction

A literature review shows that information about influence of variability physical properties on heat exchange and resistance of heat-transfer gases is restricted and often inconsistent. Most often for the account of influence of variability physical properties in the equations of heat exchange and resistance are entered corrections – multipliers. Every correction is a ratio of temperature of a wall $T_c$ to average-weight temperature $T_{cp}$ of flow in some degree. There are one corrections for laminar flows, and others for turbulent flows. They depend on conditions of a current and a direction of a thermal flow. The review of results different authors’ works, studying influence of variability of physical properties on heat exchange and resistance of turbulent flows in channels, is presented in [2]. It indicates considerable divergences of the received data and recommendations for calculations.

2. Heat exchange and resistance of heat-transfers fluids with variable physical properties

The new equations of heat exchange and resistance for turbulent flows of gas heat-transfers in the channels were received in our works [3, 4, 5], where we used conservative laws of a boundary layer. They make possible to effectively consider influence of variability of physical properties of individual gases at change of their temperature in heat or cooling processes.

The equation is received for heat exchange of a turbulent flow in a tube.

$$\text{Nu} = \frac{q_d}{(t_c - t_w) \lambda_{cp}} = \left(2 + 2.6\sqrt{\varepsilon} \left(0.177 \text{RePr}_{cp}^{0.5} \text{Pr}_{cp}^{-1} \sqrt{\varepsilon/C}\right)^5\right) \varepsilon_t,$$

(1)

where $\varepsilon_t$ – is the parameter, which consider variability of physical properties of the heat-transfer fluid in section of a flow

$$\varepsilon_t = \left[\frac{\lambda_t}{\lambda_{cp}} \left(\frac{\rho_t}{\rho_{cp}} \right)^{0.5} \left(\frac{c_t}{c_{cp}}\right)^{0.5}\right]^{5}.$$

(2)
n=0.35+0.058lgRe; C=12.7; p=1−1.2$\sqrt{\xi}$; $q_c$ – is the density of a thermal flow on a wall; $d$ – is the diameter of a tube; $t$ – is the temperature; $\xi$ – is the factor of hydraulic resistance of a friction; $\rho$ – is the density; $\lambda$ – is the factor of heat conduction; $c$ – is the heat capacity; $Re$ – is the Reynolds's number; $Nu$ – is the Nusselt’s number; $Pr$ – is the Prandtl’s number. In this article are using indexes: "c" – parameter is determined at temperature of wall $T_c$; «cp» – parameter is determined at average temperature of flow $T_{cp}$.

The equation (1) in the range of $Re=5 \cdot 10^3$ to $Re=5 \cdot 10^6$ in case of $\varepsilon_c=1$ well agree with the formula of Petuhova-Kirillova

$$Nu = RePr(\xi/8)/(1+900/Re + 12.7\sqrt{\xi}/8(Pr^{2/3}-1)).$$

(3)

This formula is considered the most multiple-purpose and fair among the known formulas, which describe convective heat exchange at a current in channels. The factor of resistance of a friction in (3) for quasiisothermal flow is defined with using the formula of Filonenko

$$\xi = (1.82\lg Re - 1.64)^2.$$ (4)

It is possible to describe the dependence of physical properties from temperature for gases with good exactitude by using power function

$$A = A_0(T/T_0)^{m_\lambda},$$

(5)

where $A_0$ and $m_\lambda$ – are the constants, the for each property $A$; $T_0 = 273K$.

Considering (5), the equation (2) is

$$\varepsilon_i(T_i/T_0)^{m_\lambda},$$

(6)

where $m=m_c-p(m_c-m_\xi+0.5)$; $m_i$ and $m_c$ – are the exponents in dependences (5) for heat conduction and thermal capacity factor accordingly. Such exponent in (5) for density is equal to unit.

The equation is received for factor of hydraulic resistance of a friction

$$\xi = (0.3Re^{-0.25} + 4.2 \cdot 10^{-4}Re^{0.12})/\xi_c.$$ (7)

The correction considering variability of properties of the heat-transfer fluid

$$\varepsilon_i(T_i/T_0)^{0.25m_\mu - 0.75},$$

(8)

where $m_\mu$ – is the exponent in the equation (5) for a dynamic coefficient of viscosity $\mu$.

On the other side the correction is a ratio of factors of hydraulic resistance of a friction

$$\varepsilon_i = \xi/\xi_0$$

where $\xi$ – is the factor of hydraulic resistance for not isothermal flow, and $\xi_0$ - the same for an isothermal flow if Reynolds's numbers are identical to both flows.

If $\varepsilon_c=1$ (an isothermal flow), the result of calculation using equation (7) for an interval of Reynolds's number $Re=10^4$ to $10^7$ almost completely coinciding with calculation using the formula (4).

The equations (1) and (2) are fair in wide intervals of changing of Reynolds's number. They allow to effectively consider influence on heat exchange and resistance of variability of physical properties of individual gases.

The results of calculations using the received equations for different gases are presented in figures 1 and 2 by the form of dependences $\varepsilon_i=\varepsilon_i(T_i/T_{cp})$ (the formula (6)) and $\varepsilon_i=\xi/\xi_0=\varepsilon_i(T_i/T_{cp})$ (the formula (8)). The value $Nu_0$ corresponds to a condition $T_i/T_{cp}=1$ (a quasiisothermal condition). There is information of other authors in drawings 1 and 2. It is given for comparison.

Figures 1 and 2 show that influence of variability of physical properties on heat exchange and resistance for individual gas heat-transfer is variously. It is not enough to consider this influence only through the temperature factor $T_i/T_{cp}$ as it often is recommended in the literature. The additional
parameters, which define the quantitative and qualitative influence is atomicity of gases, and also is Reynolds's number for heat exchange processes.

Figure 1. The dependense of the ratio of Nusselt’s numbers $Nu/Nu_0$ against the temperature factor $T_c/T_{cp}$ at $Re = 10^4$: 1 – cyclohexane $C_6H_{12}$; 2 – ethane $C_2H_6$; 3 – methane $CH_4$; 4 – ammonia $NH_3$; 5 – carbon dioxide $CO_2$; 6 – a line generalizing air experiments of L.N.Ilyin; 7 – a line generalizing air experiments of A.I.Gladuntsov, V.A.Kurganov, B.S.Petuhov, ammonia $NH_3$; 8 – helium $He$; 9 – air; 10 – combustion fuel products (average composition); 11 – water vapor $H_2O$; 12 – theoretical calculation of B.S.Petuhov and V.N.Popov; circles – experimental points of N.I.Ivaschenko, air.

Figure 2. The dependense of the ratio $\xi/\xi_0$ against the temperature factor $T_c/T_{cp}$: solid lines (1, 2, 3) – our calculation by using (8): 1 – air; 2 – $m = -0.5$; 3 – a water vapor; 4 – theoretical calculation of S.S. Kutateladze and A.I.Leontev; 5 – theoretical calculation of B.S.Petuhov and V.N.Popov, air and hydrogen; 6 – a line generalising the experimental data of N.A.Artamonov with co-authors and A.B.Ambrazjavichjus, air; 7 – an average line for experimental of V.L.Lelchuk and B.V.Djadjakin, air; 8 – experimental curve PerkinsaandWorsse-Schmidta, nitrogen; 9 – L.N.Ilyin’s experiment, air; 10 – an experimental line of V.K.Ljahov and V.I.Kugaj, air.

3. Energy efficiency of heat-transfer fluids with variable properties in processes of heat exchange

Calculations have been carried out for the purpose of definition the energy efficiency of turbulent flows of gases with various atomicity in tubes. They were carried out for conditions $T_{cp} = const$ and $T_c = var$. The density $\rho_{cp}$ and the rate $\omega_{cp}$ of flow had fixed values at Reynolds's fixed number and at a variation of $T_c$. As a result was calculated the relative factor of energy efficiency of heat exchange [1]

$$\bar{E} = \frac{\alpha/\alpha_0}{\xi/\xi_0}$$

(9)

where $\alpha$ – is the factor of heat dissipation; $\alpha_0$ and $\xi_0$ correspond to quasiisothermal conditions of heat exchange ($T_c \equiv T_{cp}$).

Considering that $\varepsilon = \alpha/\alpha_0$ according to the equation (6) it is gained
The multiplier \( k \) in an exponent of the equation (10) is defined by expression
\[
k = 1 - 0.5 \text{Re}^{0.1} \sqrt{\frac{\mu}{\lambda_0}}.
\]  

The equation for the relative factor of energy efficiency was received by considering the equations (9), (10) and (8) together
\[
\tilde{E} = \left( \frac{T_c}{T_{cp}} \right)^b,
\]
where an exponent is defined by expression
\[
b = m_k - 1.25 m_\mu + 0.25 + 0.5 ( m_\mu + 0.5 ) \text{Re}^{-0.1} \left( \frac{T_c}{T_{cp}} \right)^{0.125 m_k - 0.375}.
\]

The results of calculations \( \tilde{E} \) by using equation (12) for gases of different atomicity are presented in figures 3 and 4.

**Figure 3.**
The dependences of the relative factor of energy efficiency against the temperature factor: \( \text{Re}=10^4 \); 1 – He – helium; 2 – air; 3 – combustion fuel products (average composition); 4 – NH\(_3\) – ammonia; 5 – C\(_2\)H\(_6\) – ethane; 6 – C\(_3\)H\(_{12}\) – pentane.

**Figure 4.**
The dependences of the relative factor of energy efficiency against Reynolds' number: 1, 1 ’ – He; 2, 2 ’ – NH\(_3\); 3, 3 ’ – C\(_3\)H\(_{12}\); 1, 2, 3 – \( T_c/T_{cp} = 3 \); 1’, 2’, 3’ – \( T_c/T_{cp} = 0.4 \).

The figure 3 shows that if we heat up the flow \( \tilde{E} > 1 \) or, on the contrary, cool it \( \tilde{E} < 1 \), with increasing number of atoms in a molecule of gas, the dependence \( \tilde{E} = f \left( T_c/T_{cp} \right) \) becomes more steep. Such character of changing \( \tilde{E} \) is caused by the fact that with growth of temperature heat conduction of gases is augmented with greater speed, than viscosity, so \( m_\lambda > m_\mu \). The value distinction between \( m_\lambda \) and \( m_\mu \) increases with increase of atomicity of gases. For example, for helium (1 atom) \( m_\lambda = 0.728 \) and \( m_\mu = 0.67 \), and for pentane (17 atoms) \( m_\lambda = 1.853 \) and \( m_\mu = 0.99 \).

The figure 4 shows that influence of Reynolds's number on \( \tilde{E} \) is weak. Also it is qualitatively variously at processes of heating up and cooling. If we heat up the flow \( \tilde{E} \) it is diminished with growth \( \text{Re} \), and, on the contrary, if we cool the flow it is increases.
4. Conclusion
The new equations of heat exchange and resistance for turbulent flows in the channels make possible to effectively consider influence of variability of individual physical properties of gases. In these equations there is structural parameter, correction, which consider influence of variability of properties. The character of influence of variability of properties has the different features for gases of different atomicity.

The ratio between power transmitted in the process of heat exchange and power expended on a pumping of the heat-transfer fluids for gases more favorably at their heat, than at cooling. At $T_c/T_{cp} < 1$ (cooling) the best energy efficiency of heat exchange possess has one- and two-atomic gases, and at $T_c/T_{cp} > 1$ (heat) – multiatom.

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