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Application peculiarities of the high-temperature fluids containing nanoparticles in gas-tube boilers

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Abstract. The paper considers the application peculiarities of the high-temperature fluids containing nanoparticles in gas-tube boilers. The classification of nanofluids obtaining methods is presented, one-step and two-stepmethods for preparing the product are considered. The main thermophysical properties of materials are described. The values of the thermal conductivity coefficient for some materials that are usually used as the base ones for mixing liquids and nanoparticles are represented. The mechanisms of heat transfer in nanofluids in the forced and free convection and boiling processes determining the gas-tube boiler efficiency are considered. Criteria dependences of calculating the heat transfer in the free and forced convection and boiling when nanofluids flowing through the heat generators are proposed. It is proved that when adding nanoparticles to the base liquid, an increase in the heat transfer coefficient will be observed if its thermal conductivity is increased. Besides, the convective heat transfer is affected by the density and viscosity of the nanofluid. When the liquid boils, the critical heat flux increases, and the determining factor of the heat transfer coefficient is the particles concentration. The represented data are prerequisites of developing the efficient gas-tube boiler with a high-temperature fluid.

1. Introduction

In the development of the Russian gas industry, small-scale power engineering is increasingly using the low and medium powered gas-tube boilers utilizing the high-temperature fluid, contributing to the high degree of the production process automation, having a simple design and not requiring large material costs for installation and further maintenance during operation.

High-temperature liquids (organic and synthetic) are widely used as heat transfer fluids during heating processes. Their application is caused by a number of advantages: heating to high temperatures at the atmospheric pressure, low corrosion activity and absence of local boiling.

The research objective is to obtain the main computational dependencies characterizing the heat transfer in nanofluids during forced and free convection, as well as in boiling which are the processes determining the gas-tube boiler efficiency.

2. Problem statement

Heat exchange processes in gas-tube boilers from the heat transfer fluid are determined by the influence of a number of thermophysical characteristics of the working medium: the thermal conductivity coefficient, density and viscosity. It is necessary to examine the criteria dependences of calculating the heat transfer in the free and forced convection and boiling when nanofluids flowing through the heat generators.

3. Theory

Changing the heat transfer fluid properties influences the characteristics of heat exchange processes in the working space of the gas-tube boiler and have a direct impact on the boiler efficiency [1].

In recent years, there has been growing interest in heat transfer fluids containing nanometer-sized solid particles with high thermal conductivity.

Hence, it is necessary to develop a highly efficient low-power boiler with a high-temperature fluid.

When developing gas-tube boilers, the most important operational requirement is to provide a high heat transfer surface with optimal geometric characteristics [2].

Thermal conductivity of solids is known to be higher than that of liquids. Liquids used as heat-transfer fluids, such as water, ethylene glycol and engine oil have a low thermal conductivity compared to that of solids, especially metals. Thus, adding solid particles to the liquid can increase the liquids conductivity. The resulting liquids are called nanofluids.

A nanofluid is a liquid containing nanometer-sized particles called nanoparticles. Nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes [1].

Replacement of the heat-transfer fluid influences the heat and mass transfer processes in the gas-tube boiler.

Table 1. Thermal conductivity coefficients of various materials.

Material	**Thermal conductivity coefficient (*k*, W/m·K)**
Carbon Nanotubes	3000
Cu (copper)	401
Au (gold)	317
Si C (silicon carbide)	120
CuO (copper oxide)	40
Aluminium oxide	20
Water	0.613
Ethylene glycol	0.253
Engine oil	0.145
Ditholilmethane	0.125

Nanofluids have novel properties that make them useful in many aspects of heat transferring processes. They are characterized by the increased thermal conductivity and heat transfer coefficient compared to the base fluid. Table 1 presents the values of the thermal conductivity coefficient of some materials that are typically used as the base ones for mixing liquids and nanoparticles.

Currently various methods of preparing nanofluids are known. They can be classified as one-step and two-step methods. In the one-step method, a nanofluid is obtained in a single process cycle, in which the metal (the material of nanoparticles) is first vaporized by an electron beam in a vacuum chamber, then it settles on a rotating disk pre-coated with a base liquid (oil).

Two-step methods for preparing nanofluids are based on mixing the finished products – the working fluid and nanotechnology products.

There are two levels in the heat transfer mechanism in nanofluids under the forced convection, namely macroscopic and microscopic.

Considering the macroscopic level, the formula for calculating the heat transfer coefficient can be presented as follows:

$$h = k_f / \delta_t, \tag{1}$$

where δ_f and k_f are the local thickness of the thermal boundary layer and effective thermal conductivity of the near-wall liquid [3].

In general, when the heat transfer fluid is forced to flow in the boiler, the criterion equation of heat transfer has the following form:

$$Nu = f/8(\mathrm{Re}-1000)\mathrm{Pr}\Big/\left(1+\delta^{+}(f/8)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)\right), \tag{2}$$

where f is the non-dimensional coefficient of friction; *Re* is the Reynolds number; δ^{+} is the empirical parameter.

When transferring heat, the determining factor is the nature of the density and viscosity change. When heat is transferred in the heat transfer fluid by the free convection, the criterion heat transfer equation is generally as follows:

$$Nu = 0.68 + \frac{0.670 Ra^{0.25}}{\left[1+\left(0.492/\mathrm{Pr}\right)^{9/16}\right]^{4/9}}, \tag{3}$$

where *Ra* is the Rayleigh number, *Pr* is the Prandtl number [4].

When boiling the high-temperature fluid with the addition of nanoparticles, heat transfer is calculated by the following formula:

$$h = \mu_f h_{fg}\left(T_w - T_{sat}\right)^2 \left[\frac{g\left(\rho_f-\rho_g\right)}{\sigma}\right]^{1/2} \left(\frac{c_f}{K_{sur} h_{fg}\,\mathrm{Pr}_f^n}\right)^3, \tag{4}$$

where σ is the surface tension coefficient of the boiling liquid, g is the gravitational acceleration; c_f is the fluid heat capacity; μ_f is the fluid dynamic viscosity; h_{fg} is the interface heat transfer coefficient; K_{sur} is the roughness coefficient; T_w is the wall temperature; T_{sat} is the saturation temperature [4].

4. Results discussion

On the basis of the research results, it can be concluded that the greatest heat transfer is observed at the initial section of the pipe. This is due to the fact that the thermal boundary layer decreases at the inlet section regardless of the liquid used.

When adding nanoparticles to the base liquid, the heat transfer coefficient is expected to witness an increase if its thermal conductivity is also grows.

Analysing formula (1), one can identify the following relationship: the heat transfer coefficient will decrease if the growth of the local thickness of thermal boundary layer will exceed the growth of the fluid thermal conductivity in the near-wall region. Alternatively, if the mentioned two parameters are similarly changing, the heat transfer coefficient will remain unchanged. Whereas the near-the wall fluid thermal conductivity growth is above the thickness growth of the thermal boundary layer, in this case the heat transfer coefficient increases. The proposed mechanism is qualitatively explained by the experimental data.

Heat and mass transfer in nanofluids under the free convection differs significantly from the heat and mass transfer in a pure liquid due to the uneven distribution of temperatures and concentrations.

Taking into account the experience of previous studies, the use of nanofluids as heat transfer fluids can result in both an intensification of heat exchange and its deterioration [3].

The heat transfer coefficient is significantly reduced at the low concentrations up to 0.4 %, while the heat transfer level is reduced by 10–30 %. The determining factor of the heat transfer coefficient is the concentration of particles.

When using concentrations higher than 0.4%, the heat transfer intensification by 20-30 % occurs [3].

In the case of the high temperature fluid boiling, the critical heat flux increases. The critical heat flux increases by 3–4.5 times.

5. Conclusions

The application of nanoparticles in high-temperature fluids is currently a promising approach, as it leads to the intensification of the heat and mass exchange process.

Nanoparticles application can significantly increase the thermal conductivity of the base liquid. Moreover, the given method of intensifying the heat transfer by using the stable nanofluids as high-temperature heat transfer fluids for gas-tube boilers is a promising one.

In the natural convection of the heat transfer fluid in gas-tube boilers, a rational relationship between changes in density and viscosity needs to be determined when adding nanoparticles to enhance the heat transfer.

Nanofluids boiling leads to an increase in the heat transfer level and critical heat flux.

The represented data are prerequisites of developing the efficient gas-tube boiler with a high-temperature fluid.

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