Chapter 9

Heat Transfer Applications of TiO_2 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 TiO_2 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 TiO_2 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 $\eta = \frac{h_{nf}}{h_{bf}} = h'$ and friction factor of TiO_2 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)

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

where ω is weight concentration, ρ_{bf} is density of base fluid and ρ_p is density of nanoparticles.

To find volume concentration if mass is given, Eq. (2) can be used

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

Density of nanofluid ρ_{nf} can be calculated from Eq. (3)

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

Vakili et al. [2] measured enhancement in convective heat transfer coefficient of TiO_2 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. TiO_2 nanofluid with water/ethylene glycol as base fluid showed more enhancement in convective heat transfer coefficient as compared to TiO_2 nanofluid with distilled water as base fluid. Azmi et al. [3] used

TiO_2 and Al_2O_3 nanofluids in his experimentation to find and compare heat transfer coefficient and friction factor. At 30°C, Al_2O_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)

$$\frac{k_{nf}}{k_f} = \frac{k_p + (n-1)k_f + (n-1)\varnothing(k_p - k_f)}{k_p + (n-1)k_f - \varnothing(k_p - k_f)} \tag{4}$$

where k_{nf} is thermal conductivity of nanofluid, k_f is thermal conductivity of base fluid, k_p is thermal conductivity of nanoparticles, $\varnothing$ is volume fraction and $n = \frac{3}{\psi}$. Ψ 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:

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

where β 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	–	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_2O_3-water and ethylene glycol (60:40)	50 nm 13 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)

$$\frac{k_{\text{eff}}}{k_{\text{f}}} = 1 + 3\emptyset \tag{6}$$

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.

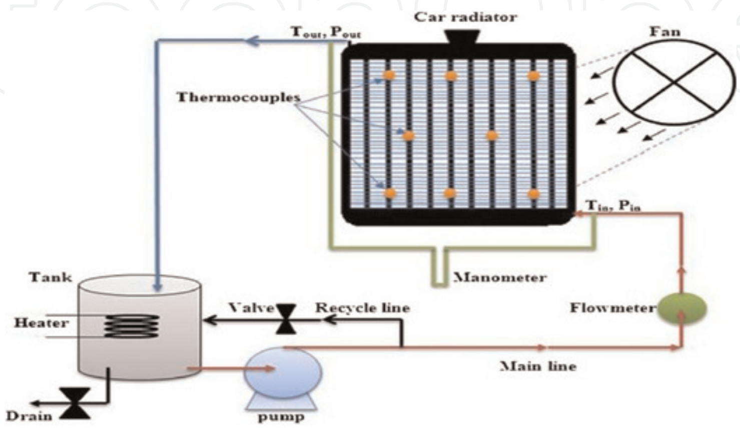

Figure 1. Flow diagram showing flow of nanofluid through radiator [11].

Sandhya et al. [13] used TiO_2 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 TiO_2/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 TiO_2. 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)

$$Q = hA_s\Delta T = hA_s(T_b - T_s) \tag{7}$$

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)

$$Q = mC\Delta T \tag{8}$$

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

$$h_{\mathrm{exp}} = \frac{mC(T_{\mathrm{in}} - T_{\mathrm{out}})}{nA_{\mathrm{s}}(T_{\mathrm{b}} - T_{\mathrm{s}})} \tag{9}$$

where n is number of tubes.

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

$$Nu = \frac{h_{\mathrm{exp}} \times D_{\mathrm{h}}}{k} \tag{10}$$

Chen and Jia [15] experimentally checked the enhancement in thermal conductivity and convective heat transfer coefficient by using TiO_2 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 TiO_2 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:

$$\Delta P = \frac{f\rho v^2 L}{2D} \tag{11}$$

$$f = \frac{0.3164}{Re^{0.25}} \tag{12}$$

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%	2, 4 and 6 m/s	Heat sink with bottom of 20 cm × 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
									Enhancement in heat flux by using SiC-water and TiO_2-water nanofluids with inlet velocity of 6 m/s was 12.43 and 12.77%, respectively.
Rafati et al. [17]	Silica(SiO_2) Alumina (Al_2O_3) Titania (TiO_2)/ water (75% vol.) and ethylene glycol (25%	SiO_2 particle size is 14 nm Al_2O_3 particle size is 40 nm TiO_2 particle size is 21 nm	–	–	Laminar	0.5, 1.0 and 1.5% for silica 0.1, 0.25 and 0.5% for titania 0.5, 0.75 and 1.0% for alumina	0.5, 0.75 and 1 LPM	Quadcore processor (Phenom II X4 965)	Twice enhancement in convective heat transfer coefficient is found for alumina with 0.5% volumetric concentration at flow rate of 1 L/min.

Table 2. TiO_2 nanofluids used in radiator and electronic devices.

where ΔP is pressure drop, f is friction factor, ρ 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)

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}} - 1\right)} \quad (13)$$

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:

$$Nu_{\mathrm{nf}} = 0.21 Re_{\mathrm{nf}}^{0.8} Pr_{\mathrm{nf}}^{0.5} \tag{14}$$

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

$$Nu_{\mathrm{nf}} = 0.0059\left(1 + 7.6286 \varnothing^{0.6886} Pe_{\mathrm{d}}^{0.001}\right) Re_{\mathrm{nf}}^{0.9238} Pr_{\mathrm{nf}}^{0.4} \tag{15}$$

where Pe 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)

$$Nu_{\mathrm{Reg}} = 0.007523 Re^{0.8} Pr^{0.5} (1 + \varnothing)^{7.6} (1 + P/d)^{0.037} \tag{16}$$

$$f_{\mathrm{Reg}} = 0.3250 Re^{-0.2377} (1 + \varnothing)^{2.723} (1 + P/d)^{0.041} \tag{17}$$

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

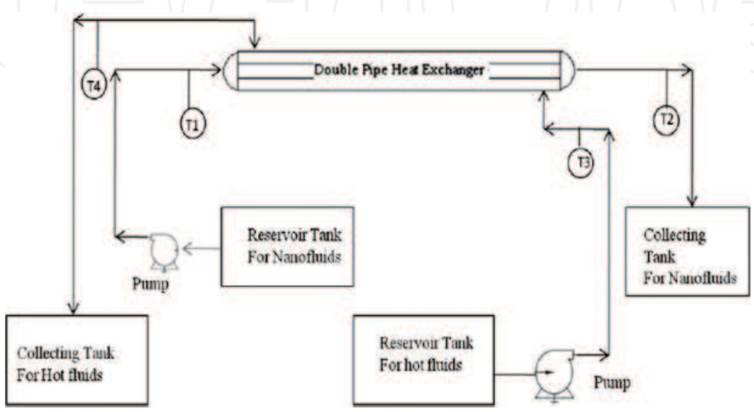

Figure 2. Schematic representation of nanofluid flow through concentric tube heat exchanger.

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.

$$Nu = 0.07Re^{0.707}Pr^{0.385}\varnothing^{0.074} \tag{18}$$

$$f = 0.961\varnothing^{0.052}Re^{-0.375} \tag{19}$$

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_2O_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_2O_3 and SiO_2 at high concentrations. $CeO_2 > Al_2O_3 > TiO_2 > SiO_2$ 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)

$$U = \frac{Q_{\text{avg}}}{AF\Delta T_{\text{LMTD}}} \tag{20}$$

$$A = N_t HW \tag{21}$$

$$\Delta T_{\text{LMTD}} = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{Ln\frac{(T_{h,o}-T_{c,i})}{(T_{h,i}-T_{c,o})}} \tag{22}$$

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 Hot water temperature range is 35–50°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. For outer tube, inner diameter is 27.8 mm and outer diameter is 33.9 mm.	Enhancement in convective heat transfer coefficient is about 6–11% as compared to base fluid.
Singh et al. [23]	TiO_2-water CuO-water	10–20 nm 30–50 nm	3500–13,500	Nanofluid temperature range 30 ± 3°C	Laminar and turbulent	0.1–0.3% by volume	Nanofluid flow rate range 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 for nanofluids. 1–3 LPM for hot fluid.	Concentric tube 8 mm diameter of inner pipe and16 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 over all heat transfer coefficient this enhancement is 2.2, 4.6 and 8.5%, respectively.

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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 Al_2O_3-water TiO_2-water SiO_2-water	30 nm 45 nm 10 nm 10 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 10 plates and heat exchanger are of 0.3 m^2.	For CeO_2/water, Al_2O_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.
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. Nu_{nf}/Nu_{water}= 1.17 Maximum pressure drop is about 8% as compared to distilled water.
Javadi et al. [30]	SiO_2-liquid nitrogen TiO_2-liquid nitrogen Al_2O_3-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_2O_3 at 0.2% concentration is 0.456 and 0.439 kg/s while for 2% concentration is	Plate fin heat exchanger.	Al_2O_3 has the highest overall heat transfer coefficient which is 308.69 W/m^2k in 2% concentration.

Researcher	Nanoparticle and base fluid	Size	Reynolds number range	Temperature range	Flow type	Nanoparticle concentration	Flow rates	Design	Results
							3.861 and 3.691 kg/s, respectively.		
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 Monoethylene glycol TiO_2-$_w$ater Monoethylene glycol	26 nm 9 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.

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_2O_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_2O_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_2O_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_2O_3 > TiO_2 > CuO > pure water > Ag.

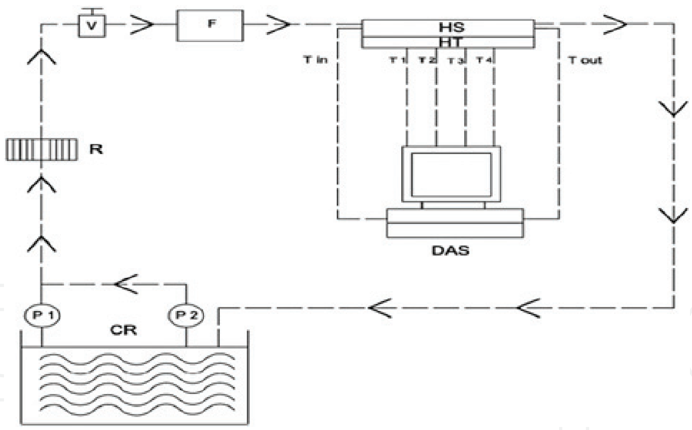

Figure 3. Schematic diagram of nanofluid flow through heat sink. CR is coolant reservoir, DAS is data acquisition system, F is flow meter, HS is heat sink, HT is heater, P is pump, R is radiator, T is thermocouple and V is valve in flow diagram.

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

$$R_{\mathrm{th}} = \frac{1}{\overline{h} \times A_{\mathrm{s}}} = \frac{1}{\frac{Q_{\mathrm{avg}}}{\Delta T_{\mathrm{LMTD}}}} \tag{23}$$

Parameters used in above equation include R_{th} as thermal resistance, $\overline{h}$ 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_2O_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_2O_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

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 TiO_2 (rutile)-water	5–30 nm 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_2O nanofluid with staggered pin fin heat sinks.
Mohammed et al. [34]	Al_2O_3-water Ag-water CuO-water Diamond-water SiO_2-water TiO_2-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_2O_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_2O_3-water TiO_2-water CuO-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]	TiO_2-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).	Heat transfer coefficient improvement was about 18.91% at flow rate of 1 LPM.
Ijam et al. [38]	Al_2O_3-water TiO_2-water	–	–	–	Laminar	0.8, 1.6, 2.4, 3.2 and 4% by volume	Nanofluid inlet velocity is 0.1 and 1.5 m/s	Mini-channel heat sink	Improvement in thermal conductivity of Al_2O_3/water nanofluids with 4% volume concentration is 11.98%, while for TiO_2/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]	TiO_2-water Al_2O_3-water	5 nm 5 nm	200–500	Temperature of nanofluid is 25°C	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.	Improvement in thermal conductivity for TiO_2 nanofluid is 6.55% at 1% volume concentration.

Table 4. TiO_2 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_2O_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_2O_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_2O_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

$$f = \frac{2\Delta P D_h}{\rho L u_{\mathrm{m}}^2} \tag{24}$$

where ΔP is pressure drop between inlet and outlet, D_{h} is hydrodynamic diameter, ρ 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°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 $\Delta T_{\mathrm{excess}}$. 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:

$$\frac{hl}{k} = 0.075 C_{sf} \left(\frac{q}{h_{\mathrm{fg}} \rho_{\mathrm{g}}^{0.5} [\sigma g(\rho - \rho_{\mathrm{g}})]^{0.25}} \right)^{0.66} Pr^n \tag{25}$$

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:

$$\frac{C_{p,l}(T_{\mathrm{s}} - T_{\mathrm{sat}})}{h_{\mathrm{fg}} Pr_{\mathrm{l}}^{m}} = C_{sf} \left(\frac{q}{\mu_{\mathrm{l}} h_{\mathrm{fg}}} \sqrt{\frac{\sigma}{g(\rho_{\mathrm{l}} - \rho_{\mathrm{v}})}} \right)^{0.33} \tag{26}$$

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

Weight concentration	ω
Density of base fluid	ρ_{bf}
Density of nanoparticles	ρ_{p}
Density of nanofluid	ρ_{nf}
Thermal conductivity of nanofluid	k_{nf}
Thermal conductivity of base fluid	k_{f}

Thermal conductivity of nanoparticles	k_p
Volume fraction	Ø
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	ΔP
Friction factor	f
Density	ρ
Velocity	v
Reynolds number	Re
Prandtl number	Pr
Peclet number	Pe
Over all heat transfer coefficient	U

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