Characteristic features of nanofluids application in power engineering

Yu V Shatskikh¹ and A V Kostanovsky ²

¹ National Research University "MPEI", Russia, 111250 Moscow, Krasnokazarmennaya, 14
² Joint Institute of High Temperature, Russia, 111116 Moscow, Krasnokazarmennaya, 17A

shatskih_jv@mail.ru

Abstract. The problem of increasing the intensity of heat transfer is an urgent and important task. Methods of increasing the heat transfer coefficient in cooling systems of power equipment are of particular interest. Over the past two decades, a promising area of research in this area is the study of heat transfer using nanofluids. To date, domestic and foreign authors have performed a large amount of research. The scientific search is conducted in several directions: the choice of a heat-conducting material and a base fluid; the study of the influence of nanoparticle concentration and size on the intensity of heat exchange. To increase the thermal conductivity of the heat transfer agents, it is proposed to use both pure metals (Au, Cu, Fe), their oxides (CuO, Al₂O₃, TiO₂), and carbon nanomaterials. The base fluid is mainly distilled water, mineral oil, or ethylene glycol. Almost all authors note an increase in the thermal conductivity of the nanofluid up to 40% on average compared to the base fluid. The concentration of nanoparticles in experiments does not exceed 4%. However, the studies performed often give results that significantly contradict the theory of convective heat transfer. Thus, many authors note that the heat transfer coefficient in the laminar mode of the nanofluid is greater than that of the base fluid, and the reverse is observed in the turbulent mode. A convincing explanation for this phenomenon has not yet been found. There is also no reliable data on the portable properties of materials used for the manufacture of nanofluid, in particular, there is little data on the properties of nanographene. In the article, the authors review the studies of heat transfer using nanofluid, consider the possibility of using nanotubes and multigraphene to increase the thermal conductivity of the heat transfer agent. The authors also analyze existing models of heat transfer in nanofluids.

1. Introduction
Increasing the intensity of heat transfer is an urgent task in various fields of engineering and energy. The inability to divert high heat flows in the equipment hinders the development of technology. Traditional methods of heat transfer intensification have reached the limit of their application. Future work in this direction is associated with the use of new heat carriers that provide higher heat transfer coefficients.

The idea of using nanofluid as a heat carrier was proposed by Choi S.U.S [1] in 1996 and has found wide application, including in power engineering. Today about 300 scientific groups around the world are engaged in research on the properties of nanofluids and heat transfer with their participation. Applications of nanofluid are very diverse: cooling of power equipment, internal combustion engines, nuclear reactor housings, cooling of electronics, use in solar collectors, etc. At the same time, convection in nanofluids is studied, as well as heat transfer during boiling of nanofluids.
2. Experimental study of the thermal conductivity coefficient of a nanofluid

The wide range of applications of nanofluids is due to a higher coefficient of thermal conductivity compared to base fluids. At the moment, a fairly extensive database of experimental data has been accumulated on the study of the coefficient of thermal conductivity and viscosity of nanofluids, as well as the coefficient of heat transfer in the simplest heat exchangers, in which nanofluid is used as a heat carrier. Experiments were conducted with various nanomaterials: pure metals (Cu, Ag, Au, Al), metal oxides (CaO, Al₂O₃, MgO, ZnO, SiO₂, Fe₃O₄, TiO₂, NPs), carbon nanomaterials (multilayers, carbon nanotubes). As the base fluid employed is water, an aqueous solution of ethylene glycol, motor oil, etc. It is obvious that the greater the thermal conductivity coefficient of the nanomaterial, the greater the thermal conductivity coefficient of the resulting nanofluid. Accordingly, from this point of view, the most promising is the use of carbon nanomaterials. The coefficient of thermal conductivity of carbon nanotubes is approximately 2000 W/(m·K), graphene has 5000 W/(m·K) [2].

All currently available experiments indicate an increase in the thermal conductivity coefficient when adding a nanomaterial to the base fluid. The degree of this increase depends on many factors and ranges from 30 to 70%. The thermal conductivity coefficient of the nanofluid depends on the following factors:

- the physical nature of the nanomaterial
- method of preparation of nanofluid,
- concentration of nanoparticles in the base fluid,
- size and shape of nanoparticles,
- nanofluid temperature

The thermal conductivity coefficient of a nanofluid is studied in more detail in [3]. It was found that the greater the concentration of nanoparticles, the greater the coefficient of thermal conductivity of the nanofluid. Moreover, the dependence of thermal conductivity on concentration is nonlinear.

The temperature dependence of the thermal conductivity of nanofluids is more complex. For some nanofluids, the thermal conductivity is completely independent of temperature; for other nanofluids, the thermal conductivity coefficient increases with increasing temperature. The researchers believe that this depends on the properties of the base fluid, as well as on the kinetics of aggregation of nanoparticles.

The dependence of the thermal conductivity coefficient on the size of nanoparticles has an extreme: the maximum thermal conductivity is observed at the value of the specific effective area of 25 m²/g. Experiments were conducted with Al₂O₃ particles with a volume concentration of 0.05%. The authors give the following explanation of this dependence. On the one hand, a decrease in particle size leads to an increase in the contact area of the particle and the fluid, and consequently to an increase in thermal conductivity. On the other hand, the average free path in a polycrystalline Al₂O₃ particle is estimated at about 35 nm, which is comparable to the size of the particle itself. The internal thermal conductivity of nanoparticles is reduced due to the scattering of primary energy carriers (phonons) at the particle boundary. This leads to a decrease in the thermal conductivity of the nanofluid. Therefore, if the size of the nanoparticles is very different from the average free path, the thermal conductivity of the nanofluid increases as the particle size decreases. If the particle size is comparable to the size of the average free path, the thermal conductivity will fall as the particle size decreases. A similar relationship is observed for carbon nanotubes.

The properties of the base fluid have a noticeable effect on the thermal conductivity of the nanofluid. The higher its thermal conductivity coefficient, the lower the increase in the thermal conductivity of the nanofluid.

To stabilize nanofluids and reduce their agglomeration, surfactants are added to them. This leads to a decrease in thermal conductivity.
3. Mathematical description of the thermal conductivity of nanofluids

Despite such extensive experimental material, there is no general understanding of the mechanism of thermal conductivity in a nanofluid. Most authors note that classical models of thermal conductivity, such as the Maxwell, Hamilton, and Cross models, do not allow calculating the thermal conductivity coefficient of suspensions. The fact is that these models are based on the fact that the nanoparticle is in a static state, that is, they did not take into account the influence of nanoconvection. Modern models of thermal conductivity take into account the Brownian motion of nanoparticles, the interfacial interaction at the particle/fluid interface, the distribution of particles and their aggregation in the fluid.

The models proposed by different authors [4-11] allow us to take into account: thermal diffusion of nanoparticles in fluids; collisions between nanoparticles caused by Brownian motion; formation of percolation trajectories with low resistance in a fluid, etc. It is important to note that such models were developed for specific nanofluids, and, in the general case, can not reliably describe the thermal conductivity of other nanofluids.

Analysis of the published data shows that further experimental studies of the effect of the concentration and size of nanoparticles on the thermal conductivity and stability of nanofluids are necessary.

4. Viscosity of nanofluids

The viscosity of nanofluids has a significant impact on heat transfer processes, so it is worth considering it separately. Numerous studies [12-14] have shown that the viscosity of nanofluids depends on the size of the particles and their material. The viscosity of fluids increases with decreasing particle size. The dependence of the viscosity on the material was determined in [15] and shown in Figure 1. The figure also shows that the viscosity of the nanofluid increases with increasing concentration of nanoparticles [16]. The higher the relative viscosity of the nanofluid, the lower the viscosity of the base fluid.

![Figure 1](image_url)  
Figure 1. Dependence of the relative viscosity coefficient of water-based nanofluids on the diameter D of nanoparticles at a fixed concentration (2%) [16].
In [12, 13] it is noted that nanofluids can be both Newtonian and non-Newtonian fluids, although the base fluid was Newtonian. Therefore, the viscosity of nanofluids is not described by classical theories for coarse suspensions. The manifestation of non-Newtonian properties is determined by the concentration of nanoparticles, their size and material, and the properties of the base fluid [16].

The viscosity of suspensions is well described by the power model, but the correlation coefficients have different numerical values for different nanofluids. To date, there are no universal empirical correlations and theoretical models describing the behavior of nanofluid viscosity in a wide range of parameters.

5. The heat transfer coefficient of nanofluids

For practical use of nanofluids as heat carriers, it is necessary to have a clear understanding of the mechanism of forced convection, which mainly occurs in power equipment.

Quite a lot of research has been done in this direction. Basically, the experiments were conducted for the forced flow of fluid inside the pipe. Most researchers note an increase in the heat transfer coefficient in the nanofluid compared to the base fluid. But the value of the increase in the heat transfer coefficient, recorded by different authors, varies and ranges from 10-17% to 30-40%. Moreover, almost all researchers note the intensification of heat transfer in the laminar flow mode. In the turbulent mode, a decrease in the heat transfer coefficient is observed in some experiments. The reason for this uncertain change in the heat transfer coefficient is due to the influence of fluid viscosity on the heat exchange process.

On the one hand, the thermal resistance of the boundary layer is reduced by increasing the thermal conductivity of the nanofluid [17, 18]. In addition, frequent collisions of solid nanoparticles with high thermal conductivity (in particular, multigraphen) with heated channel walls disturb the boundary layer, which can contribute to accelerated transfer of thermal energy to the flow core [19, 20].

On the other hand, the addition of nanoparticles to the base fluid leads to an increase in the dynamic viscosity coefficient of the suspension, which affects the thickness of the border layer and the intensity of turbulent mixing in it. An increase in the coefficient of dynamic viscosity of the heat transfer agent leads to a decrease in heat transfer. Also, when adding nanoparticles, the base Newtonian fluid can become non-Newtonian. Therefore, for a mathematical description of the heat transfer process, it is necessary to first conduct rheological studies and determine the nature of the fluid (Newtonian or not) [21]. For example, when adding up to 0.75% multigraphen, the viscosity of the base fluid increases by 49% at 90 °C.

Thus, it can be concluded that in the case of a steady motion of a fluid, the heat transfer coefficient is proportional to the thermal conductivity of the nanofluid and does not depend on the viscosity. In the laminar flow regime, there is an intensification of heat transfer, regardless of how much its viscosity has increased. With a developed turbulent flow, the heat transfer coefficient, according to the Mikheev formula, is proportional to the complex \( \eta^{2/5} \lambda^{3/5} \), where \( \eta \) – dynamic viscosity coefficient, Pa·s; \( \lambda \) – coefficient of thermal conductivity, W/(m·K). Therefore, if the increase in the thermal conductivity of the heat transfer agent due to nanoparticles is significantly less than the increase in its viscosity, there may be a deterioration in heat exchange.

In addition, the influence of the size of nanoparticles and the properties of the nanoparticle material on the value of the heat transfer coefficient and pressure drop in the channel was studied. It was found that as the size of nanoparticles increases, the value of the pressure drop decreases, while the value of the heat transfer coefficient increases [22].

It is also worth noting that due to the higher viscosity of the nanofluid, the laminar-turbulent transition occurs in the nanofluid at much higher flow rates than in the base fluid.

To mathematically describe the flow of nanofluid, a simplified model of homogeneous nanofluid is used, which is supplemented by mechanisms for restoring inhomogeneous concentrations of nanoparticles in the volume [23, 24]. This mechanism can be thermophoresis—the movement of particles under the influence of a temperature gradient, called thermodiffusion or the Soret effect. Changes in the flow mode as a result of migration of nanoparticles under the influence of a temperature gradient can
serve as a possible reason for an increase in the heat transfer coefficient in cases where this increase can not be fully explained by a simple increase in the thermal conductivity of the nanofluid. This is especially true for turbulent flows. Since the thickness of the boundary layer in the turbulent mode is very small, a significant temperature gradient will be observed in this layer. Under the influence of this gradient, a significant stratification of the nanofluid can occur due to thermophoresis. The concentration gradient of nanoparticles will lead to a significant change in the thermal properties of the nanofluid in the laminar sublayer.

In the article [25, 26], the laminar flow of the nanofluid was studied. It is shown that accounting for thermodiffusion has a noticeable effect only at high volume concentrations of nanoparticles; at low concentrations of particles (1-2%), accounting for thermodiffusion practically does not affect the value of the average heat transfer coefficient. And only at the highest concentration of particles (6%), the contribution of thermodiffusion becomes noticeable, but even here it does not exceed 5-6%.

6. Boiling of nanofluids

If we talk about the heat transfer at bubble boiling, the various authors will receive conflicting results. For example, the authors [27] obtained a significantly higher heat transfer coefficient than for the base fluid when boiling a nanofluid with Al₂O₃ and TiO₂ particles in a large volume on a disk with a diameter of 150 mm.

Researchers in [28] recorded a decrease in the heat transfer coefficient when boiling nanofluid with Al₂O₃, ZrO₂ and SiO₂ particles with a volume concentration of 0.001÷0.1%. Such contradictory results can be explained by changes of the surface wettability due to the formation of a film on it, which has a hierarchical structure.

Currently, researchers agree that the value of the critical heat flow during boiling of the nanofluid is significantly higher than for the base fluid. Moreover, as noted in [29], the crisis may not occur until the melting point of the material of the heated surface.

7. The use of nanofluids

The possibilities of using nanofluids are very diverse. For example, it is promising to use nanofluids as a cooling agent. Intensive cooling of power equipment becomes a serious problem. Previously known methods of heat transfer intensification have almost reached their limit. It is very actively proposed to use nanofluids in cooling systems of power equipment. The authors [19-21, 30] suggested using nanofluid for cooling large internal combustion engines. These engines are characterized by high intensity of operation. Accordingly, the issue of cooling the engine elements is very acute. As the researchers note, even a slight decrease in the surface temperature of the cylinder removes restrictions on increasing engine power.

It is also proposed to use nanofluids as a working fluid in solar collectors, which will increase the efficiency of these systems. It is noted that the traditional use of water in solar collectors is extremely inefficient. Is known. That the intensity of solar radiation is maximum in the wavelength range of 200 - 850 nm, and the coefficient of water absorption in the wavelength range of 200-500 nm has a minimum value. That is, the range of the maximum intensity of solar radiation coincides with the minimum range of the absorption coefficient. This significantly reduces the efficiency of solar collectors. The use of nanofluids as adsorbers can solve this problem. The authors [31] experimentally confirmed an increase in the efficiency of the solar collector to 70% when adding silver particles to the water (maximum 0.04% vol). Some authors note that collectors with a low content of CuO nanoparticles (0.005%) show the highest efficiency [32].

The use of nanofluids in emergency core cooling systems, as well as in the heat transfer agent circuit of reactor plants, is very promising.

The use of nanofluids in microchannels for cooling electronic devices can also give promising results. Experimental confirmation of this possibility is given in article [33].
8. Conclusions
A review of the results of various researchers shows that it is currently impossible to accurately predict the behavior of the viscosity and thermal conductivity coefficients of nanofluids. Theoretical models cannot generally describe the behavior of the viscosity and thermal conductivity coefficients, since they only take into account the dependence on the volume concentration, while experiments show a significant dependence on the particle diameter. Known empirical correlations cannot be considered universal. They are mathematical approximations of many experiments and are also generally not able to describe the behavior of the viscosity and thermal conductivity coefficients over the entire range of parameters of interest.

The positive effect of heat transfer intensification depends on the ratio between the viscosity and thermal conductivity of the nanofluid, and therefore on the particle material and their concentration. This makes it possible to control the heat transfer process by selecting the desired concentration of particles and their material.

It is obvious that further studies of heat transfer in nanofluids are necessary. The most promising is the study of nanofluids with the addition of carbon nanomaterials.

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