Prospects for the use of nanofluids in heating systems

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Abstract. The desire to create new, improved working fluids for heat and mass transfer systems in the industry is gaining momentum. Now more and more researchers are being attracted to analyze the use of nanofluids in heating systems due to their improved thermal and physical properties. Nanofluids are a new type of dispersed fluids that consist of a carrier fluid in the form of which water can act, as well as polymer solutions and organic liquids, and solid particles, which are mainly particles of chemically stable metals and their oxides. The heat transfer characteristics of modern liquids are significantly improved by the addition of nanoscale solid particles with a diameter of less than 100 nm. Such liquids can be considered as promising applications in such areas as solar collectors, heat pipes, nuclear reactors, electronic cooling systems, automobile radiators, etc. The paper (publication) describes nanofluids as new energy-efficient types of working fluids for heat transfer. The most promising developments in the field of creating nanofluids from the point of view of increasing the heat transfer coefficient are presented and analyzed. Further possible promising ways of studying nanofluids are formulated.

1. Introduction

Due to the sharp increase in energy consumption over the past decade, there is a need for new types of heating liquids that can increase the thermal characteristics of the heating system, reduce the overall size and energy consumption. Nanofluids are the next generation of heat carriers used for various industrial applications due to their excellent thermal characteristics [1].

The use of nanofluids, which are colloidal solutions of nanoparticles in a liquid solvent, in heating they can provide numerous advantages including improved heat transfer, minimal clogging and a reduction in the size of heat exchangers with microchannels, will reduce energy consumption by reducing the required pump power.

The processes occurring in nanofluids are quite difficult to describe. Over the past 25 years, many experimental studies were conducted to obtain data on the thermal and physical properties of nanofluids. However, the results obtained have a wide range, and often even contradictory data.

The theoretical description of the thermal and physical properties of nanofluids also raises questions. The obtained results of the thermal conductivity of nanofluids mostly do not coincide with the classical Maxwell theory. And Batchelor’s theory, which is often used to describe the viscosity of nanofluids, also has a discrepancy with experimental data. Therefore, now there is no single theory predicting experimental data on changes in the thermal and physical properties of nanofluids [2]. The paper describes the characteristics of nanofluids, the conditions for their application, and also presents
some, in our opinion, the most promising studies of the thermal conductivity of nanofluids that require further study and suggests research directions in this area.

2. Materials and methods
Nanofluids or nanoemulsions are a dispersed phase (<100nm) distributed in a dispersed environment such as water, ethylene glycol, or propylene glycol. The addition of metal particles with high thermal conductivity (copper, aluminum, silicon, silver), as well as carbon-based particles, increases the thermal conductivity of the mixture, which increases its ability to transfer energy.

Nanofluids are also considered as a promising heat carrier in thermal power plants, in the field of heat energy transportation, and in microelectromechanical systems. Technologies based on phase-change materials and core-shell particles are also being developed. Phase-change materials or phase-transition materials are substances that can absorb or emit energy during a phase transition to provide useful heat or cold. Core-shell particles are nanoscale particles in which the core and shell have a different composition and, as a result, a different functional purpose. The use of phase-change materials and core-shell particles makes it possible to expand the scope of nanofluids in the field of medicine and biology in the transportation and delivery of medicines [3-6].

There are several ways to produce nanofluids. The first method involves the production and distribution of nanoparticles in liquid using chemical methods. The second method does not limit the method of obtaining nanoparticles. It is possible to obtain by chemical (obtaining particles by enlarging individual atoms), physical (obtaining particles by grinding) and mechan-chemical methods. After getting, the particles are dispersed by ultrasound or magnetic field. For industrial applications, the second method of production is more suitable.

For nanofluids, one of the most important properties is stability, which implies a constant concentration and particle size distribution. There is a distinction between sedimentation stability, which is determined by the Brownian motion of particles that prevents deposition, and aggregative stability – resistance to coagulation. To obtain an aggregative stable nanofluid, stabilizers in the form of surfactants are often used, but these substances can significantly affect the viscosity of the nanofluid.

Despite the long history of the study, it is still difficult to describe the processes occurring in nanofluids. This is due to the inability to determine the degree of uniformity of the particle distribution. It is difficult to make assumptions about the number of agglutinated or laid-down particles. The rheology of the resulting nanofluids also has a great influence, as the aggregate concentration of particles, their shape or diameter can lead to a transition from Newtonian to non-Newtonian behavior of liquids.

Based on the above, experimental studies in this area were analyzed, the most promising ones in terms of increasing thermal conductivity were identified, and further research paths were proposed.

3. Results and discussion
Currently, there are a large number of experimental studies that study the thermal conductivity of nanofluids, but there is a significant variation in the data from different authors (Figure 1).
Despite the significant variation in the parameters, there is a tendency to increase the thermal conductivity with the addition of nanoparticles in general, and with an increase in the volume concentration of nanoparticles.

There are also a number of studies, updated year after year, which indicate data on the increase in the thermal conductivity of nanofluids in comparison with standard heat carriers. The most significant studies in this area include the works of Wang [8], Lee [9], Eastman [10]. One of the first works in which experiments sufficiently reliably showed an increase in thermal conductivity of 15-40% with an increase in the volume concentration is the work of Yu [11].

In our opinion, the most promising areas of development in the field of obtaining nanofluids can be nanofluids with the use of carbon nanotubes (CNTs). Carbon nanotubes are cylindrical molecules with a diameter from tenths to several tens of nanometers and a length from one micrometer to several centimeters. As it can be seen from Table 1, nanotubes have the highest coefficient of thermal conductivity, which determines the prospects for using this type of material [12].

Table 1. Comparison of thermal conductivity coefficients of materials for nanofluids.

| Material | Thermal conductivity coefficient, W/(m·K) |
|----------|-----------------------------------------|
| Graphene | ≈5000                                   |
| Diamond  | 2300                                    |
| CNT      | ≈2000                                   |
| Silver   | 429                                     |
| Copper   | 401                                     |
| Aluminium| 237                                     |
| SiC      | 120                                     |
| Graphite | 110-190                                 |
| CuO      | 40                                      |
| Al₂O₃    | 20                                      |
| Water    | 0.613                                   |
| Ethylene glycol | 0.253                           |
| Engine oil| 0.145                                   |

In addition, as it is shown by experimental studies [13], the increase in the heat capacity of a nanofluid in comparison with the heat capacity of pure water is proportional to the increase in the concentration of nanoparticles. Table 2 shows that the most efficient use of nanofluid is observed when using water and carbon nanotubes.
Table 2. Heat capacity (Cp, J/(kg·K)) of the studied heat carriers, depending on the concentration of nanoparticles.

| Concentration, % | Name of heat carriers | Water+graphite | Water+carbon nanotubes | Water solution of ethylene glycol + carbon nanotubes |
|------------------|-----------------------|----------------|------------------------|-----------------------------------------------|
| 0.2              |                       | 3706.8         | 5204.4                 | 2076.9                                        |
| 0.3              |                       | 3748.2         | 5338.9                 | 2037.8                                        |
| 0.35             |                       | 3753.5         | 5444.8                 | 1993.0                                        |
| 0.4              |                       | 3774.2         | 5465.4                 | 1950.5                                        |

Here they can see an increase in the heat capacity of the nanoemulsion relative to the base liquid in the case of water and carbon nanotubes. This combination led to an increase in the heat capacity of the nanofluid relative to water by 20–25%.

Based on [13], the study [14] presented the dependences of the heat transfer coefficient of the nanofluid on the Reynolds number and the heat transfer coefficient on the volume concentration. The data showed that the dependence of the relative heat transfer increases with an increase in the volume concentration from 0.5 to 3 percent. As the Reynolds number increases from 21,000 to 50,000, the heat transfer coefficient for the water/carbon nanotube nanofluid changes from 4,000 to 8,000 W/(m²·K). Based on the results of these studies, we can talk about good prospects for the use of nanofluids, including with the addition of carbon nanotubes, for improving heat exchangers, as well as for heating and heat supply systems in general.

More detailed studies using carbon nanotubes are given in [15], which investigated the change in heat transfer taking into account the magnetic nanofluid. Magnetic nanocomposites containing carbon nanotubes (CNTs) and Fe₃O₄ magnetic nanoparticles were used to produce nanofluids.

To obtain a magnetic composite nanofluid, solutions of FeCl₂·4H₂O and FeCl₃·6H₂O were obtained with the subsequent addition of CNTs. Then, using a solution of NH₃H₂O, the pH was increased to 10.0. Using a magnet, magnetic nanocomposites were inserted. The authors speak about the stability of the resulting liquid without additional surfactant due to hydrophilic carboxyl groups on the surface of the particles [16].

Further, in the study, experimental and theoretical studies were conducted to compare the heat transfer characteristics of deionized water, a mixture with the addition of Fe₂O₃, and a mixture with the addition of CNTs without an external magnetic field at the Reynolds number of 540. The results in Figure 3a show that the temperature difference at the inlet and outlet of the test zone for CNTs is higher than for deionized water and Fe₂O₃, which indicates that the liquid with the addition of CNTs can absorb more heat. The average Nusselt numbers of CNTs are higher compared to other liquids. The local values of the Nusselt number (Figure 3b) were calculated based on the measured local temperature and the measured thermal and physical properties of the liquids. Figure 3c shows the temperature distribution with different liquids at the midpoint of the pipe. In addition, the experimental average coefficients of heat transfer are lower than the theoretical ones (Figure 3d). The obtained values indicate that a liquid with the addition of CNT transfers more heat than deionized water and a liquid with the addition of Fe₂O₃ [16].
Figure 2. (a) heat transfer values, (b) local Nusselt numbers, (c) temperature at the midpoint of the pipe, (d) heat transfer coefficient of deionized water, Fe$_3$O$_4$ and CNT at the Reynolds number of 540.

In general, the study showed that in the absence of a magnetic field, a nanofluid with the addition of carbon nanotubes shows a higher heat transfer than deionized water and a nanofluid with the addition of Fe$_3$O$_4$, and a change in the magnetic field promotes heat transfer and affects the flow of magnetic nanofluids in different ways. The disadvantages of this study include the fact that the experiments were carried out at a fixed Reynolds number in the area of 540.

In real conditions, for example, in a heating system, on various sections of pipelines, the Reynolds number can vary in quite large ranges from laminar to developed turbulent mode. And as the study [17] showed, if for the laminar flow regime in most experiments, an increase in the heat transfer coefficient is invariably observed when using nanofluids relative to the base fluids, in the turbulent flow regime the situation becomes less unambiguous. In a turbulent flow regime, the improvement in heat transfer becomes dependent on the concentration, as well as on the size of the nanoparticles. Thus, at Reynolds numbers higher than the critical one, the intensification of the heat transfer process depends on the ratio between the viscosity and the thermal conductivity of the nanofluid. The larger the particle size, the lower the viscosity coefficient, but the higher the thermal conductivity is [17].

4. Summary
When using nanofluids instead of ordinary water in experimental facilities, significant changes in thermal characteristics occur. The processes occurring in nanofluids are quite difficult to describe, and the theoretical description of the thermal and physical properties leaves questions. Despite the considerable variation in the experimental data, there is a general tendency to increase the thermal conductivity when adding nanoparticles to the carrier fluid. The thermal conductivity of carbon nanotubes is several times higher than that of metal particles, which indicates the feasibility of using this type of material as a dispersed phase, which is also confirmed by the above studies. The use of nanotubes in solutions with magnetic nanocomposites looks like the most promising direction of experimental research.

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