Heat Transfer Applications of TiO₂ Nanofluids

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Additional information is available at the end of the chapter

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Abstract

To achieve acme heat transfer is our main disquiet in many heat transfer applications such as radiators, heat sinks and heat exchangers. Due to furtherance in technology, requirement for efficient systems have increased. Usually cooling medium used in these applications is liquid which carries away heat from system. Liquids have poor thermal conductivity as compared to solids. In order to improve the efficiency of system, cooling medium with high thermal conductivity should be used. Quest to improve thermal conductivity leads to usage of different methods, and one of them is addition of nanoparticles to base liquid. Application of nanofluids (a mixture of nanoparticles and base fluid) showed enhancement in heat transfer rate, which is not possible to achieve by using simple liquids. Different researchers used TiO₂ nanoparticles in different heat transfer applications to observe the effects. Addition of titanium oxide nanoparticles into base fluid showed improvement in the thermal conductivity of fluid. This chapter will give an overview of usage of titanium oxide nanoparticles in numerous heat transfer applications.

Keywords: titanium oxide nanoparticles, nanofluids, heat transfer enhancement, cooling medium, heat exchangers

1. Introduction

Nanoparticles, which were named as ultra-fine particles during the 1970s and 1980s, have size usually less than 100 nm. When a bulk material is considered then its physical properties remain nearly constant, but in case of nanoparticles it is not true. Nanoparticles are being used in many consumer goods such as paints, cosmetics and textiles. Nanoparticles are mixed with base fluid such as water, ethylene glycol and oil, to improve its properties. This mixture of nanoparticles and base fluid which is known as nanofluid can be used in different heat transfer applications.
In the following chapter effects of using titanium oxide nanofluids in heat transfer applications have been presented. Titanium oxide nanofluids have better thermal properties as compared to simple liquids. Due to their better heat transfer characteristics they can be used as an alternate for simple liquids in many heat transferring systems such as radiator of cars, heat exchangers and heat sinks. The disadvantage associated with these nanoparticles is their potential toxicity.

2. Thermal performance enhancement by using TiO₂ nanoparticles

Liquids have poor thermal properties, which is a barrier in development of energy efficient systems. Hence, some kind of technique should be adopted to overcome this problem. Addition of nanoparticles to base fluid showed better thermo-physical properties as compared to simple fluid. The reasons attributed to this enhancement in heat transfer performance could include Brownian motion and reduction in thermal boundary layer. This behaviour of nanofluids attracts many researchers to do research work in this field.

Hamid et al. [1] experimentally found performance factor \( \eta = \frac{h_{\text{nf}}}{h_{\text{bf}}} = h' \) and friction factor of TiO₂ nanofluids. Reynolds number, temperature, concentration and thermal properties have significant effect on the performance factor. At 30°C and volume concentration less than 1.2%, the performance factor was less than base fluid. However, at 50 and 70°C for all concentrations, nanofluid showed better improvement as compared to base fluid. Enhancement in Reynolds number, temperature and concentration enhanced the performance factor, while pressure drop increased as Reynolds number and concentration increased. We can convert weight concentration to volume concentration by using Eq. (1)

\[
\varnothing = \frac{\omega \rho_{\text{bf}}}{(1 - 0.01\omega)\rho_p + 0.01\omega \rho_{\text{bf}}} \tag{1}
\]

where \( \omega \) is weight concentration, \( \rho_{\text{bf}} \) is density of base fluid and \( \rho_p \) is density of nanoparticles. To find volume concentration if mass is given, Eq. (2) can be used

\[
\varnothing = \frac{m_p/\rho_p}{m_p/\rho_p + m_{\text{bf}}/\rho_{\text{bf}}} \times 100 \tag{2}
\]

Density of nanofluid \( \rho_{\text{nf}} \) can be calculated from Eq. (3)

\[
\rho_{\text{nf}} = \varnothing \rho_p + (1 - \varnothing)\rho_{\text{bf}} \tag{3}
\]

Vakili et al. [2] measured enhancement in convective heat transfer coefficient of TiO₂ nanofluid flowing through a vertical pipe. According to experimental findings, thermal conductivity has nonlinear dependence on concentration. Increment in values of Reynolds number, nanoparticle concentration and heat flux also improved convective heat transfer coefficient. TiO₂ nanofluid with water/ethylene glycol as base fluid showed more enhancement in convective heat transfer coefficient as compared to TiO₂ nanofluid with distilled water as base fluid. Azmi et al. [3] used
TiO$_2$ and Al$_2$O$_3$ nanofluids in his experimentation to find and compare heat transfer coefficient and friction factor. At 30°C, Al$_2$O$_3$ nanofluid showed higher enhancement in viscosity and its viscosity varies with temperature whereas TiO$_2$ nanofluid has viscosity independent of temperature. Lower heat transfer coefficient than water and ethylene glycol is obtained for TiO$_2$ nanofluid for all concentrations (0–1%) at 30°C. Similar trend in heat transfer coefficient for both nanofluid is achieved at higher temperature. Friction factor augmentation for both nanofluids with volume concentration is not considerable.

Wang et al. [4] added TiO$_2$ nanoparticles in paraffin wax (a phase changing material) to improve its thermal properties. Thermal properties varied with the concentration of nanoparticles. A drop in phase change temperature is observed when loading of nanoparticle was less than 1 wt% while a drop in latent heat capacity is observed when nanoparticle loading was greater than 2 wt %. Thermal conductivity of composite decreased as the temperature is increased and it is lower in liquid state than in solid state. Azmi et al. [5] experimentally investigated the effects of working fluid temperature and concentration on thermal conductivity, viscosity and heat transfer coefficient. These thermo-physical properties were greatly influenced by temperature and concentration. Thermal conductivity has direct relation with temperature at low concentration. Range of variation in viscosity is 4.6–33.3% depending on temperature and concentration.

Sajadi et al. [6] study the turbulent heat transfer behaviour of TiO$_2$/water base nanofluid. The basic aim was to study the effects of volume concentration on heat transfer coefficient and on pressure drop. Dispersion of nanoparticle is improved by mixing an ultrasonic cleaner. Increasing concentration of nanoparticle has no significant effect on heat transfer but pressure drop increased. When the Reynolds number is increased then the ratio of heat transfer coefficient for nanofluid to base fluid is decreased while the Nusselt number is increased for both base and nanofluids. Wei et al. [7] did experimentation to find thermal conductivity and stability of TiO$_2$/diathermic oil nanofluid. Effect of temperature and concentration on thermal conductivity had been examined. Thermal conductivity was having a linear correlation with concentration. Thermal conductivity of nanofluid increased with an increase in temperature. Zeta potential values of different samples indicated good stability of nanofluids. To calculate thermal conductivity, classical models are available such as Hamilton-Crosser (H-C) [8] is presented in Eq. (4)

$$\frac{k_{nf}}{k_f} = \frac{k_p + (n-1)k_l + (n-1)\mathcal{O}(k_p - k_l)}{k_p + (n-1)k_l - \mathcal{O}(k_p - k_l)}$$  (4)

where $k_{nf}$ is thermal conductivity of nanofluid, $k_l$ is thermal conductivity of base fluid, $k_p$ is thermal conductivity of nanoparticles, $\mathcal{O}$ is volume fraction and $n = \frac{3}{\Psi}$. $\Psi$ is the sphericity.

Yu et al. [9] also gave a model to find thermal conductivity of nanofluids and it is presented in Eq. (5) as follows:

$$\frac{k_{nf}}{k_f} = \frac{k_p + 2(k_p - k_l)(1 + \beta)^3\mathcal{O} + 2k_l}{k_p - 2(k_p - k_l)(1 + \beta)^3\mathcal{O} + 2k_l}$$  (5)

where $\beta$ is the ratio of the nano-layer thickness to the original particle radius.
| Researcher          | Nanoparticle and base fluid                           | Size | Reynolds number range        | Temperature range | Flow type       | Nanoparticle concentration | Flow rates | Experimental setup                                      | Results                                                                 |
|---------------------|-------------------------------------------------------|------|------------------------------|-------------------|----------------|--------------------------|-------------|-------------------------------------------------------|-------------------------------------------------------------------------|
| Hamid et al. [1]    | TiO$_2$-water and ethylene glycol (60:40)            | 50 nm| 3000–24,000                  | 30, 50 and 70°C   | Turbulent      | 0.5, 0.7, 1.0, 1.3 and 1.5% by volume | 2–20 LPM    | A tube with length of 1.25 m, inner diameter of 16 mm and outer diameter of 19 mm | Maximum performance factor obtained is 1.29 times that of base fluid |
| Vakili et al. [2]   | TiO$_2$-Ethylene glycol and water (60:40)            | 25 nm| 2030, 2960 and 3960          | –                 | Laminar and Turbulent | 0.5, 1.0 and 1.5% by volume | 0.5–5.0 LPM | A vertical copper tube with a length of 120 cm, inner diameter of 6 mm and outer diameter of 8 mm | A maximum of more than 44% enhancement in convective heat transfer coefficient is achieved. |
| Azmi et al. [3]     | TiO$_2$-water and ethylene glycol (60:40) Al$_2$O$_3$-water and ethylene glycol (60:40) | 50 nm| –                            | 30, 50 and 70°C   | Turbulent      | 0.5–1.0% by volume        | 2–20 LPM    | A tube with inner diameter of 16 mm and outer diameter of 19 mm | Maximum enhancement in heat transfer coefficient is 24.2% for TiO$_2$ nanofluids. |
| Wang et al. [4]     | TiO$_2$ (anatase)-paraffin wax                        | 20 nm| 15–65°C                      | –                 | –              | 0–7% by weight            | –           | –                                                     | Considerable increase in latent heat is achieved by addition of nanoparticles at around 0.7% by weight |
| Azmi et al. [5]     | TiO$_2$-water and ethylene glycol (60:40)            | 50 nm| –                            | 30–80°C           | Turbulent      | 0.5–1.5% by volume        | 3.9–21.15 LPM | Copper tube with length of 1.5 m, inner diameter of 16 mm and outer diameter of 19 mm | Maximum enhancement in Nusselt number is about 28.9% |
| Sajadi and Kazemi [6]| TiO$_2$-water                                        | 30 nm| 5000–30,000                  | –                 | Turbulent      | 0.05, 0.1, 0.15, 0.20, and 0.25% | –           | Copper tube with inner diameter of 5 mm, length of 1800 mm and thickness of 0.675 mm | Enhancement in heat transfer coefficient was about 22% |
| Wei et al. [7]      | TiO$_2$ (anatase)-diathermic oil                     | 10 nm| –                            | 20–50°C           | –              | 0.1–1% by volume          | –           | Test tube                                            | Thermal conductivity achieved at 50°C and 1% volume concentration is 0.136 W/m·K |

Table 1. TiO$_2$ nanofluids used to enhance thermal performance.
Timofeeva [10] gave a model, which is given in Eq. (6)

\[
\frac{k_{\text{eff}}}{k_f} = 1 + 3\varnothing
\]  

(6)

Basic information such as nanoparticle size, concentration of nanoparticles in base fluid and results, related to these research works can be obtained from Table 1.

3. TiO$_2$ nanofluids as coolant for radiator and electronic devices

Radiator (usually a cross flow heat exchanger) is an important component of automobile. It cools down the liquid which is carrying heat from engine block and protecting it from damage. For high heat transfer rate, if the size of radiator is increased then it will increase both the volume and weight, which is undesirable. Researchers are interested to increase the effectiveness and compactness of radiators by using coolants with additives such as nanoparticles to the base fluids.

Hussein et al. [11] used SiO$_2$ and TiO$_2$ nanofluids in automotive cooling system to check the effects of volumetric flow rate, inlet temperature and volumetric concentration on Nusselt number. Statistical models have been obtained by statistical softwares using multiple linear regression methods and factorial methodology. Nusselt number increases as the volume flow rate, inlet temperature and volume concentration is increased. Wadd et al. [12] performed experimentation on automobile radiator to check the performance of metal (copper/water) and non-metal (titania TiO$_2$/water) nanofluids. Sodium lauryl sulphate was used as dispersant. Copper-based nanofluids showed more thermal conductivity than TiO$_2$. The stability of metal nanoparticle was found to be less than non-metal nanoparticles. Friction factor and pressure drop was found to be nearly same for both.

Figure 1 shows the flow of nanofluid through radiator.
Sandhya et al. [13] used TiO₂ water/ethylene glycol base nanofluid in car radiator to check the improvement in cooling performance. Nusselt number showed enhancement by increasing volume flow rate, volume concentration and Reynolds number. By increasing the volumetric flow rate, outlet temperature of the nanofluid also increased. The inlet temperature of nanofluid has slight effect on Nusselt number. Bhimani et al. [14] used TiO₂/water nanofluid as a coolant in automobile radiator to study heat transfer enhancement. Chemical treatment is done to avoid agglomeration and sedimentation because of hydrophobic nature to TiO₂. Heat transfer coefficient enhanced as the flow rate and volume concentration increased.

According to Newton’s law of cooling, heat transfer can be calculated as given by Eq. (7)

\[ Q = hA_s \Delta T = hA_s(T_b - T_s) \]  

(7)

where \( h \) is heat transfer coefficient, \( A_s \) is surface area of tube, \( T_b \) is bulk temperature and \( T_s \) is tube wall temperature.

Heat transfer rate can be calculated as given by Eq. (8)

\[ Q = mC \Delta T \]  

(8)

and heat transfer coefficient can be calculated as given by Eq. (9)

\[ h_{\text{exp}} = \frac{mC(T_{\text{in}} - T_{\text{out}})}{nA_s(T_b - T_s)} \]  

(9)

where \( n \) is number of tubes.

While Nusselt number can be calculated as given by Eq. (10)

\[ Nu = \frac{h_{\text{exp}} \times D_h}{k} \]  

(10)

Chen and Jia [15] experimentally checked the enhancement in thermal conductivity and convective heat transfer coefficient by using TiO₂ nanofluid in automobile radiator. Pump damage due to application of nanofluid is studied by using cavitation corrosion test. Nanofluid showed good corrosion impediment capability under circulation. Hamid et al. [16] did experimental work to find pressure drop by application of TiO₂ nanofluid. Increase in pressure drop will lead to higher pump power requirement, which is not desired at all. Experimental findings showed no significant increase in pressure drop. Friction factor decreased at high Reynolds number.

Darcy equation to calculate pressure drop is given by Eq. (11), and to calculate friction factor Eq. (12) can be used as follows:

\[ \Delta P = f \frac{\rho v^2 L}{2D} \]  

(11)

\[ f = \frac{0.3164}{Re^{0.25}} \]  

(12)
| Researcher        | Nanoparticle and base fluid | Size | Reynolds number range | Temperature range | Flow type | Nanoparticle concentration | Flow rates | Design                                                                 | Results                                                                 |
|-------------------|-----------------------------|------|-----------------------|-------------------|-----------|-----------------------------|------------|-----------------------------------------------------------------------|------------------------------------------------------------------------|
| Hussein et al. [11]| TiO$_2$-water, SiO$_2$-water | –    | –                     | 60-80°C           | Laminar   | 1-2% by volume              | 2-8 LPM    | Radiator with louvered fins and 32 flat vertical copper tubes with flat cross sectional area | Maximum enhancement of nusselt number for TiO$_2$ obtained is 11%. Maximum enhancement of nusselt number for SiO$_2$ obtained is 22.5%. |
| Wadd et al. [12]  | Cu-water, TiO$_2$-water      | 20 nm| 3000-20,000           | 65-70°C           | Turbulent | 0.1% by weight              | 1-5 LPM    | Louvered fin and tube type, 37 vertical tubes with ellipse-shaped cross section | For copper nanoparticles maximum enhancement in Nusselt number is about 15%. For TiO$_2$ nanoparticles maximum enhancement in Nusselt number is about 13%. |
| Sandhya et al. [13]| TiO$_2$-water and ethylene glycol (60% :40%) | 21 nm| 4000-15,000            | 35, 40 and 45°C  | Turbulent | 0.1, 0.3 and 0.5% by volume | 2-5 LPM    | Radiator consists of three rows of 104 tubes with a diameter of 5 mm and length of 0.3 m. | The enhancement in heat transfer at concentration of 0.5% is about 35% as compared to the base fluid. |
| Bhimani et al. [14]| TiO$_2$-Water              | 15 nm| Nearly between 5000 and 10,000 | 80°C             | Turbulent | 0.1, 0.3, 0.5, 0.7, and 0.1% by volume | 90-120 LPM | Louvered fin and tube type, 34 vertical tubes with stadium-shaped cross section | Enhancement in heat transfer coefficient is 40-45% as compared to base fluid at concentration of 1% by volume. |
| Chen et al [15]   | TiO$_2$—85% wt. % ethylene glycol and 15% wt.% water | 18 nm| –                     | –                 | –         | 1% by weight                | 15-30 LPM  | Straight copper tube with 2 m length and 12 mm diameter               | Enhancement in thermal conductivity is 3% and in convective heat transfer is about 10%. |
| Hamid et al. [16] | TiO$_2$-water and ethylene glycol (60:40) | 50 nm| Less than 30,000       | 50 and 70°C       | Turbulent | 0.5, 1 and 1.5% by volume   | Not specified | Copper tube with length of 1.5 m having inner diameter of 16 mm | No significant increase in pressure drop for TiO$_2$ nanofluid. |
| Ijam et al. [18]  | TiO$_2$-water, SiC-water     | –    | –                     | –                 | Turbulent | 0.8, 1.6, 2.4, 3.2 and 4% by volume | 2, 4 and 6 m/s | Heat sink with bottom of 20 cm x 20 cm                              | Enhancement in thermal conductivity by using SiC/water and TiO$_2$/water nanofluid at 4% concentration is about 12.44. and 9.99%, respectively. |
| Researcher       | Nanoparticle and base fluid | Size                        | Reynolds number range | Temperature range | Flow type | Nanoparticle concentration | Flow rates | Design                        | Results                                                                 |
|------------------|-----------------------------|-----------------------------|-----------------------|-------------------|-----------|-----------------------------|------------|-------------------------------|-------------------------------------------------------------------------|
| Rafati et al. [17]| Silica (SiO₂)              | SiO₂ particle size is 14 nm | Laminar               | 0.5, 1.0 and 1.5% for silica | 0.5, 0.75 and 1 LPM | Quadcore processor (Phenom II X4 965) | Enhancement in heat flux by using SiC-water and TiO₂-water nanofluids with inlet velocity of 6 m/s was 12.43 and 12.77%, respectively. |
|                  | Alumina (Al₂O₃)            | Al₂O₃ particle size is 40 nm |                       | 0.1, 0.25 and 0.5% for titania |           |                             | Twice enhancement in convective heat transfer coefficient is found for alumina with 0.5% volumetric concentration at flow rate of 1 L/min. |
|                  | Titania (TiO₂)/water (75% vol.) and ethylene glycol (25%) | TiO₂ particle size is 21 nm |                       | 0.5, 0.75 and 1.0% for alumina |           |                             |                                                                 |

Table 2. TiO₂ nanofluids used in radiator and electronic devices.
where $\Delta P$ is pressure drop, $f$ is friction factor, $\rho$ is density, $v$ is velocity, $L$ is length and $D$ is diameter.

### 3.1. Cooling of electronic devices

Nowadays cooling of electronic devices is a challenging task because of compactness and high heat dissipation. Different approaches are being used to increase the thermal performance of electronic systems. One of such way is to enhance the thermal performance of coolant being used in the system. Nanofluids have showed better thermal performance than base fluid.

Rafati et al. [17] used three different types of nanofluids as coolant for cooling of microchips. A high conductive thermal paste is used between block and processor’s integrated heat spreader. For computer cooling, the selection of nanofluid is based on factors such as better thermal performance, economic aspect and having no chemical and corrosion impact. The highest decrease in temperature was observed for alumina nanofluid, which was about 5.5°C.

Ijam et al. [18] used SiC and TiO$_2$ nanofluids as coolant in electronic devices. Enhancement in thermal conductivity and heat flux is achieved by increasing volume concentration. Pressure drop increases as flow rate is increased, which results in increase in pumping power. Pressure drop for SiC and TiO$_2$ nanofluid increases from 2159.26 and 2170 Pa, respectively, at 0.8% volume fraction to 2319.58 and 2375.07 Pa, respectively, at 4% volume fraction with 2 m/s inlet velocity. Pumping power increased from 0.28 to 5.49 W for SiC and from 0.26 to 5.64 W and for TiO$_2$ with 4% volume fraction when inlet velocity increased from 2 to 6 m/s. Table 2 provides information about different parameters and result obtained in cooling of radiators and electronic devices.

### 4. Application of TiO$_2$ nanofluids in heat exchangers

The basic function of heat exchanger is to transfer heat energy from one fluid (which is at high temperature) to other fluid (which is at low temperature). Two fluids in heat exchanger did not come into direct contact or mix with each other. To achieve high heat transfer rate in heat exchanger is our main concern. Use of nanofluid is one of simple way to attain this purpose.

Duangthongsuk et al. [19] used a double tube counter flow heat exchanger to check heat transfer and flow characteristics of TiO$_2$ nanofluid. Nanofluid flows in inner copper tube while hot water flows in annular. Heat transfer coefficient increased as mass flow rate of hot water and Reynolds number increased while temperature of nanofluid is decreased. Hot water temperature has no significant effect on heat transfer coefficient. When compared with base fluid (water) pressure drop and friction factor are nearly the same. To calculate Nusselt number, different equations are available in literature such as Gnielinski equation [20] is defined as in Eq. (13)

$$\text{Nu} = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{0.8} \left(Pr^{\frac{1}{3}} - 1\right)}$$

(13)
where Nu is Nusselt number, Re is Reynolds number, Pr is Prandtl number and \( f \) is friction factor in above equation.

To predict Nusselt number Pak and Cho \([21]\) correlation is given in Eq. (14) as follows:

\[
Nu_{nf} = 0.21Re_{nf}^{0.8}Pr_{nf}^{0.5} \tag{14}
\]

Another correlation in Eq. (15) to predict Nusselt number is given by Xuan and Li \([22]\)

\[
Nu_{nf} = 0.0059(1 + 7.6286\mathcal{O}^{0.6886}Pr_{nf}^{0.001})Re_{nf}^{0.9238}Pr_{nf}^{0.4} \tag{15}
\]

where \( \mathcal{O} \) is Peclet number of nanofluid in above relation.

Singh et al. \([23]\) did experimental studies on double pipe heat exchanger by using CuO/TiO\(_2\) nanofluids with different flow rates and volume concentrations. Application of CuO/TiO\(_2\) nanofluids enhanced heat transfer rate as concentration and flow rate is increased. CuO nanofluid showed better results than TiO\(_2\) nanofluids because of high thermo-physical properties. Reddy et al. \([24]\) did experimentation to check heat transfer coefficient and friction factor in double pipe heat exchanger with and without helical coil inserts by using TiO\(_2\) nanofluid. Nanofluid flows in the inner tube while hot fluid flows in the outer tube. Enhancement in heat transfer coefficient and friction factor (in terms of pressure drop) is measured. New correlations for Nusselt number and friction factor developed are given in Eqs. (16) and (17)

\[
Nu_{Reg} = 0.007523Re^{0.8}Pr^{0.5}(1 + \mathcal{O})^{7.6}(1 + P/d)^{0.037} \tag{16}
\]

\[
f_{Reg} = 0.3250Re^{-0.2377}(1 + \mathcal{O})^{2.723}(1 + P/d)^{0.041} \tag{17}
\]

Khedkar et al. \([25]\) study TiO\(_2\)/water nanofluid heat transfer characteristics in concentric heat exchanger. Nanofluid with the highest concentration has the highest overall heat transfer coefficient. Flow diagram of apparatus used in experimentation \([25]\) is shown in Figure 2.

Duangthongsuk et al. \([26]\) found that enhancement in heat transfer coefficient and pressure drop is related to nanoparticle concentration. If nanoparticle concentration is increased beyond the

![Figure 2](image)

**Figure 2.** Schematic representation of nanofluid flow through concentric tube heat exchanger.
limit then a decrease in the heat transfer coefficient is observed. This is attributed to increase in viscosity. In this experiment, value of heat transfer coefficient increases as volume concentration is increased up to 1% and after that decrease in heat transfer coefficient is observed. Proposed correlations to predict Nusselt number and friction factor are mentioned in Eqs. (18) and (19), respectively.

\[
Nu = 0.07Re^{0.707}Pr^{0.385} \theta^{0.074} 
\]

(18)

\[
f = 0.961 \theta^{0.052} Re^{-0.375} 
\]

(19)

Barzegarian et al. [27] used brazed plate heat exchanger to check enhancement in overall heat transfer coefficient and pressure drop by using TiO\(_2\) nanofluid. For a specified Reynolds number, increment in weight concentration of nanoparticle in nanofluid increased the overall heat transfer coefficient and pressure drop also. Increase in Reynolds number also enhanced the overall heat transfer coefficient and pressure drop. Up to 20% enhancement in pressure drop has been observed during experimentation. Tiwari et al. [28] used four different types of nanofluids (including CeO\(_2\), Al\(_2\)O\(_3\), TiO\(_2\) and SiO\(_2\)) with different concentrations and volume flow rates. Better heat transfer behaviour of TiO\(_2\) and CeO\(_2\) nanofluid is observed at low concentrations while that of Al\(_2\)O\(_3\) and SiO\(_2\) at high concentrations. CeO\(_2\) > Al\(_2\)O\(_3\) > TiO\(_2\) > SiO\(_2\) is the order of nanofluids for which maximum heat transfer coefficient is obtained.

Overall heat transfer coefficient is calculated in Ref. [29] as by using Eqs. (20)–(22)

\[
U = \frac{Q_{avg}}{AF \Delta T_{LMTD}} 
\]

(20)

\[
A = N_tHW 
\]

(21)

\[
\Delta T_{LMTD} = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{Ln \left( \frac{T_{h,o} - T_{c,i}}{T_{h,i} - T_{c,o}} \right)} 
\]

(22)

where \(U\) is over all heat transfer coefficient, \(A\) is total surface area, \(F\) is temperature correction factor, \(N_t\) is total number of plates, and \(H\) and \(W\) are height and width of plates.

Taghizadeh-Tabari et al. [29] performed experimentation on plate heat exchanger of milk pasteurization industry by using TiO\(_2\)/water nanofluid. Peclet number is used in experiment to compare performance of nanofluid with different concentrations. Nusselt number and pressure drop increased as the Peclet number or concentration or both are increased. Experimental results showed dramatic increase in heat transfer coefficient while theoretical calculated results did not. Reasons behind this could include increase of nanoparticle Brownian motions, particle migration and reduction of boundary layer thickness. The performance index \(\eta = (h_{nf}/h_{bf})/(\Delta P_{nf}/\Delta P_{bf})\) is greater than 1 for all type of nanofluid concentrations used in the experimentation. Benefit of using nanofluid in milk pasteurization industry is to reduce energy consumption. Javadi et al. [30] did study work by using three different nanofluids in plate heat exchanger to compare thermo-physical and heat transfer characteristics with base fluid. The results confirmed that overall heat transfer coefficient, thermal conductivity, pressure drop,
| Researcher                  | Nanoparticle and base fluid | Size    | Reynolds number range | Temperature range                        | Flow type          | Nanoparticle concentration | Flow rates         | Design                                | Results                                                                 |
|----------------------------|-----------------------------|---------|-----------------------|------------------------------------------|--------------------|---------------------------|--------------------------|------------------------|--------------------------------------------------------------------------------|
| Duangthongsuk and Wongwises [19] | TiO$_2$-water              | 21 nm   | 4000–18,000           | Nanofluid temperature range 15–25°C     | Turbulent          | 0.2% by volume            | Hot water flow rate is 3 LPM and 4.5 LPM | Double tube with counter flow For inner tube, outer diameter is 9.53 mm and inner diameter is 8.13 mm. Hot water temperature range is 35–50°C | Enhancement in convective heat transfer coefficient is about 6–11% as compared to base fluid. |
| Singh et al. [23]           | TiO$_2$-water               | 10–20 nm | 3500–13,500           | Nanofluid temperature range 30 ± 3°C    | Laminar and turbulent | 0.1–0.3% by volume       | Nanofluid flow rate is 1–4 LPM | Double pipe For inner tube, outer diameter is 18 mm and inner diameter is 15 mm. For outer tube, inner diameter is 32 mm and outer diameter is 36 mm. | At volumetric concentration of 0.3% and flow rate of 4 LPM, a maximum enhancement in coefficient of heat transfer is 5% for CuO nanofluids. |
| Reddy et al. [24]           | TiO$_2$                     | 21 nm   | 4000–15,000           | –                                       | –                  | 0.004–0.02% by volume    | –                        | Double tube with and without helical coil inserts. For inner tube, outer diameter is 9.53 mm and inner diameter is 8.13 mm. For outer tube, inner diameter is 27.8 mm and outer diameter is 33.9 mm. | Enhancement in Nusselt number and friction factor for 0.02% concentration and 15,000 Reynolds number without helical coils are 10.73 and 8.73%, respectively. However, by using helical coils this enhances up to 17.71 and 16.58%, respectively. |
| Researcher          | Nanoparticle and base fluid | Size  | Reynolds number range | Temperature range                    | Flow type       | Nanoparticle concentration | Flow rates | Design                                                                 | Results                                                                                           |
|---------------------|-------------------------------|-------|-----------------------|-------------------------------------|----------------|---------------------------|-------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| Khedkar et al. [25] | TiO$_2$-water                 | 20 nm | 300–4000              | Temperature of hot fluid is 55, 65 and 75 °C | Laminar        | 2 and 3% by volume        | 0.1–1 LPM   | Concentric tube 8 mm diameter of inner pipe and 16 mm diameter of outer pipe | Maximum enhancement in overall heat transfer coefficient is 47.37% with 3% volume concentration and 3992 Reynolds number. |
| Duangthongsuk et al. [26] | TiO$_2$-water                 | 21 nm | 3000–18,000           | 15, 20 and 25 °C                    | Turbulent      | 0.2, 0.6, 1.0, 1.5 and 2.0% by volume | 3 and 4.5 LPM | Double tube with counter flow. For inner tube, outer diameter is 9.53 mm and inner diameter is 8.13 mm. For outer tube, inner diameter is 27.8 mm and outer diameter is 33.9 mm. | Maximum enhancement in heat transfer coefficient is about 26% at 1% volume concentration. |
| Barzegarian et al. [27] | TiO$_2$-water                 | 20 nm | Nearly 159–529        | –                                   | Turbulent      | 0.3, 0.8 and 1.5% by weight | 2.5–7.5 LPM | Brazed plate heat exchanger Thickness, length and width of BPHE is 0.042, 0.194 and 0.08 m, respectively. | Maximum enhancement in convective heat transfer coefficient of nanofluid at weight concentration of 0.3, 0.8 and 1.5% is 6.6, 13.5 and 23.7%, respectively. And for overall heat transfer coefficient this enhancement is 2.2, 4.6 and 8.5%, respectively. |
| Researcher            | Nanoparticle and base fluid | Size | Reynolds number range | Temperature range | Flow type | Nanoparticle concentration | Flow rates | Design                                      | Results                                                                 |
|----------------------|-----------------------------|------|-----------------------|-------------------|-----------|-----------------------------|------------|-------------------------------------------|-------------------------------------------------------------------------|
| Tiwari et al. [28]   | CeO$_2$-water              | 30 nm| –                     | 25–30 °C          | –         | 0.5, 0.75, 1.0, 1.25, 1.5, 2.0 and 3% by volume | 1–4 LPM    | Plate heat exchanger                    | For CeO$_2$/water, Al$_2$O$_3$/water, TiO$_2$/water and SiO$_2$/water nanofluids, the maximum enhancement in heat transfer coefficient at optimum volume concentration are about 35.9, 26.3, 24.1 and 13.9%, respectively. |
|                      | Al$_2$O$_3$-water           | 45 nm| –                     | –                 | –         |                             |            |                                            |                                                                         |
|                      | TiO$_2$-water               | 10 nm| –                     | –                 | –         |                             |            |                                            |                                                                         |
|                      | SiO$_2$-water               | 10 nm| –                     | –                 | –         |                             |            |                                            |                                                                         |
| Taghizadeh-Tabari et al. [29] | TiO$_2$-water              | 10–15 nm | Nearly (70–220) Critical Reynolds number is 100 | – | Laminar and turbulent | 0.25, 0.35 and 0.8% by weight | – | Plate heat exchanger. 11 plates with the length of 0.2 m each and width of 0.11 m Spacing between plates is 0.0025 m. | Maximum ratio of Nusselt number of nanofluid to distilled water obtained is about 1.17. $\text{Nu}_{\text{fluid}}/\text{Nu}_{\text{water}} = 1.17$ Maximum pressure drop is about 8% as compared to distilled water. |
| Javadi et al. [30]   | SiO$_2$-liquid nitrogen     | –    | –                     | Inlet and outlet temperatures are 310 and 124.26 K for hot fluid while 99.719 and 301.54 K for cold fluid, respectively | – | 0.2–2% by volume | Mass flow rate of SiO$_2$ at 0.2% concentration is 0.278 kg/s and at 2% is 2.079 kg/s. Mass flow rate of TiO$_2$ and Al$_2$O$_3$ at 0.2% concentration is 0.456 and 0.439 kg/s while for 2% concentration is | Plate fin heat exchanger. Al$_2$O$_3$ has the highest overall heat transfer coefficient which is 308.69 W/m$^2$K in 2% concentration. |
| Researcher          | Nanoparticle and base fluid | Size | Reynolds number range | Temperature range | Flow type       | Nanoparticle concentration | Flow rates | Design                                                                 | Results                                                                 |
|---------------------|----------------------------|------|-----------------------|-------------------|-----------------|---------------------------|-------------|------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Ashrafi and Bashirzadeh [31] | TiO$_2$-water               | 20 nm| 82–497                | –                 | Laminar         | 0.1, 0.5 and 1% by weight | –          | Shell and tube heat exchanger, 39 tubes with 29 cm length of each, 11 mm outside diameter and 10 mm inside diameter of tube, Shell with 0.253 m$^2$ exchanging area and 6.35 cm inside diameter. | The average augmentation of convective heat transfer coefficient for 1% by weight concentration is about 31.6% |
| Kumar et al. [32]   | CuO-water                   | 26 nm| 1000–5000             | 27°C              | Laminar and turbulent | 0.02, 0.04 and 0.06% by volume. | 0.5–3 LPM | Shell and tube heat exchanger.                                         | Maximum enhancement in heat transfer coefficient is about 29% at 0.06% concentration and 80°C with 3 LPM. |
|                     | TiO$_2$-water               | 9 nm |                       |                   |                 |                           |             |                                                                         |                                                                         |
|                     | Monoethylene glycol         |      |                       |                   |                 |                           |             |                                                                         |                                                                         |

Table 3. Application of TiO$_2$ nanofluids in different types of heat exchangers.
heat transfer rate and entropy generation increased with increase in volume concentration of nanoparticles. While Prandtl number decreased as concentration of nanoparticles in base fluid is increased, pressure drop is lowest for SiO$_2$. Overall heat transfer coefficient is highest for Al$_2$O$_3$. Prandtl number is highest for lowest concentration of nanoparticles. Entropy generation is lowest for SiO$_2$ as 25, while for TiO$_2$ and Al$_2$O$_3$ this value increases to 40 and 38.7, respectively.

Ashrafi et al. [31] used nanofluid as coolant in heat exchangers of swimming pool. In shell and tube heat exchanger, nanofluid flows through tubes while cold water in shell. Results show that when weight concentration of nanoparticle and Peclet number is increased, the convective heat transfer coefficient is also increased. Kumar et al. [32] used shell and tube heat exchanger to check heat transfer characteristics of TiO$_2$/water, CuO/water, TiO$_2$/ethylene glycol and CuO/ethylene glycol nanofluids with different concentrations. Hot water flows through shell and nanofluid flows through tubes. CuO/water nanofluids showed highest enhancement among all nanofluids used in the experimentation. Convective heat transfer coefficient is improved by increasing Reynolds number, volume concentration, volume flow rate and temperature.

Different enhancements achieved by researchers are given in Table 3.

5. Application of TiO$_2$ nanofluids in heat sinks

Heat sink (which is a form of heat exchanger) is used to absorb excessive heat from a system to maintain its temperature at an optimum value and to avoid from overheating. These are made of conductive metals. Air or liquid is used to remove the heat from heat sink. Design of heat sink is such as to maximize surface area contact with air or cooling liquid. Due to limitations, we cannot increase area beyond limits rather we can use cooling liquid with higher thermal conductivity. This enhancement in thermal conductivity will result in higher heat transfer and can be achieved by addition of nanoparticles to base fluid.

Ali et al. [33] experimentally compared performance of staggered and inline pin fin heat sinks under laminar flow of TiO$_2$ (rutile) and TiO$_2$ (anatase). TiO$_2$ (rutile) with staggered pin fin heat sinks showed best performance. The arrangement of staggered pin fin allows more liquid to interact with pin fins, which makes its performance better than inline pin fin. By using TiO$_2$ (rutile) with staggered pin fin heat sinks minimum temperature of base obtained is 29.4°C. The lowest thermal resistance is obtained for TiO$_2$ (rutile) with staggered pin fin heat sinks at Reynolds number of 587 which was 0.012°C/W. Schematic diagram of nanofluid flow is shown in Figure 3.

Mohammed et al. [34] used six different nanofluids in the experimentation to find enhancement in the heat transfer coefficient, wall shear stresses, friction factor and pressure drop in triangular micro-channel heat sink. Order of achieved enhancement in heat transfer coefficient is Diamond> SiO$_2$ > CuO > TiO$_2$ > Ag > Al$_2$O$_3$. CuO/water and TiO$_2$/water showed same performance in terms of heat transfer coefficient. Order of pressure drop occurred along the length of the channel in experiment is SiO$_2$ > Diamond > Al$_2$O$_3$ > TiO$_2$ > CuO > pure water > Ag.
Ag also has lowest wall shear stress. Diamond/water nanofluid has lowest thermal resistance among six nanofluids.

Naphon and Nakharintr [35] performed experiments on mini-rectangular fin heat sinks with different widths by using TiO$_2$/de-ionized water nanofluid to check heat transfer enhancement. Average outlet temperature and plate temperature decreased as Reynolds number is increased. Average heat transfer rate is increased with mass flow rate of nanofluids. Nusselt number has direct relation with Reynolds number. Increase in Reynolds number decreased the thermal resistance while slight increase in pressure drop is observed. Average heat transfer rate of heat sink with largest width is higher than the sinks with smaller width.

To calculate thermal resistance in Ref. [35], Eq. (23) can be used as

$$R_{th} = \frac{1}{\bar{h} \times A_s} = \frac{1}{\frac{Q_{avg}}{\Delta T_{LMTD}}}$$

Parameters used in above equation include $R_{th}$ as thermal resistance, $\bar{h}$ as average heat transfer coefficient and $A_s$ as total heat transfer surface area of heat sink.

Sohel et al. [36] used three different nanofluids to check thermo-physical properties and heat transfer performance of nanofluids in a circular copper micro-channel. CuO/water nanofluid showed best thermo-physical properties and heat transfer performance among the three nanofluids. Reduction in friction factor for CuO/water nanofluid is 9.38%, for Al$_2$O$_3$/water is 1.13% and for TiO$_2$/water is 1.79%. Reduction in thermal resistance for CuO/water nanofluid is 11.62%, Al$_2$O$_3$/water is 6.37% and TiO$_2$/water is 5.84%. Khaleduzzaman et al. [37] performed experimental work to find out the effect of nanoparticles volumetric concentration on flow rates, heat transfer coefficient and thermal resistance for water block heat sink. The interface temperature reduced as the volume flow rate increased. When the volume fraction and flow rate increased, thermal resistance decreased. Augmentation in heat transfer coefficient occurred when volume fraction and flow rate increased. Ijam et al. [38] performed cooling of copper mini-channel heat sink using two different types of nanofluid. Effects of nanofluid

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**Figure 3.** Schematic diagram of nanofluid flow through heat sink. CR is coolant reservoir, DAS is data acquisition system, F is flow meter, HS is heat sink, HT is heater, P is pump, R is radiator, T is thermocouple and V is valve in flow diagram.
| Researcher                        | Nanoparticle and base fluid | Size          | Reynolds number range | Temperature range | Flow type | Nanoparticle concentration | Flow rates | Design                      | Results                                                                 |
|----------------------------------|----------------------------|---------------|------------------------|-------------------|-----------|----------------------------|------------|-----------------------------|-------------------------------------------------------------------------|
| Ali and Arshad [33]              | TiO$_2$ (anatase)-water    | 5–30 nm       | Nearly between 260 and 600 | Laminar           | 4.31% for TiO$_2$ (anatase) and 3.99% TiO$_2$ (rutile) by volume | –          | Staggered and inline pin fin heat sinks | A maximum enhancement of 37.78% in Nusselt number is obtained for TiO$_2$ (rutile)/H$_2$O nanofluid with staggered pin fin heat sinks. |
| Mohammed et al. [34]             | Al$_2$O$_3$-water          | –             | 100–1000               | Laminar           | 2% by volume | 10–20 mL/min                | Triangular micro channels 20 micro channels with 10 mm length | Highest and lowest heat transfer coefficient is obtained for diamond/water and Al$_2$O$_3$/water nanofluid, respectively. Highest pressure drop is obtained for SiO$_2$/water nanofluid while Ag/water nanofluids have lowest pressure drop and wall shear stresses. |
| Naphon and Nakharintr [35]       | TiO$_2$-water              | 21 nm         | 80–200                 | 20, 22 and 24°C   | Laminar   | 0.4% by volume              | 4.5–8 g/s   | Three mini-rectangular fin heat sinks with three different height of fins 1, 1.5 and 2 mm | An increase of about 42.3% in average heat transfer rate is obtained for heat sink with $w = 2$ mm. |
| Sohel et al. [36]                | Al$_2$O$_3$-water          | –             | Maximum up to 1000     | Laminar           | 0.5–4% by volume | Nanofluid inlet velocity = 1.5 m/s | Circular micro-channel heat sinks with diameter of each is 0.4 mm | Maximum improvement as compared to pure water in mass flow rate, Reynolds number, heat transfer coefficient, thermal conductivity and heat flux at 4% concentration for TiO$_2$/water nanofluid, we have 12.76, 1.84, 7.74 9.97 and 6.20%, respectively. |
| Researcher               | Nanoparticle and base fluid | Size   | Reynolds number range | Temperature range | Flow type | Nanoparticle concentration | Flow rates | Design | Results                                                                 |
|-------------------------|-----------------------------|--------|-----------------------|-------------------|-----------|----------------------------|------------|--------|-------------------------------------------------------------------------|
| Khaleduzzaman et al. [37]| TiO₂-water                  | 21 nm  | –                     | –                 | –         | 0.1% by volume             | 1, 1.25 and 1.5 LPM |        | Dimension of copper block is (94 mm × 94 mm × 20 mm).                 |
| Ijam et al. [38]        | Al₂O₃-water/TiO₂-water      | –      | –                     | –                 | Laminar   | 0.8, 1.6, 2.4, 3.2 and 4% by volume |            |        | Heat transfer coefficient improvement was about 18.91% at flow rate of 1 LPM. |
|                         | Al₂O₃-water/TiO₂-water      | –      | –                     | –                 | Laminar   | Nanofluid inlet velocity is 0.1 and 1.5 m/s |            |        | Improvement in thermal conductivity of Al₂O₃/water nanofluids with 4% volume concentration is 11.98%, while for TiO₂/water nanofluid it is 9.97%. With 4% volume fraction and 1.5 m/s inlet fluid velocity, maximum pressure drop and pumping power required is 1105.540 Pa and 0.12437 W, respectively. |
| Xia et al. [39]          | TiO₂-water                  | 5 nm   | 200-500               | –                 | Laminar   | 0.1, 0.5, and 1.0% by volume | 150 mL/min |        | Fan-shaped micro-channel Number of micro-channels are 30 with whole width of 6 mm. |
|                         | Al₂O₃-water                 | 5 nm   | 200-500               | Temperature of nanofluid is 25 °C |          |                            |            |        | Improvement in thermal conductivity for TiO₂ nanofluid is 6.55% at 1% volume concentration. |

Table 4. TiO₂ nanofluids used for heat sink cooling.
volume fraction and inlet velocity on thermal conductivity, heat transfer coefficient, pumping power and pressure drop had been investigated. Fluid at low velocity absorbs more heat than the fluid at higher velocity. Mass flow rate and particle volume fraction has direct relation with heat transfer coefficient. By increasing mass flow rate and inlet velocity of fluid, pressure drop also increases. When volume fraction is increased then thermal resistance is decreased. Improvement in heat flux with volume fraction of 0.8% and nanofluid inlet velocity of 0.1 m/s for Al$_2$O$_3$ is 17.3% while for TiO$_2$ is 16.53%.

Xia et al. [39] compared heat transfer performance of fan-shaped micro-channel heat sink with rectangular micro-channel heat sink by using TiO$_2$/water and Al$_2$O$_3$/water nanofluids. Pressure drop and convection of heat transfer is higher in fan-shaped micro-channel heat sink. Enhancement in heat transfer is greater for Al$_2$O$_3$/water nanofluids when compared with TiO$_2$/water nanofluids, while thermal conductivity behaviour of TiO$_2$/water nanofluid is better.

To calculate friction resistance coefficient in Ref. [39] Eq. (24) is used

$$f = \frac{2\Delta PD_h}{\rho Lu_m^2}$$

where $\Delta P$ is pressure drop between inlet and outlet, $D_h$ is hydrodynamic diameter, $\rho$ is density, $L$ is length of micro-channel and $u_m$ is mean velocity. Different enhancements obtained by researchers are given in Table 4.

### 6. Application of TiO$_2$ nanofluid in nucleate pool boiling

Nucleate pool boiling is a boiling type which takes place when temperature of surface is about $5^\circ C$ greater than the saturation temperature of liquid. This boiling region is the most desirable as we can obtain high heat transfer rates with a small value of $\Delta T_{excess}$. Usually two methods are used to increase heat transfer rate in this region. One way is to increase the nucleation sites by doing surface treatment and other way is use of nanofluids.

Ali et al. [40] experimentally found boiling heat transfer coefficient enhancement by using TiO$_2$ (Rutile)/water nanofluid. Two different concentrations of 12 and 15% by weight are used in experimentation. Experimental setup accuracy is checked by using Pioro [41] correlation, which is given by Eq. (25) as follows:

$$\frac{h_l}{k} = 0.075C_{sf}\left(\frac{q}{h_{fg}\rho_g^{0.5}g_\rho g^2(\rho - \rho_g)^{0.25}}\right)^{0.66} Pr^n$$

In above equation $C_{sf}$ and $n$ are constants, which are dependent on fluid and heating surface.

By increasing wall super heat a decrease in heat flux enhancement is observed. Average heat flux and boiling heat transfer coefficient enhancement obtained at 15% concentration is 2.22 and 1.38 while for 12% concentration is 1.89 and 1.24, respectively.
Trisaksri et al. [42] experimentally investigated nucleate pool boiling heat transfer at different concentration and pressure of a refrigerant-based nanofluid on cylindrical copper tube. TiO$_2$-R141 nanofluid with three different concentrations had been used. When concentration of nanoparticle is increased, a decline in boiling heat transfer for R141 is observed. Effect of pressure is dominant at low concentrations. Rohsenow [43] correlation used in experimentation to predict nucleate boiling heat transfer is given by Eq. (26) as follows:

$$
\frac{C_p,l(T_s - T_{sat})}{h_{fg}Pr^{0.1}_l} = C_{sf}\left(\frac{q}{\mu_l h_{fg} \sqrt{\alpha \rho_l}}\right)^{0.33}
$$

Suriyawong and Wongwises [44] performed experimentation on two different circular plates made of copper and aluminium with different roughness (0.2–4 µm) to check nucleate boiling heat transfer characteristics. When concentration was greater than 0.0001% by volume, a decrease in heat transfer coefficient had been observed. The reason for this deterioration is sedimentation of nanoparticles on heating surface and decrease in nucleation sites. Rough surfaces provide more heat transfer coefficient as compared to smooth surfaces because more nucleation sites are presented on such surfaces. Aluminium plate showed high heat transfer coefficient than copper plate.

Das et al. [45] checked the effects of surface modification on nucleate boiling heat transfer. In experimentation, Cu surface is coated with crystalline TiO$_2$ nanostructure. Increase in surface roughness, surface wet ability or surface coating thickness provide enhancement in boiling heat transfer coefficient.

7. Conclusion

This chapter gives an overview of titanium oxide nanofluids application in different heat transfer systems. Because of high thermal conductivity of these fluids as compared to simple water or other fluids, heat transfer systems using titanium oxide nanofluids performed more efficiently. Pressure drop due to the presence of nanoparticles was not significant. Therefore, no extra pumping power was required for circulation of nanofluids.

Nomenclature

| Symbol          | Description                   |
|-----------------|-------------------------------|
| $\omega$        | Weight concentration          |
| $\rho_{bf}$     | Density of base fluid         |
| $\rho_p$        | Density of nanoparticles      |
| $\rho_{nf}$     | Density of nanofluid          |
| $k_{nf}$        | Thermal conductivity of nanofluid |
| $k_l$           | Thermal conductivity of base fluid |
Thermal conductivity of nanoparticles $k_p$
Volume fraction $\phi$
Heat transfer coefficient $h$
Surface area of tube $A_s$
Bulk temperature $T_b$
Tube wall temperature $T_s$
Heat transfer rate $Q$
Mass $m$
Specific heat capacity $C$
Nusselt number $Nu$
Pressure drop $\Delta P$
Friction factor $f$
Density $\rho$
Velocity $v$
Reynolds number $Re$
Prandtl number $Pr$
Peclet number $Pe$
Over all heat transfer coefficient $U$

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