

Review

# Hydrogen Containing Nanofluids in the Spark Engine's Cylinder Head Cooling System

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**Abstract:** The article is devoted to the following issues: boiling of fluid in the cooling jacket of the engine cylinder head; agents that influenced the thermal conductivity coefficient of nanofluids; behavior of nanoparticles and devices with nanoparticles in the engine's cylinder head cooling system. The permissible temperature level of internal combustion engines is ensured by intensification of heat transfer in cooling systems due to the change of coolants with "light" and "heavy" nanoparticles. It was established that the introduction of "light" nanoparticles of aluminum oxide  $Al_2O_3$  into the water in a mass concentration of 0.75% led to an increase in its thermal conductivity coefficient by 60% compared to the base fluid at a coolant temperature of 90 °C, which corresponds to the operating temperature of the engine cooling systems. At the indicated temperature, the base fluid has a thermal conductivity coefficient of  $0.545 \frac{W}{(m^2 \times ^\circ C)}$ , for nanofluid with  $Al_2O_3$  particles its value was  $0.872 \frac{W}{(m^2 \times ^\circ C)}$ . At the same time, a positive change in the parameters of the nanofluid in the engine cooling system was noted: the average movement speed increased from 0.2 to 2.0 m/s; the average temperature is in the range of 60–90 °C; heat flux density  $2 \times 10^2$ – $2 \times 10^6 \frac{W}{m^2}$ ; heat transfer coefficient 150–1000  $\frac{W}{(m^2 \times ^\circ C)}$ . Growth of the thermal conductivity coefficient of the cooling nanofluid was achieved. This increase is determined by the change in the mass concentration of aluminum oxide nanoparticles in the base fluid. This will make it possible to create coolants with such thermophysical characteristics that are required to ensure intensive heat transfer in cooling systems of engines with various capacities.

**Keywords:** internal combustion engine; cylinder head; nanofluid; nanoparticles

## 1. Introduction

The problems of modern piston engine depend on increasing the power and motor resource of the engine; the qualitative composition of combustible mixtures and ensuring multilayeredness, taking into account toxicity and harmful emissions; starting systems (for diesel engines) and fuel injection; limiting mechanical and thermal tension. Currently, work is underway to improve the characteristics of internal combustion engines and their

systems: fuel supply, combustion, lubrication, air supply, and cooling. Therefore, for example, when assessing the heat balance of ship engines, the effective power interval varies from 31.0 to 41.8%, and the losses in the coolant are from 10.5 to 22.9%.

## 2. Literature Survey

Investigation and development of a methodology for assessing the structural elements' durability in hydrogen containing environment (moister air-cooled diesel engines cylinder heads, air-cooled with sea water admixture turbine blades, hydrogen-cooled generators retaining rings, cooled and lubricated systems by nano fluids and colloids with oxides, chalcogenide's nanoparticles, etc.) is actually due to wide application of the traditional and advanced technology with possible hydrogen saturation during long term service and engines hydrogen cleaning effect [1–64]. From the investigation of the operation principle of internal combustion engines [1,3–5,9,35–37], it follows that the mechanical movement of its elements is largely determined by the kinematics of the crank mechanism, fluid hydrodynamics in the channels, as well as more complex forms of movement: chemical and thermal movement, that is the processes of releasing and transferring the heat to the working fluid in the engine cylinder. Thermodynamic and heat transfer are important systems in the engine [6–10,13,18,21].

The nature of the processes taking place in this system has a decisive influence on the processes in the mechanical and hydraulic systems and, therefore, on the engine operation overall. Thermodynamics determines the amount of heat ( $Q$ ), gas parameters (temperature, pressure, and specific volume), and specific heat flux ( $q$ ). Heat transfer includes free and forced convective heat transfer, as well as conductive and radiative heat transfer. In this case, they operate mainly with the coefficients of thermal conductivity and heat transfer, forgetting about the heat transfer coefficient. Moreover, researchers [6–10,13,18,21] do not pay attention to the thermal resistance of heat transfer types and gas–liquid boundary layers.

The use of nanofluids containing nanometer-sized particles in cooling systems of motors, generators, braking devices, heating, and ventilation can increase growth the heat transfer coefficient due to a magnification in the thermal conductivity coefficient. The large scatter of experimental data is associated with a number of objective reasons: the method of oxides, intermetallides, chalcogenides nanoparticle synthesis, the “heavy” nanoparticle size distribution function [17,22,23,25], the nanofluid preparation technology [65–115], as well as the method for measuring thermal conductivity and interpreting the results. In order to use nanofluids as a coolant, it is necessary to have information of their thermophysical properties. For this goal, an analysis of papers that are dedicated to the study of nanofluids was carried out. Papers dedicated to the study of heat transfer in nanofluids [12–14] show that the thermal conductivity of arrest of ultrafine oxides “light” nanoparticles of aluminum, silicon, and titanium in water at a bulk concentration of several percent transcend the thermal conductivity of pure fluid by tens of percent [116].

The outcome of the experiment with nanoparticles of various sizes show that the thermal conductivity of a fluid based on larger particles is well declared using Maxwell's theory [13,18]. First of all, the data received were correlative with theoretical models which were cultivated to report the thermal conductivity and roughly dissipate suspensions. The first such model was constructed by Maxwell [13], who obtained the relation between the thermal conductivity  $\lambda$  of suspensions and the base fluid  $\lambda_0$ . Analysis of the effect of the nanoparticles size on the thermal conductivity coefficient ( $\alpha$ ) shows the  $\lambda$  coefficient of nanofluids growth with a magnification of nanoparticles size [15]. The modeling of the thermal conductivity coefficient of a nanofluid is presented in [16] as a function of different nanoparticles' masses. The authors found out that  $\lambda$  at fixed sizes and concentrations of nanoparticles increases with a rise in their mass. The dependence of nanofluid's thermal conductivity coefficient on the mass of nanoparticles means the same dependability on the density of particles at the same size.

The thermal conductivity coefficient of nanofluids is also influenced by the shape of nanoparticles, which can be spherical, cylindrical, prismatic, flat, and elliptical. Thus,

in [13,14], the thermal conductivity of nanofluids with ZnO “heavy” nanoparticles having prismatic and spherical shapes was experimentally detected at different bulk concentrations of nanoparticles in the range from 0.05 to 5.0%. It was found that the  $\lambda$  coefficient of nanofluids with zinc oxide nanoparticles increased by 12.0% and 18.0%, respectively, for the globular and prismatic shapes of nanoparticles at  $\varphi = 5.0\%$ , compared to the  $\lambda$  coefficient of the base fluid—water. Nevertheless, many experimental data received to date have a wide scatter and often contradict each other. Some of the data indicate an anomalous increase in the thermal conductivity of nanofluids in comparison with theory [12]. Notwithstanding, in the course of joint research carried out by organizations from different countries, no anomalous increase in thermal conductivity at low concentrations of nanoparticles was found [17]. The classification of nanofluids and the analysis of theoretical advances to modeling the transfer coefficients are given in [19]. In particular, it is noted that a rigorous theory of transfer processes in nanofluids has not yet been developed, and the application of thermal conductivity modeling by molecular dynamics methods still gives predictions different from the classical theory [33–41]. However, none of the works mention how to avoid sediment on the bottom of the engine cooling channel of “light” nanoparticles under the action of inertial and gravitational forces. The main questions addressed in the article are the following: factors influencing the thermal conductivity coefficient of nanofluids (including very high value in pure hydrogen or hydrogen containing); boiling of liquid in the cooling jacket of the engine cylinder head; behavior of nanoparticles and devices with nanoparticles in the engine cylinder head cooling system; the discussion of the results [117–184], taking into account degradation of modern structural materials under the hydrogen containing environment influence [2,24,32,43–51,63,118,175,176].

### 3. Problem Formulation

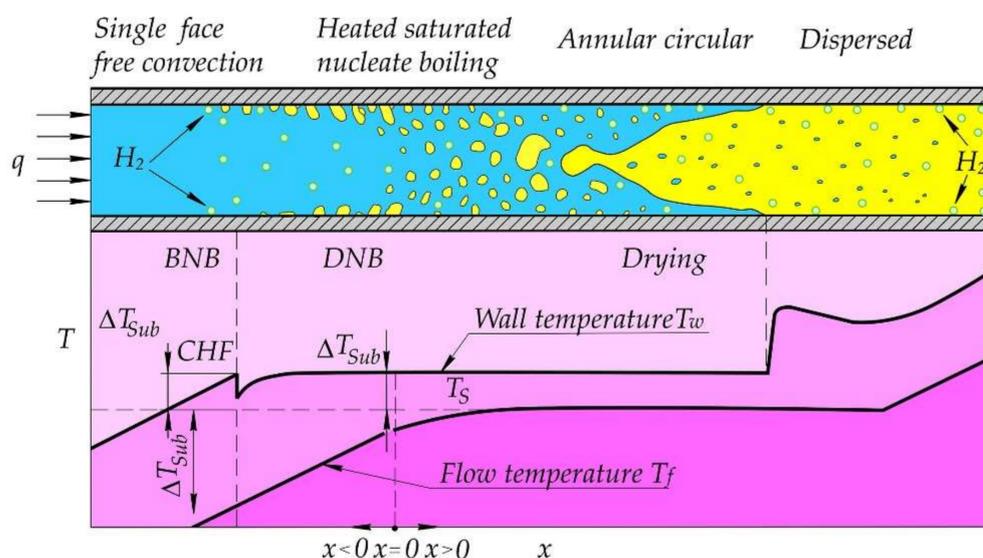
Nanofluids can be used in heat exchange systems for cooling machines and units for various purposes: in disc-shoe brakes of hoisting machines, in self-ventilated disc-shoe brakes of vehicles, in tape-shoe brake pulleys of drawworks. In this case, hydrogen containing cooling systems with nanoparticles can be stationary and rotating. The purpose of this work is to substantiate the role of nanoparticles and their devices in increasing the thermal conductivity of a fluid in the internal combustion engine’s cooling system.

### 4. Fluid Boiling in the Cooling Jacket of the Engine Cylinder Head

Boiling is the thermal process of substance transition from a liquid to a gaseous phase, which occurs near a heated solid surface or in a layer of superheated liquid near the surface. The boundaries of the phase transition arise in the process of vaporization during boiling. Boiling can occur in a stationary and mobile liquid volume. The second option takes place in the cooling system of an internal combustion engine.

The bulk saturation temperature of the liquid  $T_s$  is taken as the reference point, considering the boiling of the liquid. Liquid below the saturation volume  $T_f$  is called underheated temperature. Underheating is indicated by  $\Delta T_{Sub} = T_s - T_f$ . In relation to the jacket’s wall overheating is the excess of the saturation temperature. The difference between the wall temperature  $T_w$  and the saturation temperature is called overheating and is denoted by  $\Delta T_{Sub} = T_w - T_f$ .

The boiling process of an underheated liquid in a channel with heat supply from the walls is characterized by a number of alternating modes as the heating increases. The regularities of changing the parameters of the heated liquid in the engine’s cooling system channel of the cylinder head are shown in modified Figure 1 [13].



**Figure 1.** Regularities of the heated liquid parameters' changes in the channel of the engine's cylinder head cooling system: *BNB* and *DNB*—the beginning of nucleate boiling and its development; *CHF*—point of critical heat flow;  $x$ —mass steam quality [13].

The first segment on the graph is the single-phase free convection mode at nonsteaming conditions. As the bulk temperature of the wall rises above the saturation temperature of the liquid, vapor bubbles begin to form in microcavities and irregularities on the surface of the jacket wall. This point is called the beginning of nucleate boiling (hereinafter-*BNB*). At some distance from the *BNB*, bubbles are formed on the inner surface of the jacket. With heating increase, the bubbles grow in size and begin to detach from the wall. From this moment, the flow becomes two-phase. With further heating, the rate of growth and detachment of bubbles increases, and they merge into steam jets coming from the wall surface. This process is called developed (advanced) nucleate boiling (hereinafter *DNB*).

Heat transfer between *BNB* and *DNB* in this mode is mainly convective with an increasing input from boiling. With heat transfer constant increase at the *BNB* point, a decrease in the wall temperature occurs, due to the fact that part of the heat is spent on the transition phase. With an enlargement of the heat supply, convective heat transfer decreases, and by the time of the transition to the *DNB* it noticeably decreases.

Local heat exchangers with different shapes and masses provide intensive heat removal from different levels of the base fluid circulating in stationary and rotating equipment cooling systems. When removing Joule heat using a local heat exchanger in a branch of a thermoelectric cooler, the Peltier effect increases significantly. Local heat exchangers with different shapes and masses provide intensive heat removal from different levels of the base fluid circulating in stationary and rotating equipment cooling systems. When removing Joule heat using a local heat exchanger in a branch of a thermoelectric cooler, the Peltier effect increases significantly. The goal of enhanced heat transfer is to encourage or accommodate high heat fluxes. Cooling is one of the most important challenges facing engine performance. Due to limited space at the front of the engine, the size of the radiator is restricted and cannot be essentially increased. Therefore, it is necessary to increase the heat transfer capabilities of working fluids. With the advancement of nanotechnology, the new generation of heat transfer fluids called nanofluids have been developed and these fluids offer higher heat transfer properties compared to that of conventional automotive engine coolants [183]. One cooling technique that has demonstrated good performance in the cooling of electronics is the Peltier effect thermo electric cooler (*TEC*). The (*TEC*) is compact and provides a temperature differential below the ambient conditions without the need for moving parts or vapor compression plumbing [184].

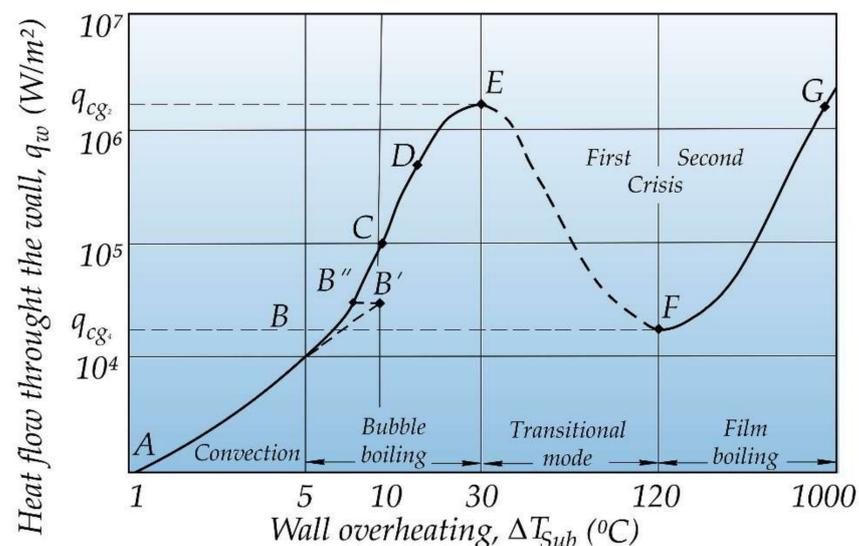
The bubbles detached from the wall after the *BNB* have a hydrogen saturation temperature of the fluid, while the fluid itself is subcooled in the flow. In this case, vapor and liquid are in a nonequilibrium thermodynamic state. When the liquid reaches the saturation temperature, an equilibrium state of the two-phase flow is established, and the boiling mode is called saturated. The equilibrium state is characterized by the relative enthalpy of the flow  $x_b$ :

$$x_b = \frac{h_f - h'}{r} \quad (1)$$

here,  $h_f$ —specific enthalpy of the flow;  $h'$ —specific enthalpy of liquid in saturation state;  $r$ —specific heat of vaporization.

The relative enthalpy has a negative value at subcooled boiling and is equal to the mass vapor content  $x$ , that means it is in the range  $0 \leq x \leq 1$  at the saturated state.

The boiling curve is the dependence of the heat flow through the wall on the wall temperature or the degree of wall overheating. An example of a boiling curve is shown in Figure 2. The first segment of the  $A - B$  curve is a zone of free convective heat transfer, there is no boiling at this stage. Point  $B'$  corresponds to *BNB*. The transition from point  $B'$  to point  $B''$  goes with the temperature drop which is associated with the consumption of heat, needed for the steam bubbles formation [16,101,104,108,137,139,143,145,150,157,159]. In the transient mode, the intensity of the process is influenced by various factors: the physical properties of the liquid and the material of the heating wall, the shape and orientation of the heating surface, its roughness, etc. This is followed by the area of partially developed nucleate boiling ( $B'' - C$ ), which passes into the *DNB* ( $C - D$ ). Point  $D$  in the nucleate boiling mode corresponds to the *CHF*. At this moment, an insulating vapor film begins to form on the inner surface of the wall, affecting heat exchange processes. A transition to film boiling occurs on the  $D - E$  segment, and the  $E - F$  segment corresponds to developed film boiling. The first crisis is characterized by the value  $q_{cr}$ , which depends mainly on the properties of the liquid, the density of its vapor, the acceleration of gravity, the shape and orientation of the heating surface. In addition to that, the conditions of wettability, roughness, and the material of the heating surface have a certain influence. The position of the second boiling crisis ( $q_{cg2}$ ,  $\Delta T_{cg2}$ ) is determined by the same parameters as the first crisis. At the same time, there are two fundamental approaches to determining the position of the second crisis—hydrodynamic and thermodynamic. The part of the  $D - E$  curve marked with dots denotes a sharp jump in the wall temperature after the *CHF*.



**Figure 2.** Regularities of modification in the heat flow penetrating the wall of cylinder head cooling jacket from the wall of its overheating.

With a heating increase the mode of developed nucleate boiling is replaced by slug, annular, and dispersed modes which are characterized by an increase in the volumetric vapor content. When the layer of liquid covering the wall evaporates, it dries up and that goes with a sharp decrease in the heat transfer coefficient, which leads to an increase in the bulk temperature of the wall. Heat fluxes corresponding to these modes are outside the range which is typical for engine cooling systems [60,82,124,160].

In addition to the drying mode, a decrease in heat transfer can also be observed with developed nucleate boiling and it is associated with the vapor layer formation caused by the accelerated growth of bubbles and its coalescence. Ultimately, the vapor film completely covers the surface, isolating it from the liquid. This mode is called film boiling. The point of transition to film boiling corresponds to the maximum heat flux and is called the point of critical heat flux (hereinafter *CHF*). It was established that the introduction of light nanoparticles of aluminum oxide  $Al_2O_3$  into the water in a mass concentration of 0.75% led to an increase in its thermal conductivity coefficient by 60% compared to the base fluid at a coolant temperature of 90 °C, which corresponds to the operating temperature of the engine cooling systems. At the indicated temperature, the base fluid has a thermal conductivity coefficient of  $0.545 \frac{W}{(m^2 \times ^\circ C)}$ , for nanofluid with  $Al_2O_3$  particles its value was  $0.872 \frac{W}{(m^2 \times ^\circ C)}$ . At the same time, a positive change in the parameters of the nanofluid in the engine cooling system was noted: the average movement speed has increased from 0.2 to  $2.0 \frac{m}{s}$ ; the average temperature is in the range of 60–90 °C; heat flux density  $2 \times 10^2$ – $2 \times 10^6 \frac{W}{m^2}$ ; heat transfer coefficient 150–1000  $\frac{W}{(m^2 \times ^\circ C)}$ .

When there is a boiling in the cooling cavities, the calculation of heat transfer becomes more complicated. The phase action process affects both the heat transfer mechanism and the dynamics of the liquid flow [55,68,84,94,158].

## 5. Factors Affecting the Thermal Conductivity Coefficient of Nanofluids

In order to intensify heat transfer in cooling systems of heat engines, the possibility of using cooling nanofluids providing an increased coefficient of thermal conductivity has been recently considered [14]. Nanofluids have new properties that make them promising in the fields of heat transfer, tribology, etc. [15].

Nanofluids are persistent and stable two-phase suspensions “liquid–solid particles”. These solid particles are called nanoparticles, which have sizes up to 100 nm and provide a thermal conductivity coefficient many times higher than the thermal conductivity coefficient of the base coolant. Metals, oxides of metals, and non-metals, as well as materials based on carbon can be used as materials for nanoparticles. Base fluids can be used as liquids that allow to create cooling nanofluids which meet the main operational requirements and this happens when solid nanoparticles are added into liquids. The values of the thermal conductivity coefficients of nanoparticles of various materials are presented in Table 1.

**Table 1.** The values of thermal conductivity coefficient  $\lambda$ ,  $\frac{W}{(m \cdot K)}$  of nanoparticles of various materials at temperature 20 °C [14].

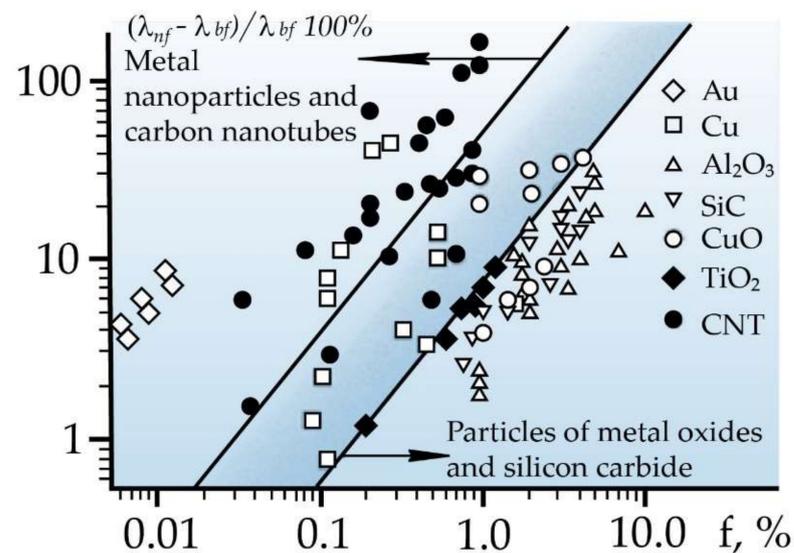
Material of nanoparticles	Thermal conductivity coefficient	$\lambda$ , $W/(m \cdot K)$
Aluminum, Al		237
Aluminum oxide, $Al_2O_3$		40
Cooper, Cu		401
Copper oxide, CuO		76.5
Carborundum, SiC		120
Aurum, Au		318
Carbon nanotubes		~3000
Graphene oxide		~3500
Graphene		~3000–5000

From the working efficiency point of view, nanofluids should be stable, resistant to agglomeration of solid nanoparticles and their precipitation during service life. It is

important to note that there should be no chemical reactions in nanofluids. From the operational point of view, when using nanofluids as a coolant for the engine cooling system, they should not cause corrosion of structural metals which are used in engine building, should not corrode non-metallic materials of seal systems, hoses, gaskets, etc.

The thermal conductivity coefficient of nanofluids is influenced by the following main factors: concentration of nanoparticles in the base fluid; nanofluid temperature; thermal conductivity coefficient of nanoparticles; size, shape and weight of nanoparticles; specific surface area of nanoparticles; technology of nanoparticles manufacturing; methods for dispersing nanoparticles in a base fluid; physical and mechanical properties of the base fluid.

An increase of nanoparticles concentration in base fluids, in the general case, provides an increase of nanofluid thermal conductivity (Figure 3) [13].



**Figure 3.** Dependence of the relative thermal conductivity coefficient of nanofluids on the volume concentration ( $\phi, \%$ ) of various types of nanoparticles:  $\lambda_{nf}$  and  $\lambda_{bf}$  thermal conductivity coefficients of the nanofluid and the base fluid [16].

It should be noted that there is a general tendency towards a linear dependence of the thermal conductivity coefficient on the nanoparticles concentration. The nonlinear dependence of the thermal conductivity coefficient on the concentration of carbon nanotubes and nanoparticles having a spherical shape is presented in [13,14]. Nanofluids that are made based on nanoparticles with more thermally conductive materials show a greater increase in the  $\lambda$  coefficient compared to less thermally conductive materials.

The thermal conductivity coefficient of nanofluids with planar two-dimensional nanoparticles depends on the specific surface area of those particles, i.e., on the ratio of surface area of a particle in its mass (Table 2) [13].

**Table 2.** Thermal conductivity coefficient of nanofluids with flat nanoparticles depending on their specific surface area at various mass concentrations of nanoparticles in the base fluid ( $\varphi_m$ ) [14].

$\varphi_m, \%$ $s, \text{m}^2/\text{g}$	Thermal Conductivity Coefficient $\lambda, \text{W}/(\text{m}\cdot\text{K})$			
	0.025	0.05	0.075	0.1
300	0.66	0.68	0.70	0.72
500	0.69	0.72	0.74	0.77
750	0.71	0.75	0.77	0.80

One of the perspective ways to control the value of nanofluids' thermal conductivity coefficient is the concentration of nanoparticles. The technology for producing nanoparticles and the method of their dispersion in base fluids determine many of the factors considered. Three methods of dispersion are best known: method 1—mechanical crushing of nanoparticles; method 2—the use of polymers wrapping around the nanoparticles; method 3—the usage of filtration of nanoparticles.

All three methods will be implemented further on.

All other conditions being equal, the technology of dispersing or nondispersing the same solid nanoparticles in different base fluids will affect the thermal conductivity of the nanofluid.

When creating nanofluids, it is necessary to select the base fluid, the material of nanoparticles and their shape, based on the energy load of the engine cylinder head.

## 6. Behavior of Nanoparticles in the Engine Cylinder Head Cooling System

Let us consider the types of nanofluids and their thermophysical parameters. The dynamic viscosity of a liquid is primarily defined by molecular interactions that limit the mobility of molecules. In a liquid, a molecule can penetrate into an adjacent layer only when a crack appears in it, sufficient for the molecule to penetrate it. The formation of cracks ("loosening" of the liquid) requires the activation energy of viscous friction. This energy decreases with temperature increase and pressure decrease. This is one of the reasons for the sharp decrease in the viscosity of the liquid with increasing temperature and its growth at high pressures.

The appearance in dispersed systems of spatial structures which are formed by macromolecules causes a sharp increase in viscosity. During the structured fluid flow, the work of the external force is spent not only on overcoming the true (Newtonian) viscosity, but also on the destruction of the structure. The viscosity of a liquid depends on the chemical structure of the molecules and increases with the increase of molecular weight. Studies have shown that nanofluids, starting with a certain concentration of nanoparticles in them, become non-Newtonian [12]. The considered water-based nanofluids with copper oxide ( $CuO$ ) nanoparticles at their volume concentrations above 3.0% turn out to be viscoplastic, and their rheology is described by power functions for the liquid. The degree of rheology deviation of nanofluids from Newtonian values increases with an increase in these concentrations. The difficulty lies in the fact that the determination of the heat transfer coefficients is a complex task, since this requires the values of nanofluids' dynamic viscosity and their thermal conductivity coefficients.

The heat transfer coefficient of a nanofluid can be increased by varying the size of the particles, i.e., their interaction area with the liquid or by converting it into vapor. At the same time, an increase of particle size contributes to a decrease of heat transfer coefficients. In addition, during heat transfer in systems with nanofluids, the volume concentration of nanoparticles and their thermal conductivity coefficient have the main effect [35,53,77,84,89,95,114,132,150,158].

The fluid is coming into motion under the influence of volumetric and surface forces. Volumetric forces occur as a result of the fluid density gradient. The surface forces are caused by a local change in the surface tension of the fluid, which is mainly associated with the appearance of a nonuniform distribution of the bulk temperature or concentration of nanoparticles on the surface, which is, as a rule, a consequence of a change in their thermodynamic state in the fluid volume (the Marangoni effect).

Concentration-capillary convection contains several new hydrodynamic effects caused by the concentration inhomogeneity of nano-heat carriers close to the surfaces of the cooling channel. This facilitates the appearance of bubbles and drops near the microroughness of their surfaces. The structure of nanocarriers movement in the cavity of the cooling channel depends on its shape, configuration, and mechanical cleanliness of the cavity surface, as well as on the location in the area of the heated engine cylinder head.

In this case, surface forces prevail over volume forces arising in nano-heat carriers. This condition is typical for thin horizontal layers and films of fluid, near the surface of droplets and air bubbles in the fluid. There are two main factors to consider. The first factor is that the specific time of heat diffusion is hundreds and even thousands of times shorter than the time of existence of concentration inhomogeneities. As a result, the latter exist much longer in fluids than the thermal ones, and their duration and action intensity of capillary forces at the interface increases many times. This promotes the intensification of heat removal from the nano-heat carriers to the walls of the channel cavity. The second factor is the adsorption of nanoparticles on the fluid surface, which promotes the concentration-capillary drift of air bubbles. The action of Marangoni forces on the free fluid surface causes its movement in the direction of increasing surface tension. The surface lugs away the adjacent layers of liquid. As a result, if the free surface belongs to the bubble, it begins to be displaced in the direction opposite to the liquid flow. This ability of air bubbles to spontaneously move in the fluid in the direction of decreasing surface tension causes their capillary drift [73,78,85,95,109,128,136,151].

### 7. Devices with Nanoparticles in the Engine Cylinder Head Cooling System

If bubbles are located on a horizontal liquid layer bounded at the top and sides of the channel walls, such conditions suppress their floatation.

The action of the condensation-capillary effect is observed only for a limited time, determined by the rate of the adsorption process.

Let us note that in the thermal version of the problem of fluid motion near stationary bubbles and drops, only its stationary flow develops (the ratio of the kinematic viscosity and thermal diffusivity coefficients, as a rule, does not exceed one order of magnitude).

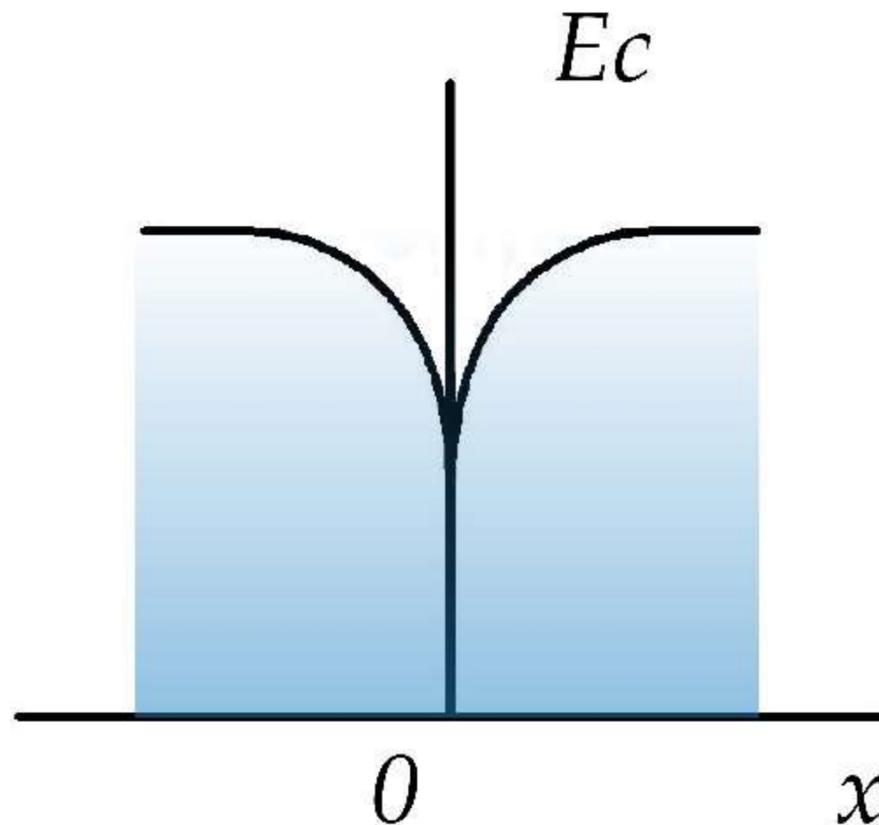
It has been established that as soon as the ascending capillary movement of the bubble over the surface stops, the dynamic equilibrium of the concentration “cap” (as being heavier than the surrounding liquid) is violated. The restoration of the difference in the concentration of nano-heat carriers between the poles of the bubble again activates capillary forces, which contribute to a sharp acceleration of the upward current. As a result, an intense convective liquid motion occurs at the side surface of the cylindrical bubble due to the appearance of two symmetric vortices. While developing, vortex cells capture an increasing volume of liquid with a high concentration of nanoparticles. Due to this, the average density of the nano-heat carrier in the cells increases, and they move downward, cutting off the liquid stream from the lower pole of the cells, which backs up its movement [74,92,113,129,135,149,156].

Displacement of electrons in powder particles under the action of a temperature field goes with potential energy of interaction between polarized charges particles:

$$U_e = -qN(\varphi^+ - \varphi^-)/2 \quad (2)$$

here,  $q$ —the average charge rate of the dipoles;  $N$ —algebraic sum in  $1 \text{ m}^3$ ;  $\varphi^+$  and  $\varphi^-$ —self-consistent of positive and negative the average value of the charges of the dipoles; accepting the Gibbs-Helmholtz equation is a thermodynamic equation  $U = F - T\left(\frac{\partial F}{\partial T}\right)_V$  and equality in partial derivatives; partial differential  $\left(\frac{\partial F}{\partial T}\right)_V = 0$ , we come up with  $U_e = F$ , position  $F$ —free energy of polarized nanoparticles.  $T$ —temperature.

Due to the local nature electric fields of nanoparticles polarized and the long-range action of the Coulomb synergistic, a drastic change in the polarization charge of one of the particles goes with a change in the potential energy (Figure 4) of the powder  $U_e$  and hence a significant change in the state of all electrons in the system. Accordingly, it is probable to have conditions under which all free electrons of the powder nanoparticles participate in the exchange correlation function synergistic and provide a single system.



**Figure 4.** Dependence of conduction electrons potential energy in the powder particles on the  $x$  coordinate directed along the plane of their contact,  $x = 0$ .

Forced radiation of a thermodynamic system to a permanent state corresponds to a reduction of its inside (adiabatic process) or free energy (isothermal process) of a thermodynamic system.

Nanoparticles' spontaneous polarization with area donor centers situated on the surface of its nanoparticles can be circumspect as a transition phase in the powder electron subsystem to a state whereabouts  $F < 0$ .

The role of contacts between powder nanoparticles in the exchange–correlation function synergistic of their free electrons is obvious by the incoming experimental results.

If globular nickel or aluminum oxide nanoparticles are located between the powder microparticles using an accurately mixed mixture of micro- and nanoparticles, then under the same conditions, the state of spontaneous polarization of the  $KMnO_4$  powder with chemisorbed hydrogen does not appear.

In this case, due to the lack of direct contacts between microparticles, free electrons belong to different particles, the exchange–correlation interaction between them is loosened, so the status  $F < 0$  is not contented.

Therefore, the donor centers its position on the surface of powder nanoparticles given the emergence of self-consistent states of free electrons connected with their common potential wells in the area of contacts between microparticles.

Powder nanoparticles comprise positively loaded donor centers on their area, generating area bending of the zones.

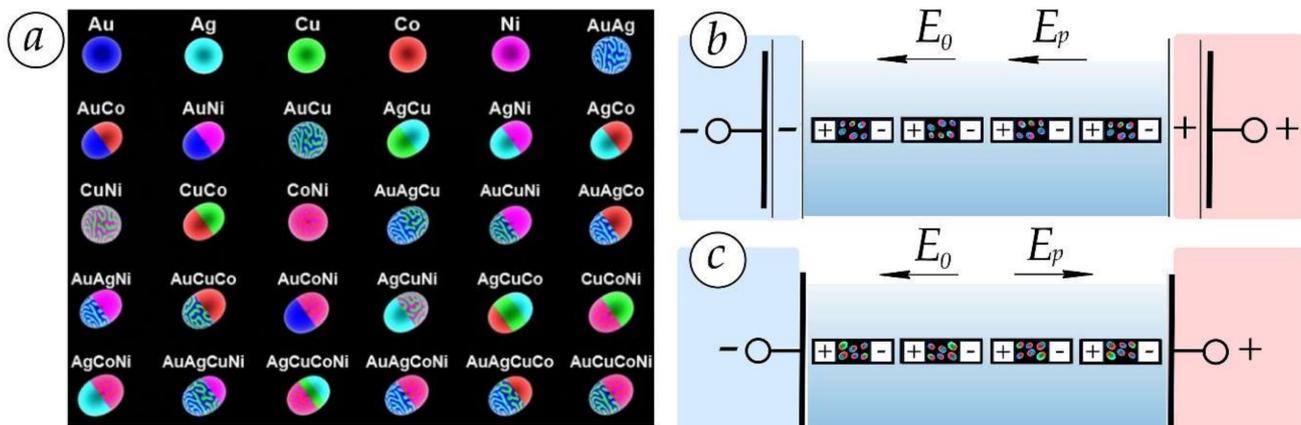
It was fixed that the insertion of light and heavy nanoparticles of aluminum oxide  $Al_2O_3$  into the water in a mass concentration of 0.75% led to a magnification in its thermal conductivity coefficient by 60% compared to the base fluid at a coolant temperature of 90 °C, which matches the operating temperature of the engine cooling systems.

At the shown temperature, the base fluid has a thermal conductivity coefficient of  $0.545 \frac{W}{(m \times ^\circ C)}$ ; for nanofluid with  $Al_2O_3$  nanoparticles its meaning was  $0.872 \frac{W}{(m \times ^\circ C)}$ .

Let us view a powder model in the form of a nanoparticles chain. We will suppose that the outermost nanoparticles of the chain are in contact with a spherical dielectric.

When a powder is polarized by a temperature field, free electrons of the nanoparticles are crowded out under the action of the field.

Opposite polarization charges located on opposite boundaries of the particles chain create an additional field inside the powder, the intensity vector  $E_p$  of which is directed in the same way as the intensity vector of the temperature field of the liquid  $E_0$  (Figure 5b).



**Figure 5.** Unary, binary, ternary, and quaternary types of nanoparticles synthesized for industrial application [166] (a). Model of a powder in the form of grouped particles chain, the outermost of which are in interaction with devices that have nanoparticles coated with dielectric (b) and metal (c) shells.

Consequently, the following conditions are met:

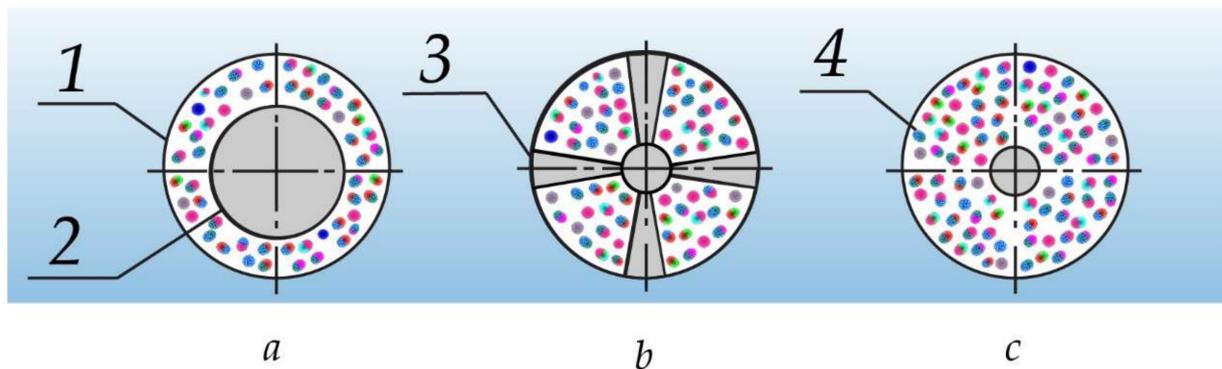
$$E = E_0 + E_p = E_0 + \aleph E = \frac{E_0}{(1 - \aleph)} \quad (3)$$

where,  $E$ —field density in nanoparticle;  $E_0$ —temperature field density;  $E_p$ —field density of polarizing charges located at counter boundaries of the nanoparticle grade;  $\aleph$ —its dielectric impressionability. Let us denote  $1 - \aleph = e$ . We can assume that the  $\varepsilon$  value is a macroscopic characteristic of the powder if referable to the connection among its particles, the free electrons of the powder form a single system. The amount  $\varepsilon$  will be called the static dielectric constant of the powder. Consequently to the Kramers–Kronig dispersion bonds, one of the provision  $\varepsilon \geq 1$ ;  $\varepsilon \leq 0$  is complacent for the static dielectric constant of a random field-polarized material. Accordingly, using the expression  $1 - \aleph = e$ , where  $\aleph > 0$  for the static dielectric constant of the powder, we obtain  $\varepsilon < 0$ .

According to Figure 5c, the energy level of the nanofluid will be weakened since its components are directed in different directions.

Figure 6a–c shows device schemes stuffed with nanoparticles with different densities, which act as local heat exchangers at different levels of nanofluid driving flow. The dimensions of the devices depend on the reduced diameter of the cooling channel. Nanoparticle devices can have a polymer coating on one of the shells.

According to Figure 6b, if the fluid absorption occurs from below and by dry nanoparticles of a spherical device, then the radius of the widest hole should be taken; if absorption occurs from above or the body has been pre-wetted, then the radius of the narrowest part of the hole should be taken.



**Figure 6.** Structure diagrams of devices made of various weights nanoparticles, in the form of (a)—washers with an inner hole; (b,c)—spherical shape with diffusers and nanoparticles; 1 and 2—outer and inner shell; 3—diffuser holes; 4—nanoparticles.

Adding to water of aluminum oxide  $Al_2O_3$  “light” and “heavy” nanoparticles in a mass concentration of 0.75% led to an increase of its thermal conductivity coefficient by 60% compared to the base fluid at a coolant temperature of 90 °C, which is characteristic of the engine cooling systems operating temperature. Thus, at the indicated temperature, the base fluid had thermal conductivity coefficient of  $0.545 \frac{W}{(m \times ^\circ C)}$ , while for nanofluid with  $Al_2O_3$  its value was  $0.872 \frac{W}{(m \times ^\circ C)}$ , i.e., increased by 58.0%. At the same time, a parameter change of the nanofluid in engine cooling system was achieved; average travel speed from 0.2 dL to 2.0  $\frac{m}{s}$ ; average temperature 65–90 °C; heat flux density  $2 \times 10^2$ – $2 \times 10^6 \frac{W}{m^2}$ ; heat transfer coefficient 150–1000  $\frac{W}{(m^2 \times ^\circ C)}$ ; heat transfer coefficient 100–750  $\frac{W}{(m^2 \times ^\circ C)}$ .

Therefore, it has been established that nanoparticles of the same or different chemical composition, introduced into devices of various shapes and masses, physically interact with each other. The choice of a device that is a local heat exchanger depends on the shape of the cooling system chamber and the thermodynamic state of the base fluid. Devices with nanoparticles can be given additional effects: diffuser, confuser, thermoelectric, etc. Local heat exchangers without a base fluid enhance the Peltier effect by reducing the amount of Joule heat in the branch of the thermoelectric cooler. Nanofluids can be used in heat exchange systems for cooling machines and units for various purposes: in disc-shoe brakes of hoisting machines, in self-ventilated disc-shoe brakes of vehicles, in tape-shoe brake pulleys of drawworks. In this case, hydrogen containing cooling systems with nanoparticles can be stationary and rotating. So far, nanoparticles have been used in engine oil, transmission oil, and radiator coolant to enhance heat transfer removal from vehicle engines [182].

## 8. Conclusions

The results of theoretical and experimental studies of nanofluids and devices made of nanoparticles of various weights in the cylinder head cooling system allow us to state the following:

- an increase of the cooling nanofluid thermal conductivity coefficient is determined by a change in the mass concentration of aluminum oxide nanoparticles in the base fluid. This will make it possible to create coolants with such thermophysical characteristics that are required to ensure intensive heat exchange in engine cooling systems of various capacities;
- a viscosity has been achieved, at which, on the one hand, losses of nanofluid through all kinds of seals and connecting nodes will be excluded, and, on the other hand, significant power consumption will not be required for pumping the nano-heat carrier through the engine cooling system;
- the set of gradients in the carrier stream of nanofluids should provide them with such a boiling point that will be 25–30 °C higher than the maximum allowable temperature

- of the nano-heat carrier in the cooling system, which will prevent the appearance of air-vapor cork in it and reduce losses of the nano-heat carrier during evaporation due to local heat exchangers, i.e., devices with nanoparticles;
- the possibility to provide a needed engine temperature mode with a relatively small volume of nano-heat carrier circulating in the cooling system is ensured by a high specific heat capacity;
  - thermodynamics and molecular kinetic theory complement each other, the same theoretical and experimental material is a subject to synthesis and complex analysis; moisture transfer is inseparable from heat transfer and the phenomenon of heat and mass transfer must be considered in its inseparable connection: therefore, it is proposed to introduce a new concept “potential of heat-conducting transfer by nanoparticles in a fluid”.
  - it has been established the role of contacts between powder parts in the exchange–correlation interaction of their free electrons is evidenced by the following experimental results. If spherical nickel or aluminum oxide nanoparticles are placed between the powder microparticles using a thoroughly mixed mixture of micro- and nanoparticles, then under the same conditions, the state of spontaneous polarization of the  $KMnO_4$  powder with chemisorbed hydrogen does not appear.
  - Thus, the permissible temperature level of internal combustion engines is ensured by intensifying heat transfer in cooling systems due to the modification of coolants with “light” and “heavy” nanoparticles.

**Author Contributions:** The scope of work of individual authors during the performance of this project was the same. The authors performed the study together and then analyzed its findings. The paper was written together. The authors equally contributed to the paper assembly. Partially: conceptualization, A.B., V.K. and K.F.A.; data curation, O.B., D.V. and V.S.; formal analysis, D.Z., I.B., V.K. and M.O.; investigation, A.B., M.K. and K.F.A.; methodology, A.B., O.B., K.F.A. and M.K.; writing—original draft, A.B.; writing—review and editing, A.B. and K.F.A. All authors have read and agreed to the published version of the manuscript.

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## Nomenclature and Abbreviations

$\lambda$	thermal conductivity coefficient,
$\lambda_0$	thermal conductivity coefficient of base fluid,
$Q$	the amount of heat,
$T$	temperature,
$P$	pressure,
$V$	specific volume,
$q$	specific heat flux,
$T_s$	bulk liquid saturation temperature,
$T_f$	saturation temperature,
$T_w$	wall temperature,
$\Delta T_{sub}$	$\Delta T_{sub} = T_s - T_f$ .—underheating,

BNB	the beginning of nucleate boiling,
DNB	the development of nucleate boiling,
CHF	point of critical heat flow,
TEC	thermo electric cooler,
$x$	mass steam quality,
$x_b$	the relative enthalpy of the flow,
$h_f$	specific enthalpy of the flow,
$h'$	specific enthalpy of liquid in saturation state,
$r$	specific heat of vaporization,
$q_{cg2}$	position of the second boiling crisis,
$\Delta T_{cg2}$	position of the second boiling crisis,
$\varphi$	the volume concentration,
$\lambda_{nf}$	thermal conductivity coefficients of the nanofluid,
$\lambda_{bf}$	conductivity coefficients of the base fluid,
$\varphi_m$	mass concentration of nanoparticles in the base liquid,
$s$	specific surface area,
$U_e$	displacement of electrons in powder particles,
$q$	average value of dipoles charges,
$N$	number of particles in $1\text{ m}^3$ ,
$\varphi^+$ and $\varphi^-$	self-consistent potentials of positively and negatively charged regions of particles created by all charges of the system,
$E$	field density in powder,
$E_0$	temperature field density,
$E_p$	field density of polarizing charges located at opposite boundaries of the powder layer,
$\aleph$	dielectric susceptibility,
$\lambda$	thermal conductivity coefficient of suspensions.

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