Theoretical Study of the Film Boiling Heat Transfer of Different Nanofluids on the Vertical Heated Surface

Kadhum Audaa Jehhef1 Salah Haji Abid Aun2 and Mohamed Abed Al Abas Siba3
1Department of Mechanical power, Institute of Technology, Middle Technical University, Baghdad, Iraq , Email: kadhumaudaa@gmail.com
2Department of Mechanical power, Institute of Technology, Middle Technical University, Baghdad, Iraq , Email: salah_haji@yahoo.com
3Department of Mechanical power, Institute of Technology, Middle Technical University, Baghdad, Iraq , Email: Moh_siba@yahoo.com

Abstract. The use of boiling nanofluids for cooling high-temperature perforating surfaces allows intensifying considerably the process of cooling by increasing the heat transfer coefficient nanofluid compared to the pure base fluid. A significant influence on the intensity of heat transfer during the boiling of nanofluid will turn out properties of nanoparticles and their concentration in the base fluid, under heating of base fluid to saturation temperature. In this study, the mathematical model of the numerical solution and the results of the simulation calculation of characteristics of film boiling of Al2O3, CuO, ZnO, TiO2, ZrO2 and SiO2 water nanofluid for various nanoparticles concentration $\varphi_\infty$ of (0.1, 0.2, 0.3, 0.4, and 0.5) Water nanofluid on the vertical heated wall were presented. The theoretical results obtained allow us to estimate the influence of physical properties of nanofluids on heat and mass transfer during cooling low-temperature surfaces. It is shown that the greatest impact on the processes heat and mass transfer during film boiling nanofluids overheating of the wall depended upon the ratio of temperatures, Brownian diffusion, and concentration of nanoparticles in a base fluid. Also, the results showed that the use of nanofluids as coolants for heat exchange equipment in the mode of supercritical heat exchange increases the heat transfer and accelerate the process of cooling high-temperature surfaces. Increasing the concentration of nanoparticles in the nanofluids will contribute to a greater increase in heat transfer in the supercritical heat transfer due to the low thermal capacity of steam compared to that fluid conductivity. While increasing the nanoparticle concentration will lead to an increase in the effective viscosity of the nanofluids.

Keywords: Nanofluid Boiling, Supercritical Heat Exchanger, Heat Transfer Coefficient.

1. Introduction

Not related to the description of physical processes in the field of supercritical heat exchange for water-cooled nuclear reactors are always attracted the attention of researchers as simple design nuclear power installations, and at the stage of operation of power units [1]. The heat transfer with the formation of film boiling of the coolant can be observed in the reactor core in the following cases: in emergency mode with increased power, when the heat flux density on the heated wall is it becomes more critical, and when the core is refilled as a result loss of coolant.

The main objectives of future research in the field of nano-thermal physics to improve nuclear power plant safety conditions were considered by [2]. The authors concluded that the nanofluids can be successfully used to increase the efficiency of the effectiveness of emergency nuclear cooling systems power units of nuclear power plants. The increasing attention of researchers is attracting the ability to use the nanofluids (suspensions of nanoparticles in the base fluid such as the water) as a coolant to intensify the processes of heat transfer in boiling film. A significant increase in the thermal conductivity of nanofluids compared to...
the base fluid allows hope for an increase in the heat transfer coefficient in nanofluid boiling regimes. However, the results of many experimental studies of heat transfer during boiling nanofluid showed an indication of an increase in heat transfer coefficients compared to the pure base fluid. After analyzing a large number of the amount of experimental data, the authors of [3] noted that there are two groups of data on the heat transfer when film boiling of the nanofluid depending on nanoparticle concentrations for low concentration of (less than 0.4% by volume) is characterized by an increase heat exchange by 20-40% but with a higher concentration, there is a decrease in heat transfer by 10-30%. To ensure no dangerous effect of heat exchange equipment in the modes boiling it will need a reliable prediction of conditions the occurrence of supercritical heat transfer. In contrast to the bubble boiling regime, the new film boiling of base fluids is characterized by the heating surface is separated from the mass of boiling base fluid bones to steam. Significant effect on the intensity heat transfer during film boiling have physical properties of a boiling medium, geometric dimensions and orientation of the surface in the field of mass forces, pressure and under-heating of base fluid to saturation temperature and other factors [4]. The result of the assessment of the use of nanofluids in the emergency cooling system reactor casing lagging was presented [5]. The results showed the nanofluid increased the cooling process of the reactor vessel at critical heat flux from 1.2 MW/m² to 1.88 MW/m² with bulk nanoparticle concentration of 0.001%. The use of nanofluids for cooling the active zone of the reactor vessel will hard of metal products and will allow to speed up the cooling process significantly [6]. The temperature change charts presented in walls indicated that the dependence of the speed of the process cooling on the number of tests. It was discovered that with their increase nanoparticles accumulate on the surface of the sphere; this leads to destabilization of the smooth film and greatly accelerates the cooling process. There is a strong effect of nanofluid under-heating at the cooling rate. In the underheated base fluid film of the steam is thinner and the transition from film boiling is faster. In more detail, the mechanism of film boiling is considered in [7]. It presents the results of the heat transfer cooling spheres and stainless steel rods in pure water and in case of using nanoparticles of Al₂O₃ with a concentration of 0.1 % by volume. The experiments were carried out at atmospheric pressure for different conditions of fluid under-heating to saturation patterns. Particular attention is paid to the mechanisms film boiling of the nanofluids on clean surfaces. Precipitation on the heated surface led to the formation of the structure of a height of 2-3 microns, similar to sand roughness. The results showed an increase in film thickness with increased overheating walls and reducing the film thickness of steam with increasing under-heating of nanofluids. However, when boiling saturated base fluid-vapor film thickness increases from 105 microns with overheating of the wall 200 K to 142 microns with overheating 700 K. When boiling nanofluid under-heating to the saturation temperature of the film thickness decreases to 24 microns at under-heating is 70 K and overheating of the wall is 200 K [7]. The effect of nanoparticles on the heat transfer, taking into account the phase transitions were also studied in [8]. In these studies, the results showed that the heat transfer characteristic during boiling base fluid nitrogen and water on a heated surface with a nanostructured porous coating. On surfaces coated with heat transfer efficiency increased 4 times for base fluid nitrogen and 3.5 times for water compared to the ratio volume of heat transfer on a smooth surface. Significant the effect of nanoporous coatings has on the development phenomena with a stepped energy release. With the rapid increase in heater power value, critical heat flux is 2 times more than in stationary mode. [9] studied experimentally the heat transfer by pool boiling characteristics of gamma Fe₃O₄ aqueous nanofluids on a flat disc heater with 0.1–0.3% concentration of nanoparticle and heat flux was 0–1546 kW/m². [10] carried out experiments to investigate the boiling heat transfer characteristics of Al₂O₃-water nanofluids. The volume concentration of Al₂O₃ nanoparticles was varied from 0.07% to 0.1%. Their results showed that the acceleration direction and magnitude had significant influences on the boiling heat transfer. The widespread of use nanofluids in technology impeded by a lack of understanding of the mechanisms responsible for drastic changes in film boiling heat transfer in base fluids (water) with the addition of nanoparticles Al₂O₃, CuO, ZnO, TiO₂, ZrO₂ and SiO₂ water nanofluid for various nanoparticles concentration φ∞ of (0.1, 0.2, 0.3, 0.4, and 0.5) to the pure water, and the absence of forecasting these
The purpose of the present study is to analyze the effect of thermal and fluids physics properties of using nanofluid on heat transfer during film boil mode.

2. Mathematical Modeling

In the present study, the heat transfer during film boiling of Al₂O₃, CuO, ZnO, TiO₂, ZrO₂ and SiO₂ water nanofluid for various nanoparticles concentration φ∞ of (0.1, 0.2, 0.3, 0.4, and 0.5) water nanofluids was considered on a flat vertical heated surface. Schematic diagram of the domain of heat and mass transfer is presented in Figure 1. The thickness of the vapor film on the wall is small compared to the height of the wall, which allows you to simulate the film in the approximation of the boundary layer. [7]. The temperature of the heated surface is constant (Tₚ), and the vapor interface temperature is base fluid (T∞) equal to the saturation temperature of the Al₂O₃, CuO, ZnO, TiO₂, ZrO₂ and SiO₂ water nanofluid for various nanoparticles concentration φ∞ of (0.1, 0.2, 0.3, 0.4, and 0.5) water nanofluid at a given pressure. Wall temperature is considered higher than the Al₂O₃-water nanofluid temperature (T_w > T∞). The concentration of nanoparticles in the vapor is constant and equal to the concentration nanoparticles in base fluid (φ∞). The present mathematical model does not take into account the effect of heat exchange processes of change structure of the heated surface as a result of nanoparticles but it allows us to estimate the effect of various thermal parameters on the intensity of deposition of nanoparticles on a heated wall. The following assumptions are made as:

1. Neglected the inertia force in the film boiling.
2. The viscosity and thermal conductivity depended on the concentration nanoparticles.
3. The convective heat transfer and mass transfer in a vapor film in the direction of flow (along with the x coordinates) significantly less than in the direction perpendicular to the wall (along the y coordinate).
4. The mechanical interaction on the base fluid-vapor interface is not taken into account.

Thus, for the steady-state, the heat and mass transfer in the steam can be described by the following system of equations [8]:

\[
\frac{d}{dy}\left(\mu \frac{du}{dy}\right) = -g\left[(1 - \varphi_{\infty})\rho_v + \varphi_{\infty}\rho_p\right] \tag{1}
\]

\[
0 = \frac{d}{dy}\left(k \frac{dT}{dy}\right) + \rho_p c_p \left(D_B \frac{d\varphi}{dy} \frac{dT}{dy} + \frac{d\varphi}{dy} \frac{dT}{dy} \right) \tag{2}
\]

Figure 1. Scheme of the simulation area.
0 = \frac{d}{dy} \left( D_B \frac{d\varphi}{dy} + \frac{D_T}{T_\infty} \frac{dT}{dy} \right) \quad (3)

Viscosity and thermal conductivity in a vapor film are determined by the following formula:

\begin{align*}
\mu_{nf} &= \mu_f \left[ \frac{1}{(1-\varphi)^m} \right] \quad (4) \\
k_{nf} &= k_v \left[ \frac{k_p + 2k_f - 2\varphi(k_f - k_p)}{k_p + 2k_f + \varphi(k_f - k_p)} \right] \quad (5)
\end{align*}

Boundary conditions assuming no interaction at the vapor-base fluid interface, it can be written as:

\begin{align*}
u &= 0, \quad T = T_w, \quad \left( D_B \frac{d\varphi}{dy} \right)_{y=0} = -\left( \frac{D_T}{T_\infty} \frac{dT}{dy} \right) \text{ at } y = 0; \\
u &= 0, \quad T = T_\infty, \quad \varphi = \varphi_\infty \text{ at } y = \delta;
\end{align*}

And

\begin{equation}
\frac{d\sigma}{dx} = \frac{q_w}{r} \quad (6)
\end{equation}

The increase in the mass flow rate of steam in the film boiling as a result of boiling is described by the following heat balance equation [11]:

\begin{equation}
G = \int_{0}^{\delta} \rho u dy \quad (7)
\end{equation}

The system of equations (2) and (3) is autonomous with respect to equations (1) and can be solved independently of the equation movement. As a result of integrating the equations (2), (3) taking into account the boundary conditions (6) and (7). Thus, the temperature distribution in the film boiling can be written as:

\begin{equation}
\theta = \frac{1}{3A(K-1)} \left( K + 2 + 3(A + \varphi_\infty)(K - 1) \right) - \\
\sqrt{3A(K-1)(1 - \eta)(3A(K-1) + 2(K + 2 + 3(K-1)\varphi_\infty)) + (K + 2 + 3(K-1)\varphi_\infty)^2} \quad (8)
\end{equation}

And the concentration of nanoparticles distribution in the film boiling can be written as:

\begin{equation}
\varphi = \frac{1}{3(K-1)} \left( (K + 2) \right) - \\
\sqrt{3A(K-1)(1 - \eta)(3A(K-1) + 2(K + 2 + 3(K-1)\varphi_\infty)) + (K + 2 + 3(K-1)\varphi_\infty)^2} \quad (9)
\end{equation}

Where

\begin{align*}
\eta &= \frac{y}{\delta}, \quad \theta = \frac{T - T_\infty}{T_w - T_\infty}, \quad \Delta T = T_w - T_\infty, \quad A = \frac{D_T}{D_B T_\infty}, \quad K = \frac{k_p}{k_f}
\end{align*}

The dimensionless parameter (A) characterizes the effect of wall heating relative to the saturation temperature and relations between temperature and Brownian diffusion. Now we get the expression for the
vapor velocity and the coefficient heat transfer coefficient in the film, taking into account the temperature profile ratios of equation (8) and nanoparticle concentrations of equation (9). Convert formula for the viscosity of nanofluids of equation (4) by using simple approximation:

$$\mu_{nf} = \mu_f \left[ \frac{1}{(1-\varphi)^m} \right] = \left[ \frac{1}{(1-m\varphi)} \right]$$

(10)

The value of (m) can vary wide range [11] and the density of the nanofluids given by:

$$\rho_{nf} = \varphi_{\infty} \rho_p (1 - \varphi_{\infty}) \rho_f$$

(11)

Also, the steam film thickness profile is given by:

$$\delta = \delta_0 \sqrt{\frac{F_G(K,\varphi)}{F_G(A,K,\varphi_{\infty},m,R_{pv},R_{pf})}} \left( \frac{d\theta}{d\eta} \right)_{\eta=0}$$

(12)

Where

$$\delta_0 = \sqrt{\frac{12k_v \mu_v \Delta T_x}{g \rho_f \rho_v}}$$

(13)

The steam film thickness at no nanoparticles given by:

$$R_{pv} = \frac{\rho_p}{\rho_v F_G(K,\varphi)}$$

(14)

The dimensionless velocity U is given by [12]:

$$U = \frac{w_{\mu_v}}{g \delta^2 \rho_f (1-\varphi_{\infty}) + \varphi_{\infty} \rho_f}$$

(15)

Where

$$R_{pf} = \frac{\rho_p}{\rho_f}$$

(16)

And $F_G(A,K,\varphi_{\infty},m,R_{pv},R_{pf})$ represent the complex functions of thermophysical parameters. Using expressions for temperature profile of equation (8), the vapor film thickness of equation (9) and heat conductivity of equation (5), it will get the following expressions for heat transfer coefficient (h) [13]:

$$h = \frac{k}{\delta_0} \left[ F_G(K,\varphi) \left( \frac{d\theta}{d\eta} \right)_{\eta=0} \right]^{3/4} \left[ F_G(A,K,\varphi_{\infty},m,R_{pv},R_{pf}) \right]^{1/4}$$

(17)

And Nusselt number (Nu) depending on the parameters characterizing the properties nanofluids:

$$Nu = \frac{h \delta_0}{k} \left[ F_G(K,\varphi) \left( \frac{d\theta}{d\eta} \right)_{\eta=0} \right]^{3/4} \left[ F_G(A,K,\varphi_{\infty},m,R_{pv},R_{pf}) \right]^{1/4}$$

(18)
By introducing the nanofluid volume fraction \((\phi)\), the thermophysical properties equations of the Nanofluid are presented in Table 1, namely the density and heat capacity.

**Table 1.** The thermophysical properties equations are used in numerical simulations.

| Thermo-Physical Property | Equation | Reference |
|--------------------------|----------|-----------|
| Density                  | \[ \rho_{nf} = \phi \rho_p (1 - \phi)\rho_f \] | [14] |
| Specific heat            | \[ C_{p,nf} = \frac{\rho_p C_p + (1 - \phi)\rho_f C_f}{\rho_{nf}} \] | [15] |
| Dynamic viscosity        | \[ \mu_{nf} = \frac{\mu_f}{(1 - \phi)^{2.5}} \] | [16] |
| Thermal conductivity     | \[ k_{nf} = \frac{k_f + 2k_f - 2\phi(k_f - k_p)}{k_f + 2k_f - 2\phi(k_f - k_p)} \] | [17] |

In the present work, Al\(_2\)O\(_3\), CuO, ZnO, TiO\(_2\), ZrO\(_2\), and SiO\(_2\) nanoparticles were used and Table 2 illustrates all the needed thermophysical properties of nanoparticles and water [11].

**Table 2.** Specification thermophysical properties of several nanoparticles and water at \(T=293\) k [14].

| Material | \(\rho\) (kg/m\(^3\)) | \(C_p\) (J/kg K) | \(k\) (W/m K) | \(\beta\) (1/l K) | \(\mu\) (Pas.) |
|----------|------------------------|------------------|---------------|-----------------|--------------|
| Water    | 998.2                  | 4182             | 0.597         | 2.1 \times 10^{-4} | 993 \times 10^{-6} |
| Al\(_2\)O\(_3\) | 3880                  | 773              | 36            | 1.7 \times 10^{-6} | -            |
| CuO      | 6500                   | 536              | 20            | 2.8 \times 10^{-6} | -            |
| ZnO      | 5600                   | 495              | 13            | 3.6 \times 10^{-6} | -            |
| TiO\(_2\) | 4250                  | 686              | 8.95          | 5.7 \times 10^{-6} | -            |
| ZrO\(_2\) | 5680                  | 418              | 2             | 4.6 \times 10^{-6} | -            |
| SiO\(_2\) | 2200                  | 745              | 1.4           | 5.8 \times 10^{-6} | -            |

3. Results and Discussion

The effect of the parameter \((A)\) on the norm concentration profile of nanoparticles in vapor film is shown in Figure. 2. The results showed that the concentration of nanoparticles in the film is maximum at the vapor-base fluid interface and minimal on the wall. Calculations showed that the concentration of nanoparticles on a heated wall primarily depends on the overheating of the wall relative to saturation temperature, Brownian ratio diffusion, and thermal diffusion. With increasing the parameter \((A)\), the movement of nanoparticles to the wall is reduced and the profile nanoparticle concentration becomes nonlinear. The results indicated that the deposition of nanoparticles on the heated surface during film boiling. The influence of parameters \((A)\) and \((K)\) on the temperature profile in the vapor film is shown in Figures. 3 and 4. For small values of these parameters, the temperature profile is close to linear, but with increasing it, the temperature gradient on the wall increases. The effect of the parameter \((K)\) on the temperature profile is slightly and decreases with increasing \((K)\).

The effect of nanoparticle concentration \((\phi)\) and the parameter \((K)\) on the normalized Nusselt number with small values of the parameter \((A)\) are presented in Figure. 5. It can be seen from this figure, the heat transfer increases with increasing the concentration of nanoparticles in a base fluid, and more intense for small values of \((\phi)\). Increasing the concentration of nanoparticles in the base fluid showed that it increases the influence of the relative coefficient of heat conduction \((K)\) of the heat transfer in a vapor film due to increasing the thermal conductivity of the base fluids. A stronger influence The \((R_{pu})\) and \((R_{pf})\)
parameters provide an effect on the Nusselt number. Also, the increase in the relative density of nanoparticles caused increases in the heat transfer as shown in Figure. 6. The present results obtained allow us to assess the impact six dimensionless parameters of \((A, \varphi_{\infty}, R_{p\infty}, R_p, K, \text{ and } m)\) on the heat transfer during film boiling of the \(\text{Al}_{2}\text{O}_{3}, \text{CuO, ZnO, TiO}_2, \text{ZrO}_2\) and \(\text{SiO}_2-\text{water}\) nanofluid for various nanoparticles concentration \(\varphi_{\infty}\) of \((0.1, 0.2, 0.3, 0.4, \text{ and } 0.5)\) on the vertical heated wall. Increase any of these parameters leads to an increase in heat transfer [16]. The results showed that the maximum enhancement in the Nusselt number for the \(\text{Al}_{2}\text{O}_{3}-\text{water}\) nanofluid and the minimum enhancement in the Nusselt number for the \(\text{SiO}_2-\text{water}\) nanofluid. The greatest influence on heat exchange processes is a parameter \((A)\), which characterizes the wall overheating and the ratio of thermal diffusion and Brownian diffusion. The increase in thermal diffusion contributes to an increase in low productivity, whereas an increase in Brownian diffusion contributes to its reduction. In this case, the main physical factors affecting the intensification of during film boiling of \(\text{Al}_{2}\text{O}_{3}-\text{water}\) nanofluid, overheating of the wall and concentration of nanoparticles near walls. Increasing the concentration of nanoparticles in a pair contributes to an increase in heat transfer since \((K)\) parameter for vapor film is much larger than for base fluids due to the low thermal conductivity of steam compared to with the thermal conductivity of the fluid. However Figure. 7 presented the effects of using various nanoparticles type on the Nusselt enhancement ratio \(\text{Nu}/\text{Nu}_0\) for the ratio of the densities of the nanoparticles \(R_p=8000\). The results showed that the highest value of the Nusselt enhancement ratio \(\text{Nu}/\text{Nu}_0\) will obtain when using the \(\text{Al}_{2}\text{O}_{3}-\text{water}\) nanofluid. The dimensionless profile velocity is plotted in Figure. 8 for various concentrations of nanoparticles that varied between 0.1 to 0.5. The results showed that the dimensionless profile velocity is decreased with increasing the nanoparticle concentration, due to increasing the viscosity of the nanofluids when increasing the nanoparticle concentration. Finally, the effect of types of nanoparticles on the dimensionless profile velocity is presented in Figure. 9. The results showed that the maximum velocity is achieved when using \(\text{SiO}_2\) nanoparticles but the minimum velocity profile given by using \(\text{SiO}_2\) nanoparticles, due to increasing the density of the nanoparticles.

![Figure 2. Effect of the parameter (A) on the profile of dimensionless temperature.](image-url)
Figure 3. Effect of the parameter (A) on the profile of nanoparticles concentration ratio.

Figure 4. Effect of the parameter (K) on the profile of dimensionless temperature.
Figure 5. Effect of nanoparticles concentration $\varphi_\infty$ on Nuasselt enhancement ratio $\text{Nu}/\text{Nu}_o$. 
Figure 6. Effect of nanoparticles type on the Nuasselt enhancement ratio $\frac{Nu}{Nu_0}$ for various ratios of the densities of the nanoparticles.
Figure 7. Effects of the nanoparticles type on the Nuasselt enhancement ratio $\frac{Nu}{Nu_0}$ for the ratio of the densities of the nanoparticles $R_{po}=8000$.

Figure 8. Effects of the nanoparticles concentration $\varphi_\infty$ on the velocity profile.
4. Conclusions

Successful of using nanofluids for cooling high-temperature surfaces of bodies in the case of film boiling heat transfer requires developing a mathematical model to predict the heat transfer and fluid flow characteristics depending on the nanoparticle concentration in the base fluid. The present study performed a theoretical study of processes of film boiling heat transfer by using Al₂O₃, CuO, ZnO, TiO₂, ZrO₂ and SiO₂ water nanofluid for various nanoparticles concentration φ of (0.1, 0.2, 0.3, 0.4, and 0.5) on a flat vertical heated surface. The results obtained allow us to estimate the impact physical properties of nanoparticles and their concentration in the base fluid for heat and mass transfer during the film boiling of the nanofluid. Also, the results showed that when using the nanofluid as a coolant fluid for heat exchange equipment, there is a good enhancement of the supercritical heat transfer process. However, the results indicated that the main physical factors that affect the intensification of heat transfer at film boiling nanofluid are wall heat flux and the nanoparticle concentration near the wall. Also, increasing the concentration of nanoparticles in a pair contributes to an increase in heat transfer.

Nomenclatures

\( c_p \)  \( \text{heat capacity, J/(kg} \cdot \text{K)} \)

\( D_B \)  \( \text{Brownian diffusion coefficient, } D_B = \frac{k T}{3 \pi \eta d_p} \)

\( d_p \)  \( \text{diameter of nanoparticles, nm} \)

\( D_T \)  \( \text{thermal diffusion coefficient, } D_T = \frac{\beta \mu \phi}{(1-\phi) \rho_v + \phi \rho_p} \)

\( g \)  \( \text{gravitational acceleration, m/s}^2 \)

\( k \)  \( \text{thermal conductivity, W/(m} \cdot \text{K)} \)
kB constant Boltzmann
m index
Nu Nusselt number
Nu0 Nusselt number for pure base fluid in the absence of nanoparticles).
qw wall heat flux density, W / m²
r heat of vaporization, J / kg
T temperature, K
u streamwise velocity component, m/s
U dimensionless velocity
w stands for parameter value on the wall.
x longitudinal coordinate, m
y vertical coordinate, m

Greek symbols
∞ The value of the parameter on the interfacial vapor-base fluid surfaces.
v kinematic viscosity of the fluid, m²/s
α thermal diffusivity, m²/s
β coefficient of volume expansion, 1/K
δ vapor film thickness
θ dimensionless temperature
μ dynamic viscosity, Pa · s
ρ density of the fluid, kg/m³
φ mass nanoparticles concentration
φ∞ concentration nanoparticles in a base fluid

References
1. Nosovskij, A. V., Sharaevskij, I. G., Fialko, N. M., Zimin, L. B., Sharaevskij, G.I. (2017), “Thermal physics of the resource of nuclear power plants”, Monography, Chernobyl, Institute for Nuclear Safety Problems, 624.
2. Klyuchnikov A. A., Sharaevskij I. G., Fialko N. M., Zimin L. B. (2013), “Prospects for improving the safety of nuclear power plants based on nanotechnology”, The safety of nuclear power plants and Chernobyl, Issue 20, pp. 45—56.
3. Terekhov V. I., Kalinina S. V., Lemanov V. V. (2010), “The mechanism of heat transfer in nanofluids: the current state of the problem (review). Part 2. Convective heat transfer”, Thermophysics and Aeromechanics, V.17, No2, pp. 173—188.
4. Tolubinskiy V. I. (1980), “Boiling heat transfer”, Kyiv, Naukova Dumka, 316 p.
5. Sirotkina A. L., Fedorovich E. D., Sergeev V. V. (2017), “Prospects for the use of nano-base fluids in heat recovery systems in design accidents accompanied by the melting of the active zone”, Global Nuclear Safety, No. 2(23), pp. 81—88.
6. Ramesh, G., Prabhu, N. K. (2011), “Review of thermo-physical properties, wetting and heat transfer characteristics of nanofluids and their applicability in industrial quench heat treatment”, Nanoscale Research Letters, 6:334, pp. 1—15.
7. Kim, H., Buongiorno, J., Hu, L.W., McKrell, T. (2010), “Nanoparticle deposition effects on the minimum heat flux point and quench front speed during quenching in water-based alumina nanofluids”, International Journal of Heat and Mass Transfer, 53, pp.1542–1553.

8. Avramenko A. A., Shevchuk I. V., Moskalenko A. A., Lohvynenko P. N., Kovetska Yu. Yu. (2018) “Instability of a vapor layer on a vertical surface at the presence of nanoparticles”, Applied Thermal Engineering, 139, pp. 87 – 98.

9. Salari, E.; Peyghambarzadeh, S.M.; Sarafraz, M.M.; Hormozi, F.; Nikkhah, V. Thermal behavior of aqueous iron oxide nano-fluid as a coolant on a flat disc heater under the pool boiling condition. Heat Mass Transf. 2017, 53, 265–275.

10. Sujun, P., DONG, Hongsheng, JIANG Yongqi XIE Xiaoming WANG Zhongliang, HU Jun, Experimental investigation on boiling heat transfer characteristics of Al2O3-water nanofluids in swirl microchannels subjected to an acceleration force, Chinese Journal of Aeronautics, Volume 32, Issue 5, May 2019, Pages 1136-1144.

11. Khanafer, K., Vafai, K. (2011), “A critical synthesis of thermophysical characteristics of nanofluids”, Int. Journal of Heat and Mass Transfer, 54, pp. 4410—4428.

12. Avramenko, A.A., I.V. Shevchuk, A.I. Tyrinov, D.G. Blinov, (2015) Heat transfer in stable film boiling of a nanofluid over a vertical surface, International Journal of Thermal Sciences 92 (2015) 106e118.

13. Jehhef, K.A., Khanjar, R.H. & Siba, M.A. (2019). Convection Heat Transfer Enhancement in Square Cross-Section with Obstacle Using Nanofluids Materials Science and Engineering 518 (2019) 032004.

14. Pak, Bock Choon, and Young I. Cho. "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles." Experimental Heat Transfer an International Journal 11.2 (1998): 151-170.

15. Xuan, Yimin, and Wilfried Roetzel. "Conceptions for heat transfer correlation of nanofluids." International Journal of Heat and Mass Transfer 43.19 (2000): 3701-3707.

16. Einstein, Albert. "Eine Neue bestimmung der moleküldimensionen." Annalen der Physik 324.2 (1906): 289-306.

17. Maxwell, J.C., A Treatise on Electricity and Magnetism, second ed., Clarendon Press, Oxford University, UK, (1881).