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Cao, J, Ding, Y and Ma, C (2014) Aqueous Al2O3 nanofluids: the important factors impacting convective heat transfer. Heat and Mass Transfer, 50 (12). pp. 1639-1648. ISSN 0947-7411

https://doi.org/10.1007/s00231-014-1374-5

Aqueous Al_2O_3 Nanofluids
The Important Factors Impacting Convective Heat Transfer

Jianguo Cao and Yulong Ding

Dispersia Ltd, 103 Clarendon Road, Leeds LS2 9DF, UK

Caiyun Ma
Institute of Particle Science and Engineering, University of Leeds, Leeds LS2 9JT, UK

Abstract

A high accuracy, counter flow double pipe heat exchanger system is designed for the measurement of convective heat transfer coefficients with different nanofluids. Both positive and negative enhancement of convective heat transfer of alumina nanofluids are found in the experiments. A modified equation was proposed to explain above phenomena through the physic properties of nanofluids such as thermal conductivity, special heat capacity and viscosity.

Nomenclature

a	thermal diffusivity [m^2/s]
A	heat exchanging area [m^2]
C_{peff}	effective heat capacity [J/K]
C_{pH_2O}	heat capacity of water [J/K]
$C_{pAl_2O_3}$	heat capacity of Al_2O_3 particle [J/K]
D	tube inner diameter [m]
d_f	fractal dimension of the aggregates [m]
$dTln$	log mean temperature difference [K]
dt_i	inlet temperature difference [K]
dt_o	outlet temperature difference [K]
f	friction factor
h	convective heat transfer coefficient [W/K m^2]
k_e	effective thermal conductivity [W/K m]
k_m	thermal conductivity of the base liquid [W/K m]
k_p	solids phase thermal conductivity [W/K m]
k_a	aggregate thermal conductivity [W/K m]
Nu	Nusselt number
Pr	Prandtl number
Q	heat flux [W/m^2]
Re	Reynolds number
r_p	particle radius [m]
r_a	aggregate gyration radius [m]
T	Temperature [K]
t_{pi}	inlet primary fluid temperature [K]
t_{si}	inlet secondary fluid temperature [K]
t_{po}	outlet primary fluid temperature [K]
t_{so}	outlet secondary fluid temperature [K]
V	flow rate [l/min]

v	velocity of fluid [m/s]
v_p	volume fraction of the particle
w	weight fraction of the particle

Greek symbols

ρ	nanofluid density [kg/m^3]
ρ_f	base fluid density [kg/m^3]
μ	nanofluids viscosity [Pa s]
μ_f	base fluid viscosity [Pa s]
μ_w	viscosity at tube wall temperature [Pa s]

1. Introduction

Liquid coolants are widely used in equipment such as electronic devices, heat exchangers and vehicles to remove excess heat and keep the equipment below a certain design temperature. Trends are moving towards higher power and smaller sized equipment, which require higher amounts of heat to be removed through smaller surface areas. Applications of conventional heat transfer fluids such as water and water glycol mixture are limited due to their low thermal properties. A potential solution to improve these thermal properties is to add nanoparticles into the conventional fluids, hence forming so-called nanofluids.

Nanofluid is originally named by Choi in 1995 [1] when referring to a fluid with added nanoparticles. Much attention has been paid in the past decade to this new type of composite material, due to its enhanced properties and behaviour associated with heat transfer. It has been reported that the thermal conductivities of metallic or non-metallic particles such as Al_2O_3, CuO, Cu, SiC, and TiO_2 suspensions [2-6], are typically higher than those of the base fluids. Therefore when applied to heat transfer system, nanofluids are expected to enhance heat transfer compared with conventional liquids.

Most researchers have reported the positive enhancement of convective heat transfer with nanofluids. Pak and Cho [7] investigated convective heat transfer in the turbulent flow regime using Al_2O_3/water and TiO_2/water nanofluids. They found that the Nusselt number of the nanofluids increased with the volume fraction of the suspended nanoparticles or the Reynolds number. Xuan and Li [8] measured convective heat transfer coefficient of Al_2O_3/water nanofluids and found substantial heat transfer enhancement. For a given Reynolds number, the heat transfer coefficient of the nanofluids containing 2% volume Al_2O_3 nanoparticles, showed to be approximately 35% higher than that of pure water. Zienali Heris et al. [9-11] investigated the convective heat transfer of Al_2O_3/water and CuO/water nanofluids in circular tubes. They observed that the heat transfer coefficient was enhanced by increasing the concentration of nanoparticles in the nanofluids. Furthermore, the nanofluids with 20nm Al_2O_3 nanoparticles showed an improved heat transfer performance compared with the 50nm CuO nanoparticles, especially at higher nanoparticle concentrations. Wen and Ding [12] studied the entrance region of a tube flowing under laminar conditions with a constant heat flux. Their results showed an increase of over 40% in the convective heat transfer coefficient at an x/D location of 63 when adding 1.6% by volume of 27-56nm Al_2O_3 particles to de-ionized water. Anoop et al. [13] conducted an experimental investigation into convective heat transfer characteristics, in the developing region of a tube flow, with alumina-water nanofluid. They found that the enhancement of heat transfer coefficient of Al_2O_3 nanofluids depended on particle sizes. Furthermore, they concluded that the convective heat transfer coefficient of nanofluids was enhanced with increasing nanoparticle concentration. Oluwole Daniel Makinde [14] numerically investigated the convective heat transfer of water based copper(Cu), alumina(Al_2O_3), and titania (TiO_2) nanofluid. It was found the heat transfer rate at the plate surface with Cu-water nanofluid is higher than that of Al_2O_3-water and TiO_2-water nanofluid.

However, research results from several other literatures showed that heat transfer enhancements were very trivial or even negative for similar nanofluid systems. Fotukian et al. [15] experimentally investigated turbulent convective heat transfer of γ-Al_2O_3/water nanofluid inside a circular tube. Their results indicated that changing the volume fraction of nanoparticles from 0.054% to 0.2% did not show much effect on the convective heat transfer enhancement. Ni et al. [16] measured alumina nanofluid in turbulent convective flow and found that the convective heat transfer coefficient, h, Nusselt number, Nu, and Rayleigh number, Ra, decreased when increasing the volume fraction of the nanoparticles. Under certain conditions, the Nusselt number of alumina nanofluid was significantly lower than that of water.

The main objective of the present work is to quantify the argumentation of the heat transfer of nanofluids in a convective environment. Firstly, a high accuracy counter-current flow double pipe heat exchanger system is designed and applied to convective heat transfer coefficient measurements. The mechanism of the system is perspicuity and the heat transfer behaviour in this system is well understood. Secondly, two kinds of alumina nanofluids are well prepared at both high and low pH values, respectively. The experimental results demonstrated that Al_2O_3 (pH H) samples have a positive convective heat transfer enhancement, but Al_2O_3 (pH L) samples show a negative response, when comparing them to that of pure water. A modified equation of heat transfer coefficient was proposed to explain the benefit and disadvantage of nanoparticle additives to the convective heat transfer enhancement.

2. Experimental Studies

2.1. Materials and nanofluids preparation

Two kinds of commercially available alumina nanoparticles/suspensions were used to prepare sample nanofluids with different concentrations. The Al_2O_3 (pH L) sample was prepared by a two-step method. Dry alumina nanoparticles were purchased from Degussa (Germany) with an average primary particle size being about 13nm. The dry nanoparticles were in the form of large agglomerates. In order to break down the large agglomerates, hence obtaining the desired nanofluids with certain nanoparticle concentrations, ultrasonication applied for 30 mins to the mixture of a preset amount of nanoparticles and water. Then the suspension was processed in a medium-mill to further reduce the agglomerate size (Dyno Multi-Lab Mill, Willy A. Bachofen of Switzerland). As no stabiliser was used in this sample, the pH value of the suspension was adjusted to approximately 4.4 by adding HCl solution which can also prevent the milled samples from re-agglomeration. Water based alumina suspension (Al_2O_3 (pH H) sample) was supplied by ItN Nanovation (Germany) which may contain surfactants, alkali and buffs. The average primary particle size is about 30nm with an original pH value of about 9.2. The initial nanoparticle weight fraction was 40wt%. The suspension was diluted with de-ionized water to obtain a nanofluid of low concentration. Prior to each measurement, the nanofluid was ultrasonicated for 10-30 minutes using an ultrasonic processor (Hielscher ultrasound technology) to break and de-agglomerate clustered nanoparticles. To distinguish between the two different alumina nanofluids, the nanofluid prepared by Degussa particles with a low pH value is called Al_2O_3 (pH L) and the nanofluid from ItN Nanovation with a high pH is named Al_2O_3 (pH H).

A Malvern nanosizer (Malvern Instruments, UK) was used to measure the particle size distributions of the suspensions. The results show that there is no obvious particle size difference among different concentrations of the same sample. The particles size of Al_2O_3 (pH L) is about 100nm and that of Al_2O_3 (pH H) is about 200nm. Note that the sizes given here are the hydrodynamic diameters of aggregates of nanoparticles. They are less dense than the primary nanoparticles. Both nanofluids were found to be very stable for several weeks.

2.2. Effective thermal conductivities and viscosities of Al_2O_3 nanofluids

The thermal conductivity was measured by using a Lambda system (PSL Systemtechnik GmbH, Germany). This system measures the thermal conductivity for fluid, powder, gel and nanofluids from -30^{o}C to 190^{o}C, with accuracy to 0.1^{o}C. In order to study the effect of different temperatures on the effective thermal conductivity of nanofluids, a thermostat bath (IMI Cornelius, UK) was used. It is able to maintain temperature uniformity within ± 0.1^{o}C. At least five measurements were taken for each sample, at a given temperature, to ensure the accuracy of the measurements. The viscosity was measured by using a rheometer (Physica MCR 301, Anton Paar Austria) with a 75mm diameter cone at 20^{o}C. The measurement shear rate is between ~50 and 1,000 s^{-1}.

2.3 Experimental system

There are a limited number of published studies on the forced convective heat transfer of nanofluids. Most of the experimental apparatus has a circular tube with a constant heat flux in various flow regimes. Numbers of thermal couples are soldered on the tube surface at different locations along the test section for the estimation of local convective heat transfer data. The experimental systems and further details can be found in literature [7~13]. However, the real inhomogeneity of the heat flux and the interface heat resistant between thermal couple and the tube surface will bring large error in the above apparatus. In the present experiment, the convective heat transfer measurement system is a simple counter flow double pipe heat exchanger, as shown schematically in Fig 1. It consists of a flow loop, a heat unit, a cooling part, and a measuring and control unit. The flow loop includes a pump, a flow meter, a reservoir, and a test section. The test section, “double pipe heat exchanger”, is composed with two 1.8 m straight stainless steel tubes with ¼ inch and 1/8inch outer diameter, respectively, which are connected through a reducing union tee (Swagelok, UK). The thicknesses of inner and outer tubes are both 0.6mm. The inside nanofluids were cooled by the water flowing in the annular section between the inner and outer tubes under a counter-current mode. Nanofluids were heated by a 2,000 W water bath (F25, Julabo, UK) through a plate heat exchanger (IC5, SWEP, UK). The temperature range of the water bath is up to 200^{o}C. A 2,000 W chiller (ThermoFlex 2,500 Fisher, UK) was used for the water cooling. The flow rate is monitored by a C-flow coriolis mass flow meter (Küppers Elektromechanik GmbH, Germany) whose error is within

±0.5%. There is a thick thermal isolating layer surrounding the whole double pipe to prevent excessive heat losses to the surrounding. Eight Pt 100-1/10 thermocouples with ±0.03^{o}C accuracy (TC direct, UK) are mounted on the test section. All of them are immersed into nanofluids or cooling water. Each measurement point has 2 thermocouples to ensure the accuracy of the temperature measurement. The pump used in this work is a centrifugal pump (RS, UK) whose flow rate is controlled by a 0~15V DC power supply (PS1503SB HQ Power).The maximum flow rate that the pump delivers under experimental conditions is 2.8 l/min. The temperature range of this pump is between -20^{o}C and 120^{o}C. The pressure drop of nanofluids was measured by a low differential pressure transducer (PX2300, Omega, UK) whose accuracy is ± 0.25%.There is a three way valve in the flow loop for flow rate calibrations and flow system cleaning between runs even with the same nanofluid. The temperature readings from 8 thermocouples, the flow rate, and the pressure drop are registered by a data requisition system. In the heat transfer experiments, the flow rates and temperatures of heating and cooling water bath are also recorded. It is worth to note that although a simple counter-current double pipe heat exchanger was used in this study, some other non-regular convective configurations, such as plates and bend tubes, reported in literature for the enhancement of heat transfer with pure fluids could be adopted to investigate the effect of nano-particles, which can be the further research tasks.

2.4 Calculation of convective heat transfer coefficient

In the experiment, the average convective heat transfer coefficient (h) is obtained through the heat dissipation of the nanofluids:

$$Q = h\, A\, dTln \qquad (1)$$

where Q is the exchanged heat duty (in watts), A is the heat exchange area, and dTln is the log mean temperature difference (LMTD) which is defined as:

$$dTln = (dt_o - dt_i) / \ln(dt_o/dt_i) \qquad (2)$$

where

$dt_i = t_{pi} - t_{si}$ = inlet primary and secondary fluid temperature difference
$dt_o = t_{po} - t_{so}$ = outlet primary and secondary fluid temperature difference

The heat dissipation of the nanofluid is also expressed as:

$$Q = \rho\, C_{peff}\, V\, (t_{pi} - t_{po}) \qquad (3)$$

where ρ is the nanofluid density, C_{peff} is the effective heat capacity of nanofluid which will be discussed further in the next section, V is the flow rate, t_{pi} and t_{po} are the inlet and outlet temperature of the nanofluid, respectively. Combining Equations (1) and (3), the average convective heat transfer coefficient (h) can be calculated using Equation (4) with the experimentally measured data.

$$h = \rho\, C_{peff}\, V\, (t_{pi} - t_{po}) / (A\, dTln). \qquad (4)$$

3. Results and discussion

3.1. TEM analysis

Fig. 2 shows the transmission electron microscopy (TEM) images of alumina particles. It is clearly seen that the primary nanoparticles of Al_2O_3 (pH H) are approximately spherical with an average diameter of about 30nm and that of agglomerate is about 200nm, which are consistent with the results of nanosizer. The compact structure and smooth shape of Al_2O_3 (pH H) agglomerates would lead to a low viscosity. In Fig. 2 (b), it is found that the primary nanoparticle size of Al_2O_3 (pH L) is about 13 nm. Nanoparticles tend to aggregate in porous fractal shape agglomerates which would result into a high viscosity.

3.2. Thermal conductivities of nanofluids

Fig. 3(a) shows the measured effective thermal conductivities of Al_2O_3 nanofluids with various particle concentrations. Also included in Fig. 3(a) are the predicted results from two theoretical models: Maxwell [17] and Prasher, et al. [18]. The Maxwell model calculates the effective thermal conductivity k_e in a very dilute suspension with spherical particles by ignoring the interactions among the particles:

$$k_e = k_m + 3v_p \frac{k_p - k_m}{2k_m + k_p - v_p(k_p - k_m)} k_m \qquad (5)$$

where k_m and k_p are the thermal conductivities of the base fluid and particles, respectively. v_p is the volume fraction of the particles. A great number of extensions to the Maxwell equation (5) have been carried out ever since the Maxwell's initial investigation. One of them, Prasher et al [18], considered the effects of both aggregation of particles and Brownian induced convection:

$$k_e = k_m + 3(r_a / r_p)^{3-d_f} v_p \frac{k_a - k_m}{2k_m + k_a - (r_a / r_p)^{3-d_f} v_p (k_a - k_m)} k_m \qquad (6)$$

where $\left[1 - (r_p / r_a)^{3-d_f}\right] \frac{k_m - k_a}{2k_a + k_m} + (r_p / r_a)^{3-d_f} \frac{k_p - k_a}{2k_a + k_p} = 0$ and $1.75 \le d_f \le 2.5$

r_p and r_a are the particle radius and the aggregate gyration radius, respectively. k_a is the thermal conductivity of aggregates and d_f the fractal dimension of the aggregates.
Fig. 3(a) shows that the measured effective thermal conductivities of Al_2O_3 nanofluids increase with nanoparticle concentration in a linear fashion at high concentrations. The measured effective thermal conductivities of Al_2O_3 (pH L) are even lower than the prediction of the Maxwell model. As we known, water is the fluid which almost has the highest thermal conductivity. Adding salts, surfactants, and other liquids may reduce the thermal conductivity of water. The impurity of raw nanoparticle of Al_2O_3 (pH L) is the most possible reason for its low thermal conductivity enhancement. The thermal conductivity of Al_2O_3 (pH H) sample is well predicted by the model of Prasher et al. by considering the particle aggregation effect.

Fig. 3(b) shows the effect of temperature on the effective nanofluids thermal conductivity. It is clearly shown that the effective thermal conductivity increases with the temperature which has been observed by Das et al. [3] and Li et al. [19]. However, the increasing ratios of alumina nanofluids are slower than that of the base fluid: water. The same results were only reported by Masuda et al. [20] who measured the effective thermal conductivities of water based alumina nanofluids under different concentrations with temperature range from 31.85^{o}C to 66.85^{o}C.

3.3. Viscosities of nanofluids

Rheological measurements in this work show that the Al_2O_3 nanofluids behave nearly as the same as Newtonian fluids even at 20wt% nanoparticle concentration over the shear range from 50 to 1,000 1/s. Fig. 4(a) shows the shear viscosities as a function of shear rate for 5wt%, 9wt% and 20wt% Al_2O_3 (pH L) samples. The results of Al_2O_3 (pH H) sample are similar. Fig. 4(b) shows the average shear viscosities of the two samples under shear rates from 50s^{-1} to 1,000 s^{-1}. Two observations are made from the results in Fig. 4(b). First, the measured viscosity of nanofluids is much higher than that predicted by the Einstein equation, indicating the strong interactions between particles in the nanofluids. Second, the viscosity of Al_2O_3 (pH H) is lower than that of Al_2O_3 (pH L), which means that the interactions of same material nanoparticles may be different due to different pH levels, surfactants and preparation process used.

Duan et al. [21] compared the viscosities of aqueous suspensions of Al_2O_3 nanoparticles stored for 2 weeks with and without refresh. It is found that the viscosity of refreshed Al_2O_3 nanofluid is above 10 times lower than that of 2 weeks stored one without refresh. In this study, the Al_2O_3 (pH L) samples were stored more than a month and their viscosities were measured directly without any further treatment. The Al_2O_3 (pH H) samples were refreshed by ultrasonic process and then measured. The viscosities of two alumina samples obtained in this work are both lower than that of the refreshed samples of Duan et al [21].

3.4 Special heat capacity

The specific heat capacity of a nanofluid is an important parameter that has to be evaluated to analyze the heat transfer properties of the nanofluid. In this analysis, the nanofluid is considered as a homogenous mixture. The specific heat capacity formula for homogeneous mixture is given by

$$C_{peff} = wC_{pAl_2O_3} + (1-w)C_{pH_2O} \qquad (7)$$

To determine the special heat capacity of Al_2O_3, the following equation is used [22]:

$$C_{pAl_2O_3} = 1.2492 + 0.0005075(T)-(29561.11/T^2), \qquad (8)$$

In the experiments of this study, the special heat capacity was also measured by Lambda system together with the measurement of thermal conductivity. The theoretical prediction agrees with the measurement results well (Fig. 5). Fig. 5 also shows the specific heat capacity decreases with the concentration of alumina at room temperature.

3.5 Convective heat transfer

3.5.1. Convective heat transfer coefficient of pure water

Before systematic experiments are performed with Al_2O_3 nanofluids, the experimental system was tested with pure distilled water as a working fluid. Fig. 6 shows the temperatures of working fluids on the measurement points. The maximum standard deviation is less than 0.04^{o}C which proves that the accuracy of the rig reaches the design standards. The results with the distilled water also serve as the basis for comparison with the results of nanofluids.

In this work, instead of the same Reynolds number, the same output power of the pump was used to compare convective heat transfer coefficient. As discussed in 3.3, the viscosities of Al_2O_3 nanofluids could be different due to the different pH levels, the surfactants and/or preparation processes used. The Reynolds number is defined by:

$$Re = \rho vD/\mu \qquad (9)$$

where D is the hydraulic diameter of the pipe and v is the mean velocity of the fluid. By comparing the convective heat transfer between Al_2O_3 (pH H) and Al_2O_3 (pH L) at the same Reynolds number, it can be found that the flow rate of Al_2O_3 (pH L) is always larger than that of Al_2O_3 (pH H) due to the relative high viscosity of the Al_2O_3 (pH L) nanofluids. In other words, the pump output power of Al_2O_3 (pH L) is larger than that of Al_2O_3 (pH H) at the same Reynolds number. In such case, it is difficult to judge that the convective heat transfer enhancement comes from the nanofluid itself or from the increase of pump output power. The same problem also exits in the comparison between nanofluids and water.

Fig. 7 shows the convective heat transfer coefficient with the distilled water at flow rates from 0.1l/min to 0.8l/min which cover from laminar to turbulence regions (1800<Re<8500). Also shown in the figure are the predicted results with the following Gnielinski equation:

$$Nu = \frac{(f/2)(Re - 10^3)Pr}{1 + 12.7(f/2)^{1/2}(Pr^{2/3} - 1)} \qquad (10)$$

The Prandtl number is defined as $Pr = \mu C_p / k_e$ with its value for the base fluid (water) being 6.5. f in Eq. (10) is the friction factor given by $f \approx 0.078Re^{-1/4}$. The Nusselt number can also be defined by:

$$Nu = h D/k_e \qquad (11)$$

Combining Eqs. (10) and (11), the following equation for theoretical prediction of convective heat transfer coefficient can be obtained. As showing in Fig. 7, the experimental results and theoretical prediction matched very well, which indicates the system can achieve high accuracy (< 1%).

$$h = \frac{k_e}{D} \frac{(f/2)(Re - 10^3)Pr}{1 + 12.7(f/2)^{1/2}(Pr^{2/3} - 1)} \quad (12)$$

3.5.2 Effect of nanoparticle concentration on the convective heat transfer

Fig. 8(a) and (b) show the experimental results of heat transfer coefficients of nanofluids (calculated by equation (4)) with different particle concentrations for Al_2O_3 (pH L) and Al_2O_3 (pH H) samples, respectively. It is found that the influences of nanoparticles are not always positive. The Al_2O_3 (pH L) samples showed negative impact on convective heat transfer comparing to that of pure water. With the increase of nanofluid concentrations, the convective heat transfer coefficient of Al_2O_3 (pH L) samples decreased dramatically. On the contrary, 5wt% Al_2O_3 (pH H) samples showed about maximum 6% heat transfer enhancement comparing to pure water. However, increasing the concentration of alumina nanoparticles can only achieve limited convective heat transfer enhancement. The experimental convective heat transfer coefficients of 9wt% and 20wt% Al_2O_3 (pH H) samples demonstrated the similar behaviour.

The heat transfer coefficient of laminar fluid flow through circular tube can be calculated from Seider-Tate equation [23] in the following form:

$$Nu = 1.86\ (Re\ Pr\ D/L)^{1/3}\ (\mu/\mu_w)^{0.14} \quad (13)$$

In Fig. 8, the calculation results of equation (13) are also shown. It is found that the maximum root mean square deviation is about 40%. Moreover it cannot describe the trend of the Al_2O_3 (pH L) sample. The convective heat transfer coefficients of 20wt% Al_2O_3 (pH L) are larger than those of water, which does not match the experimental results.

For a fully developed turbulent flow through a pipe with a constant wall heat flux, the following correlation was proposed [24] to calculate the heat transfer coefficient,

$$h\ D/k_f = 0.022\ Re^{0.84}\ Pr^{0.36} \quad (14)$$

where the values of 0.022 and 0.84 are constants for a tube bank in a flow under a particular case of $2\times10^5 < Re < 2\times10^6$. In Fig. 9, the calculation results of equation (14) are compared with the experimental results. It is found that the calculation results from equation (14) are over 5 times higher than those from experiments.

For our case, the conditions are different from the assumptions of Equations (13) and (14): First, the wall heat flux is not constant. Second, the flow rate covers from laminar to turbulence. However, by adjusting the constants to fit the experimental results in this study, the following equation can be obtained.

$$h = 0.0177\left(\frac{\rho^{0.8} v^{0.8} C_{peff}^{0.33}}{D^{0.2}}\right)\left(\frac{k_e^{0.67}}{\mu^{0.47}}\right) \quad (15)$$

The calculation results are also showed in Fig. 10 (a) and (b) with dash lines. Both positive and negative effects can be explained well with equation (15). The root mean square deviation between the experimental and calculation results is reduced to less than 10%

The equation (15) indicates that the convective heat transfer coefficient depends on multiple factors such as viscosity, thermal conductivity of fluids and heat capacity. The main impacts of nanoparticles on the fluids are the increasing viscosity, decreasing special heat capacity, and increasing thermal conductivity. Obviously, the first two factors are negative to the convective heat transfer. Only the third one can lead to the enhancement of the convective heat transfer.

4. Conclusions

An experimental study has been carried out on the heat transfer and flow behaviour of aqueous Al_2O_3 nanofluids through a counter flow double pipe heat exchanger system. The effects of nanoparticle concentration, viscosity, thermal conductivity, and special heat capacity were investigated. The following conclusions can be drawn:

- In general, addition of nanoparticles into the base liquid can enhance the thermal conduction, and also increase the viscosity and reduce the special heat capacity
- Nanofluids used in this work show nearly Newtonian behaviour and have very low viscosity when shear rates are larger than $50s^{-1}$. Suitable surfactants and pH levels are considered as the important factors to affect convective heat transfer.
- Comparing the convective heat transfer enhancement at the same Reynolds number is considered as an unpractical method as it is possible to conclude that high viscosity fluids have better heat transfer properties than low viscosity fluids, when other factors are the same.
- For a given pump power, the convective heat transfer coefficient increases with the increase of the thermal conductivity and heat capacity and the decrease of the viscosity. Comparing with the pure base fluid, nanofluid can improve and also deteriorate convective heat transfer depending on the complex interactions of the fluid properties. The convective heat transfer coefficient does not always increase with the increase of the nanoparticle concentration.

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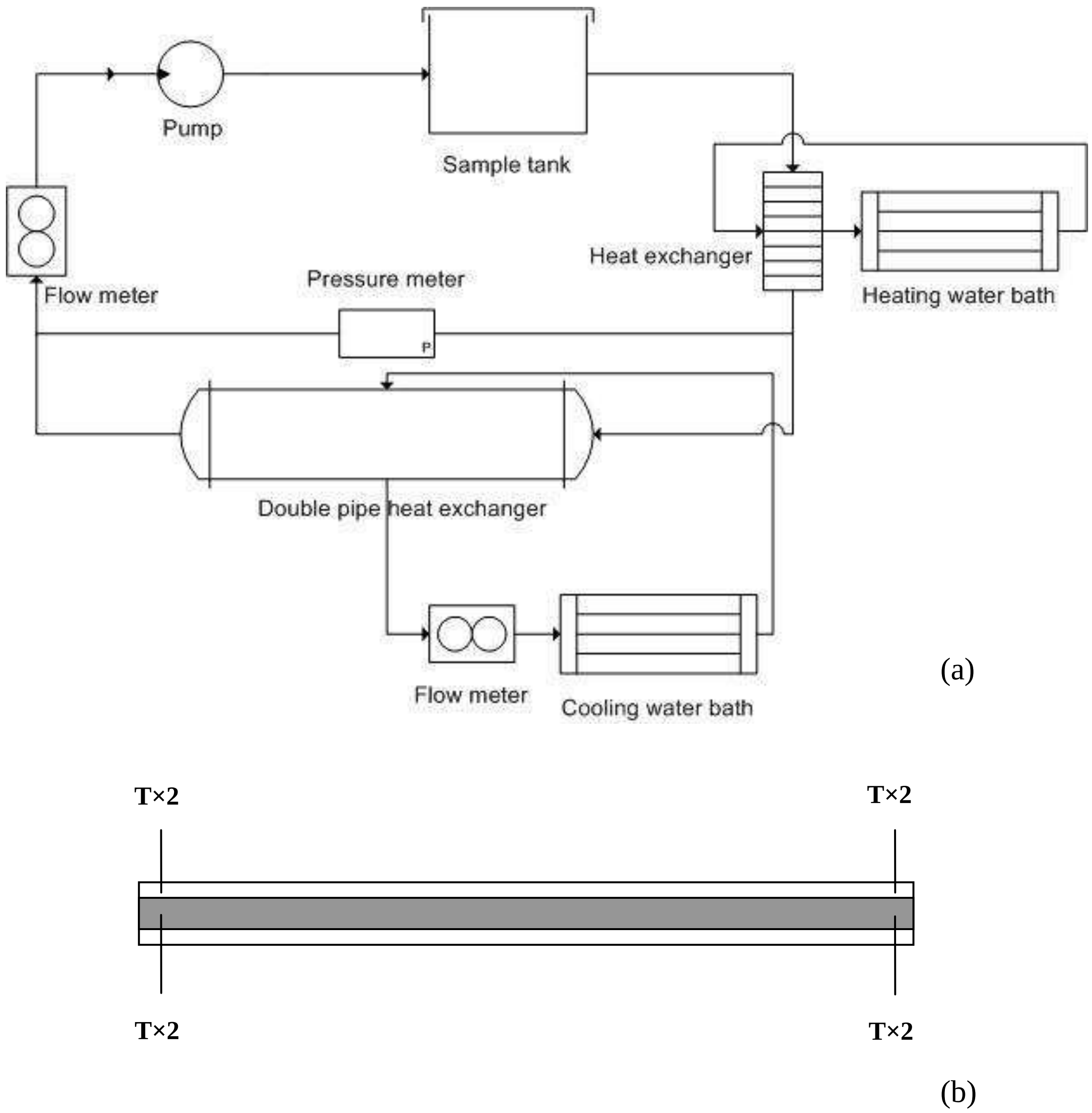


Fig. 1. (a) Counter flow double pipe heat exchanger system and (b) The inlet and outlet temperature of nanofluids and water are monitored by eight thermocouples.

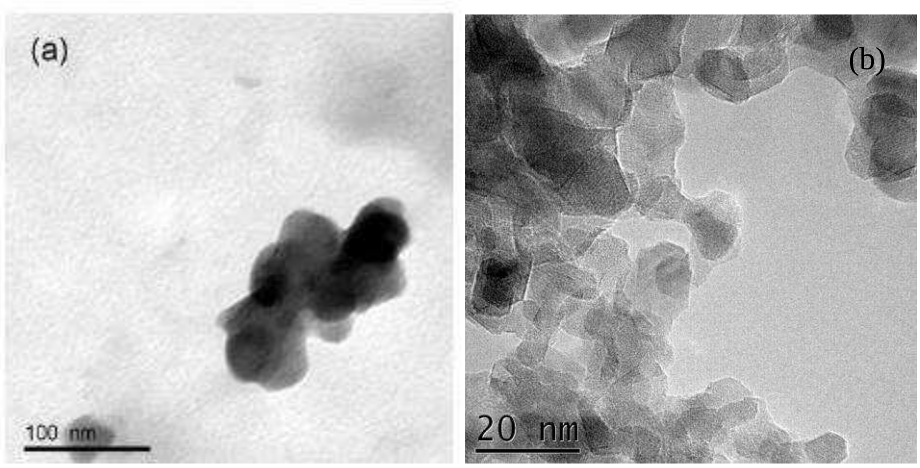


Fig. 2. TEM images of alumina particles: (a) Al_2O_3 (pH H) and (b) Al_2O_3 (pH L) particles and agglomerates.

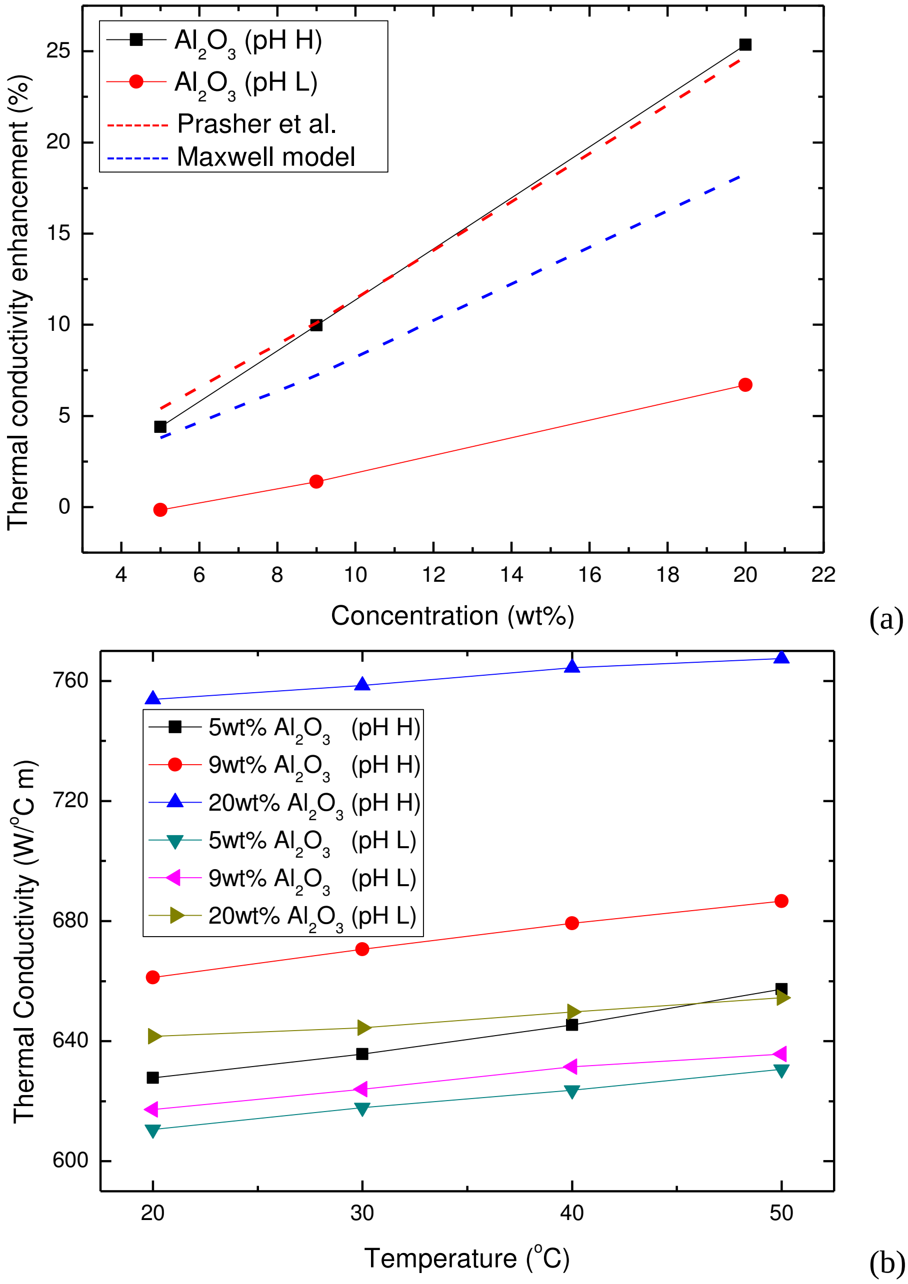
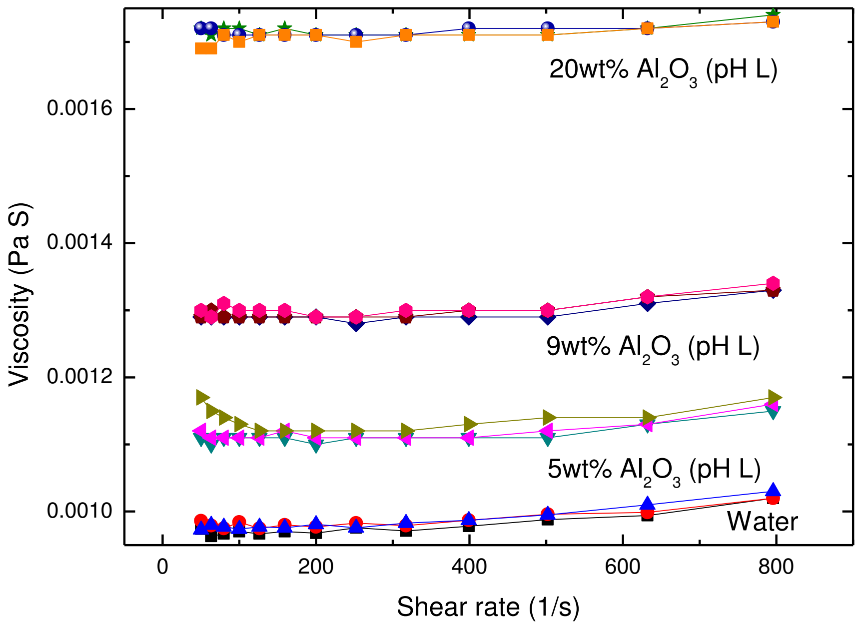
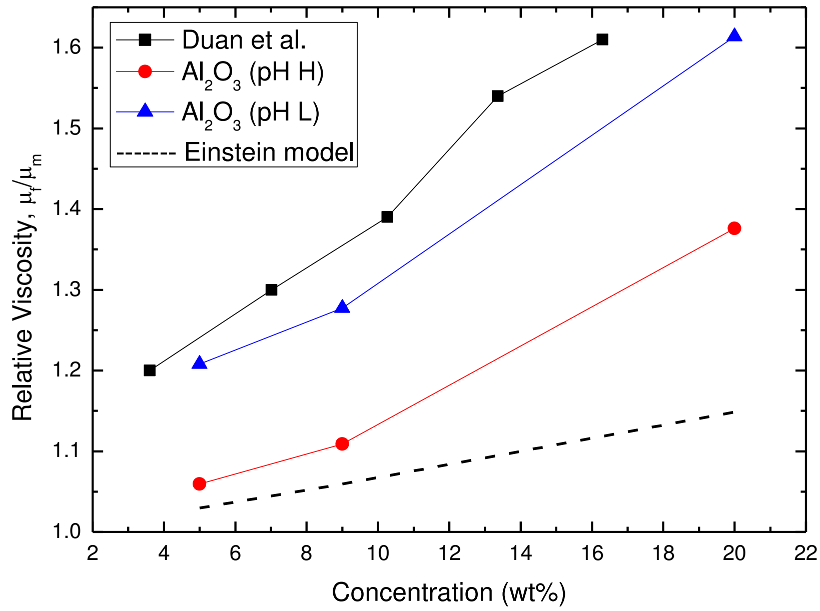


Fig. 3. Effects of (a) particle concentration and (b) temperature on the thermal conductivity of aqueous Al_2O_3 nanofluids.



(a)



(b)

Fig. 4. Effects of shear rates and particle concentration on the alumina nanofluid viscosity. (a) viscosity of nanofluids as a function of shear rate and (b) effect of particle concentration.

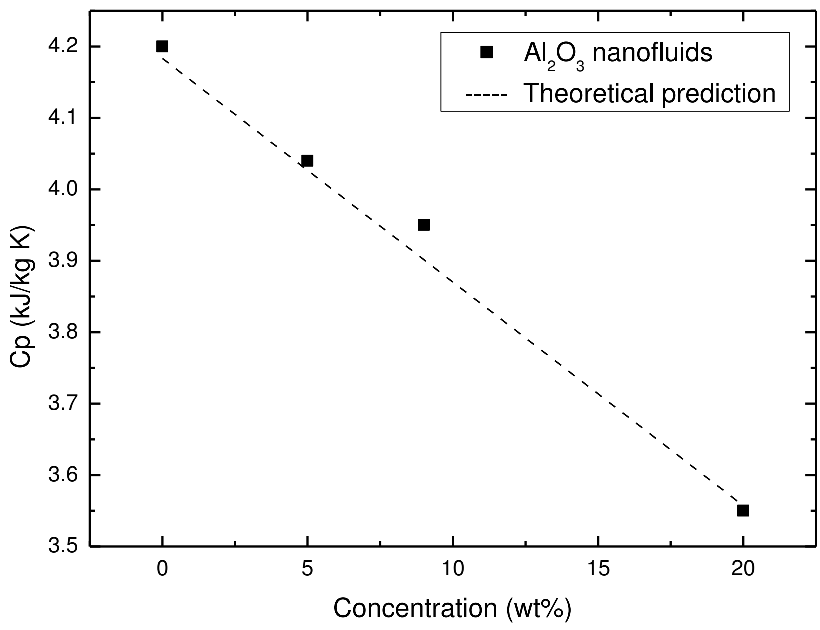


Fig. 5. Depict the specific heat at different volume fractions.

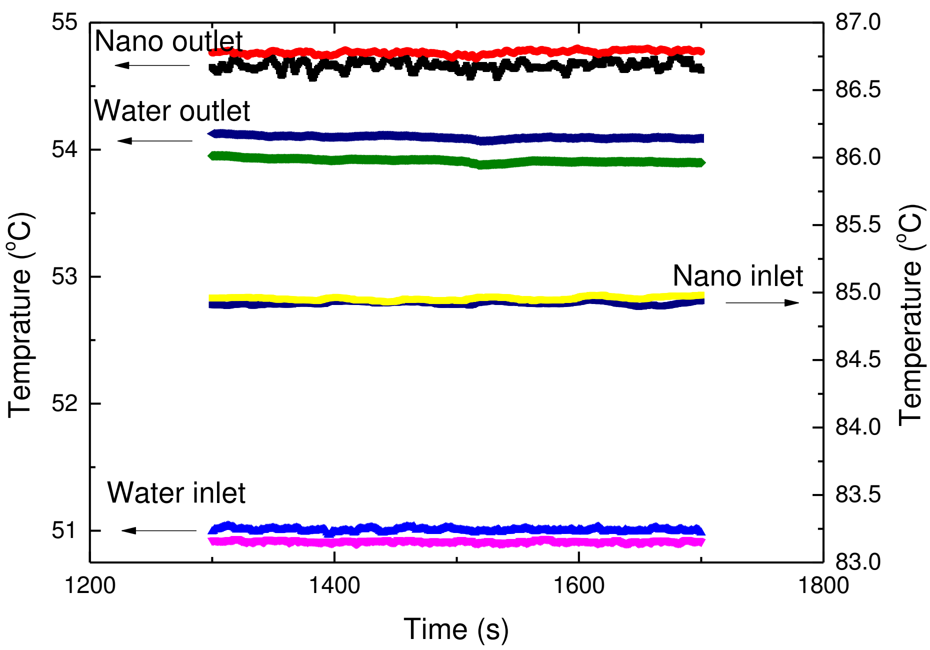


Fig. 6. The temperatures of the working fluids on the measurement points.

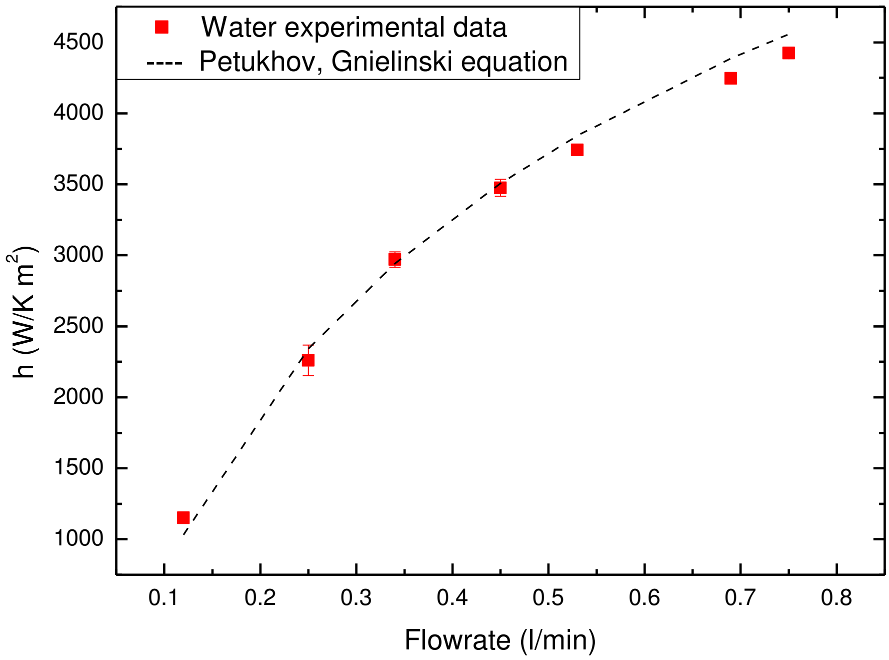


Fig. 7. Comparison of the measurements with the empirical Gnielinski equation for pure water.

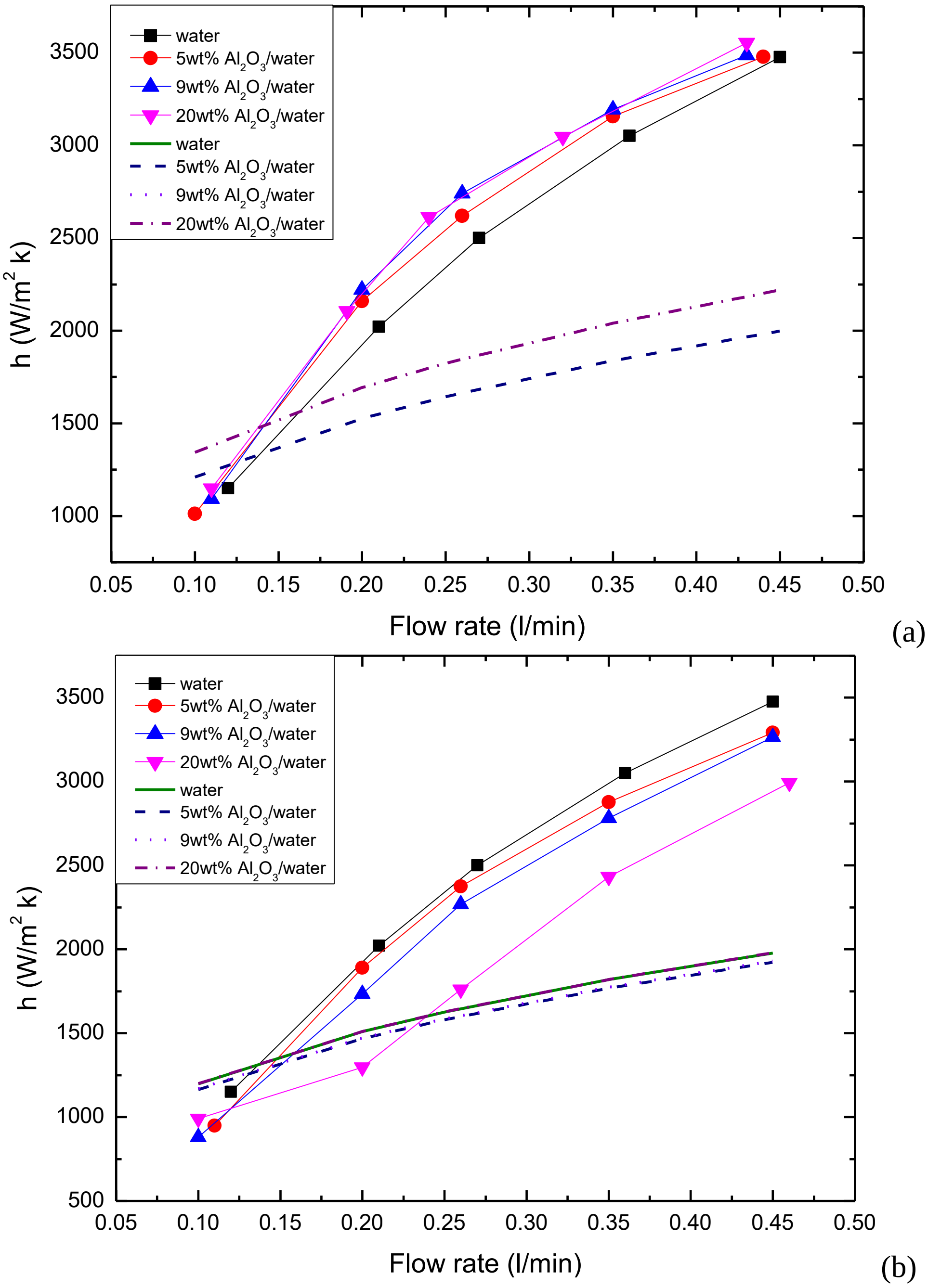


Fig. 8. The experimental convective heat transfer coefficients results of (a) Al_2O_3 (pH H) samples and (b) Al_2O_3 (pH L) samples. Solid lines with symbols denote the calculation results using equation (13).

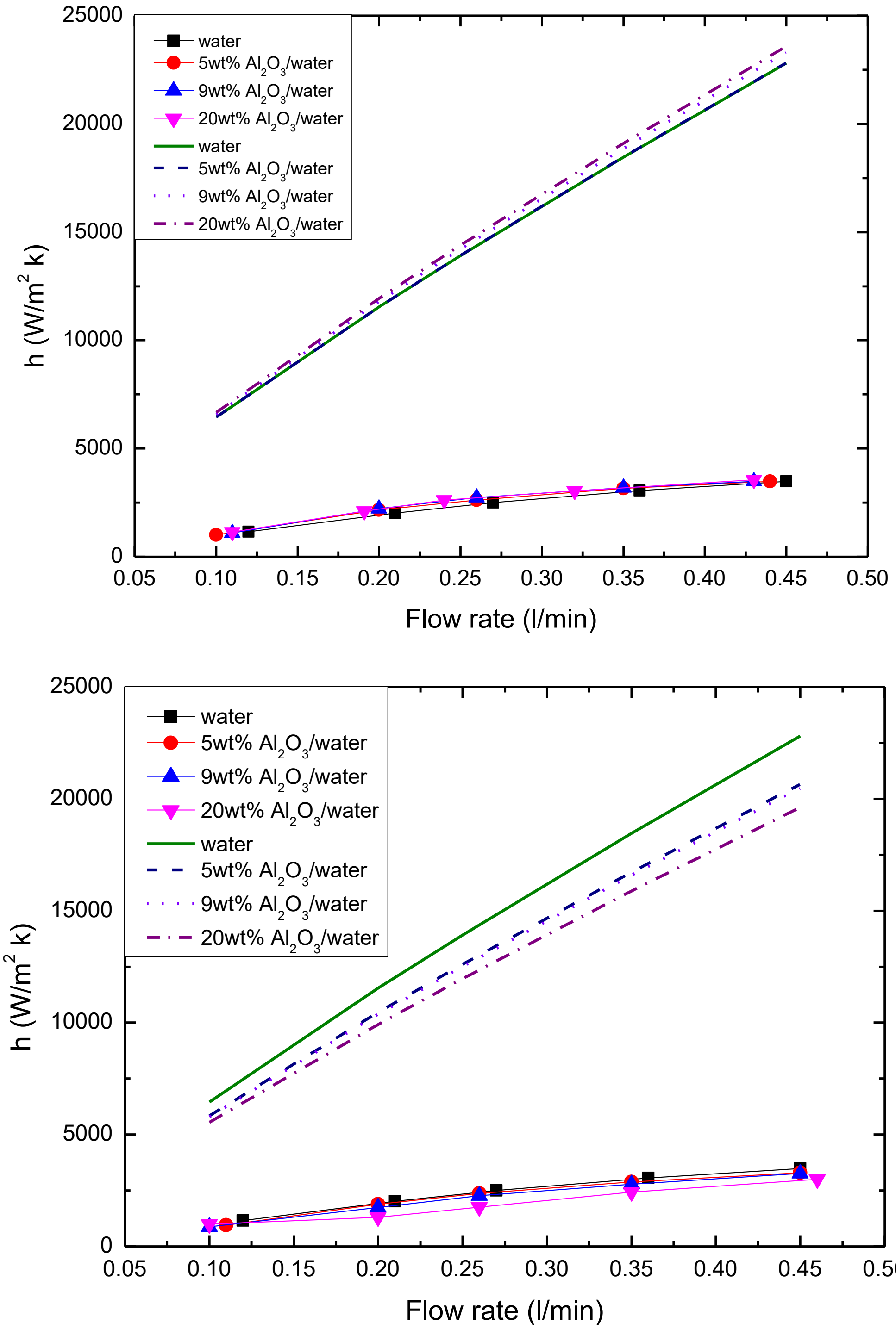
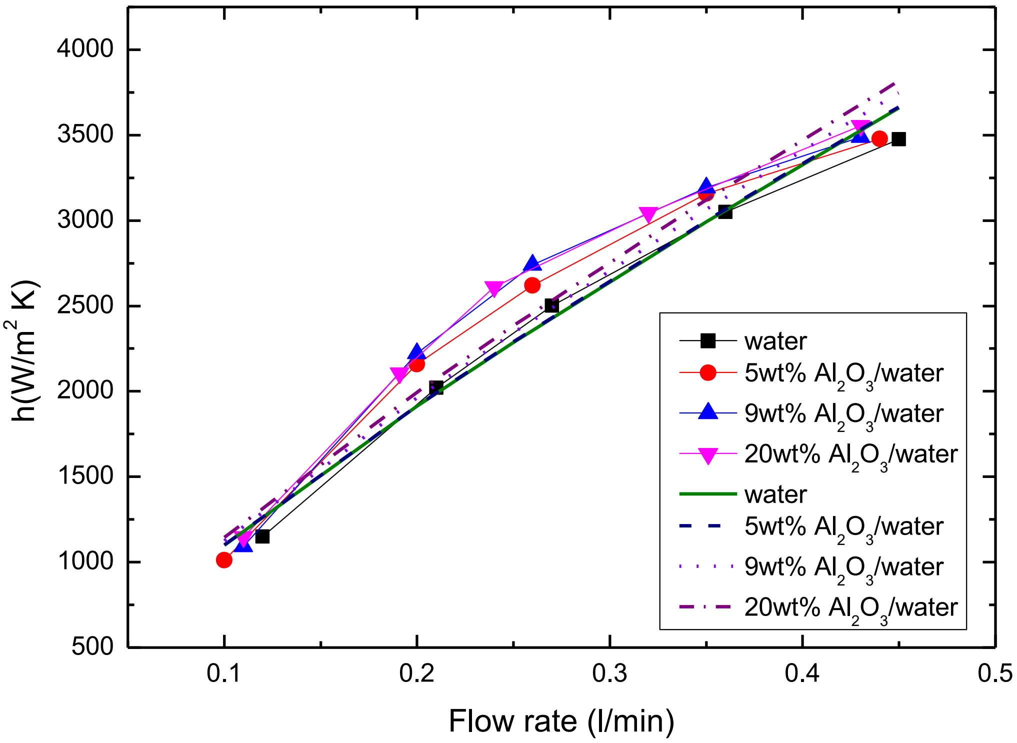
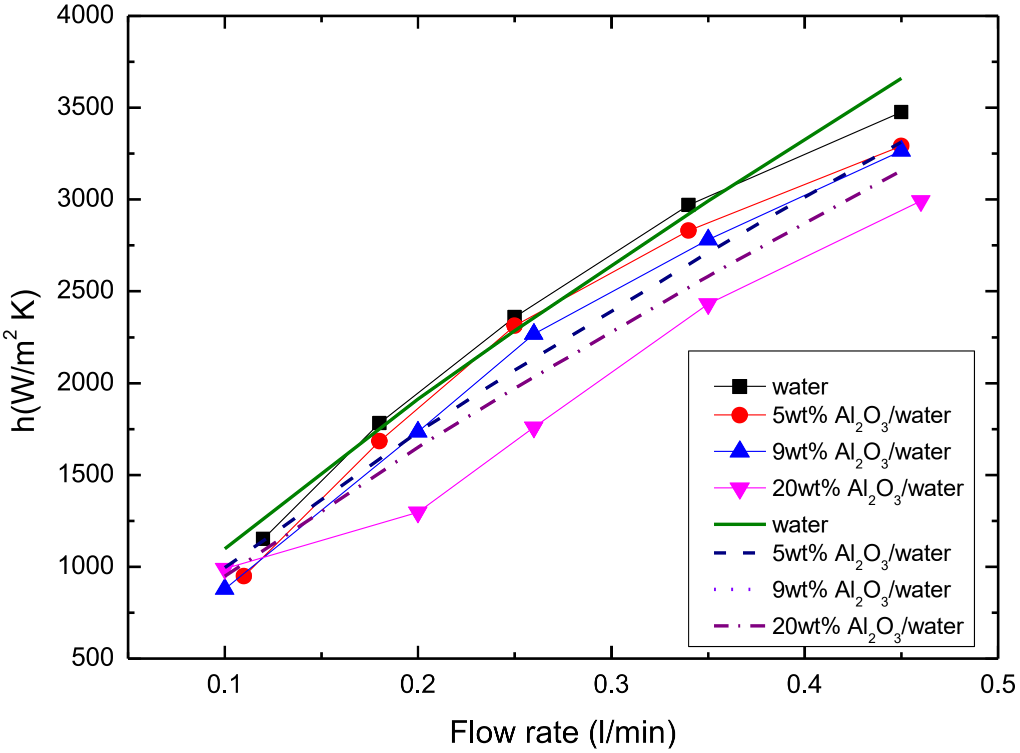


Fig. 9. The experimental convective heat transfer coefficients results of (a) Al_2O_3 (pH H) samples and (b) Al_2O_3 (pH L) samples. Solid lines with symbols denote the calculation results using Seider-Tate equation (14).



(a)



(b)

Fig. 10. The experimental convective heat transfer coefficients results of (a) Al_2O_3 (pH H) samples and (b) Al_2O_3 (pH L) samples. Solid lines with symbols denote the calculation results using equation (15).