EFFECT OF NANOPARTICLE SHAPES ON HEAT TRANSFER CHARACTERISTICS AND THERMODYNAMIC PERFORMANCE OF A SHELL AND TUBE HEAT EXCHANGER

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FACULTY OF ENGINEERING

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ABSTRACT

The use of nanofluids as working fluids have resulted in increased performance for various applications involving heat transfer in today's industrial sector. Many studies on nanofluids have been conducted for shell and tube heat exchanger performance based on spherical shaped nanoparticles. The objective of this research project is to study the effects of different nanoparticle shapes for nanofluids in terms of heat transfer characteristics (i.e. heat transfer coefficient, and overall transfer coefficient), and also determine the thermodynamic performance for a shell and tube heat exchanger used in a waste heat recovery industry (i.e. heat transfer rate, and entropy generation). The effect of four types of nanoparticle shapes were studied (i.e. platelets, blades, cylinders, and bricks) for this research project. The results showed an increase in both heat transfer characteristics and thermodynamic performance for all nanoparticle shapes when compared to conventional basefluid. From the results obtained, it was established that EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles was the best performing nanofluid with an increase of 3.9% for heat transfer coefficient (h), 1.9% for overall heat transfer coefficient (U_o), and 1.3% for heat transfer rate (q). Although increase in entropy generation minimization for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticle was lowest (1.48%) compared to the remaining EG/H_2O-AlOOH nanofluids containing the remaining nanoparticle shapes, the percentage difference was less 0.5%. Two comparison studies were conducted with respect to EG/H_2O-AlOOH nanofluid containing the best performing nanoparticle shape. The first comparison study was between EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles and EG/H_2O-AlOOH containing spherical shaped nanoparticles. While the second comparison study was between EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles with and

without considering the size factor of the nanoparticle shape. Comparison between EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticle and EG/H_2O-AlOOH nanofluid containing conventional shaped nanoparticle showed an increase in heat transfer characteristics (2.4% for heat transfer coefficient, h and 1.14% for overall heat transfer coefficient, U_o) and thermodynamic performance (0.88% for heat transfer rate, q) for the former nanofluid. While comparison between EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles with and without considering the size factor, heat transfer characteristics and thermodynamic performance were slightly lower (0.88% for heat transfer coefficient, h, 0.40% for overall heat transfer coefficient, U_o, and 0.30% for heat transfer rate, q). The reason behind this was that if size factor was not taken into consideration, the thermal resistance between nanoparticles and basefluid was neglected, resulting in the increase in theoretical performance. Overall, this study clearly showed the effect of different nanoparticle shapes in terms of heat transfer characteristics and thermodynamic performance.

ABSTRAK

Penggunaan bendalir nano sebagai media pengangkutan telah menyebabkan peningkatan dari segi kecekepan dan prestasi bagi pelbagai aplikasi yang melibatkan pemindahan haba di dalam sektor industri pada masa kini. Penyelidikan terhadap kegunaan bendalir nano yang mengandungi zarah nano berbentuk sfera untuk alat pemindahan haba jenis "shell and tube" telah banyak dijalankan sejak kebelakangan ini. Objektif penyelidikan ini adalah untuk mengenal pasti kesan bendalir nano yang mengandungi zarah nano berlainan bentuk dari segi ciri-ciri pemindahan haba dan prestasi termodinamik di dalam alat pemindahan haba jenis "shell and tube" yang digunakan di dalam sektor industri. Kesan daripada empat bentuk zarah nano berlainan seperti "platelets", "blades", "cylinders", dan "bricks" telah diselidiki di dalam penyelidikan ini. Keputusan daripada hasil kaji selidik ini telah menunjukan peningkatan dari segi ciri-ciri pemindahan haba dan prestasi termodinamik untuk bendalir nano yang mengandungi zarah nano berlainan bentuk berbanding bendalir biasa. Apabila dibandingkan prestasi diantara keempat-empat bentuk zarah nano tersebut, zarah nano berbentuk "cylinder" menghasilkan peningkatan yang tertinggi dari segi ciri-ciri pemindahan haba dan kadar pemindahan haba. Namun begitu, zarah nano berbentuk "cylinder" juga mencatatkan peningkatan tertinggi dari segi pembentukan entropi. Walau bagaimanapun, peningkatan tersebut adalah kurang daripada 1%. Perbandingan prestasi dilakukan diantara zarah nano berbentuk "cylinder" bersama zarah nano berbentuk sfera, yang merupakan zarah nano yang sering kali digunakan di dalam bendalir nano dan juga bersama zarah nano berbentuk "cylinder" akan tetapi tidak mengambil factor saiz zarah nano tersebut. Bagi perbandingan prestasi diantara zarah nano berbentuk "cylinder" dan sfera, prestasi bagi zarah nano berbentuk "cylinder" mencatatkan prestasi yang lebih tinggi dari segi ciri-ciri pemindahan haba

dan prestasi termodinamik. Bagi perbandingan prestasi bersama zarah nano berbentuk "cylinder" tanpa mengambil faktor saiz pula, prestasi bagi zarah nano yang terdahulu adalah lebih rendah. Ini kerana jika factor saiz zarah nano tidak diambil kira didalam pengiraan, rintangan terma yang berlaku diantara zarah dengan bendalir biasa juga tidak di ambil kira. Ini adalah faktor yang menyebabkan kenaikan prestasi bagi zarah nano berbentuk "cylinder" yang tidak mengambil kira faktor saiz zarah. Secara keseluruhan, kaji selidik ini telah menunjukkan kesan daripada zarah nano berlainan bentuk terhadap ciri-ciri pemindahan haba dan prestasi termodinamik.

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A	Area, m^2
A_{cf}	Cross flow area, m^2
$A_{o,t}$	Tube side flow area per pass, m^2
B	Baffle spacing, m
$C_{\min}$	Minimum capacity ratio
$C_{\max}$	Maximum capacity ratio
C^*	Capacity rate ratio
C_p	Specific heat, J/kg K
D	Diameter, m (shell side)
d	Diameter, m (tube side)
h	Heat transfer coefficient, W/m^2 K
$\dot{m}$	Mass flow rate, kg/s
n	Shape factor
NTU	Number of heat transfer units
N_{TC}	Total number of tubes
Nu	Nusselt number
k	Thermal conductivity, W/m K
k_w	Thermal conductivity of copper wall, W/m K
L	Length, m
P_t	Square tube pitch, mm
Pr	Prandtl number
Re	Reynolds number
q	Heat transfer rate, W
$\dot{S}_{gen}$	Entropy generation, W/K
T	Temperature, K
U_o	Overall heat transfer coefficient, W/m^2 K
u	Velocity, m/s

Greek symbols

ε	Heat exchanger effectiveness
ϕ	Volume fraction
ρ	Density, kg/m^3
μ	Dynamic viscosity, Ns/m^2
ψ	Sphericity

Subscripts

b	Base
f	Fluid
e	Equivalent
m	Mean
nf	Nanofluid
p	Particle
s	Shell
t	Tube
i	Inlet
o	Outlet
c	Cold
h	Hot
eff	Effective

CHAPTER 1

INTRODUCTION

1.0 Introduction

Due to the increase in demand of energy in the world today it is necessary to improve the performance of liquid cooling devices, diversely used in applications such as power electronics, renewable energy, transportation, and medical equipment to ensure improved energy efficiency, enhance heat dissipation, and increase devices lifetime [1].

These improvements can be achieved by improving the heat transfer process of the devices making it more efficient and effective during its operation. Changes to boundary conditions and flow geometry, as well as enhancing thermal conductivity of the conventional base fluid used are mooted as passive ways to improve the convective heat transfer for the devices [2].

The idea of enhancing thermal conductivity of conventional base fluids have been conducted by researchers beginning with the suspension of micro or larger-sized solid particles in fluids. Unfortunately, it was difficult to ensure that the solid particles would settle out of suspension resulted in lack of stability which contributes to possible erosion and additional flow resistance. The high density and large size of the particles were the main reasons to why its commercialization was never pursued.

However, as a result of technological advancement, the increase interest in the field of nanotechnology has been steadily gathering pace providing researchers with opportunities to process and produce materials at a nano-scale level. Similarly with previous studies, these particles are suspended in conventional base liquids termed as nanofluids.

1.1 Nanofluids for heat transfer enhancement

The term nanofluids refer to dilute suspension of particles and fibres of nanometre-size dispersed in a liquid. With the addition of these foreign materials in the base fluid, physical properties such as viscosity, density, and thermal conductivity of the nanofluid will differ from the original base fluid. For many applications the most important physical property of nanofluids is the thermal conductivity [3].

The particle which can be either metallic or non-metallic materials such as Al_2O_3, CuO, Cu, SiO, and TiO have higher thermal conductivity compared to the conventional base fluid even at low concentrations. As a result of having higher thermal conductivity, heat transfer coefficient increases significantly. Therefore the effective thermal conductivity of nanofluids is expected to enhance heat transfer compared with conventional heat transfer liquids [4].

Various studies both experimental and numerical have been conducted to analyse the effect due to increase in thermal conductivity of nanofluids in a wide range of applications. The application to which this study is focused in is the use of nanofluids in heat exchangers. Heat exchangers are devices where the efficiency of heat transfer between the working fluids is an important factor during operating conditions. The increase in heat transfer efficiency will result in energy and cost savings. Therefore with the use of nanofluids, there is a potential enhancement effect on the performance of heat exchangers.

Many researchers have studied on the potential impact of nanofluids on heat exchanger performance. There is a growing interest in enhancing heat exchanger performance by adding nanofluids to the base fluid to enhance rate of heat transfer. A lot of experimental studies have been conducted to study the effect of nanofluids in terms of heat exchanger efficiency, pressure drop, and friction factor.

Study by B. Farajollahi et al. [5] using two types of nanofluids to base fluid water on heat transfer characteristics in shell and tube heat exchanger under turbulent flow shows improvement in heat transfer. The study states that nanoparticle concentration for both type of nanofluids show different heat transfer characteristic. Another study by Jahar Sarkar [6] using nanofluids as a coolant in a shell and tube gas cooler of CO_2 cycle shows improvement in terms of effectiveness, cooling capacity, and coefficient of performance (COP) without penalty of pumping power. From the results, the best type of nanofluid-water combination was Al_2O_3-H_2O giving a COP improvement of 26.0%. Similarly an experimental study has shown that using multi-walled carbon nanotubes (MWNT)/water nanofluid [7] increases the heat transfer enhancement in comparison with the base fluid inside a horizontal shell and tube heat exchanger.

The studies mentioned above are basically using nanofluids with conventional shell and tube heat exchangers. Studies have also been conducted where nanofluids are used with shell and tube heat exchangers that have been improved by passive methods. In an experimental study conducted by Saeedinia et al. [8], improvement using passive methods were studied by inserting different types of wire coils into the smooth tube of a shell and tube heat exchanger and the effects were determined. The nanofluid used for the study was CuO-base oil under laminar flow conditions. Heat transfer coefficients were improved for each type of wire coil when compared to base liquid. The maximum heat transfer improvement was 40.2% achieved when using wire coils with the highest wire diameter. This shows that heat transfer performance are better when nanofluids flows through tubes with wire coils inserts compared to conventional smooth tubes. However, like all other ways to improve performance of shell and tube heat exchanger, the problem comes in the form of increase in friction factor. In the same study, increase in friction factor was observed for both pure oil and nanofluids flow in a shell and tube heat exchanger with wire coil inserts. When comparing friction factor results between basefluid and nanofluids, increase in friction factor was recorded as particle concentration increases for all nanofluids. However, due to the anti-friction properties of CuO nanoparticles, increase in friction factor for all nanofluids became insignificant as the Reynolds number increases. This is because within the same range of particle concentration, results for friction factor for all nanofluids were more or less the same when compared to each other. When comparing increase of friction factor results with pure oil base fluid, a 68% increase in friction factor was recorded for the tube set with the highest wire diameter.

In a study by M.N. Pantzali et al. [9], performance of a miniature plate heat exchanger with modulated surface using CuO in water as working fluid showed that substituting water with nanofluid as the cooling medium resulted in the enhancement of heat transfer. Using CuO nanofluid as the cooling liquid, a 10% increase in heat flow rate was recorded when compared to water working as its cooling liquid. The experimental study showed that enhancement of heat transfer coefficient was only at lower cooling liquid flow rates with an increase 13%, while at higher flow rates the nanoparticle contribution to heat transfer were less with a drop to about 6%. To validate the experimental result obtained, a numerical simulation was conducted using computation fluid dynamics (CFD) and the result showed that the percentage difference between both heat flow results was less than 10%. The use of nanofluid also resulted in lower volumetric flow rate (up to 3 times lower) required to remove the specific heat load compared to water for a given heat duty, which in turn resulted in lower pressure drop (about 5 times lower).

A study using nanofluid consisting of water and TiO_2 nanoparticles were conducted for a double tube counter flow heat exchanger [10]. The heat transfer enhancement and pressure drop characteristics were investigated under turbulent flow conditions. Factors which contribute to the increase in heat transfer coefficient were decrease in nanofluid temperature and increase in nanofluid and hot water mass flow rate. With no significant effect coming from the temperature of heating fluid and pressure drop were nearly the same as of water under similar working conditions. Overall the results showed an increase between 6-11% in terms of convective heat transfer when substituting water with nanofluid. The effects of different particle concentration were recommended for future works involving convective heat transfer coefficients and nanofluids flow features.

Using Al_2O_3-water nanofluid as working fluid, a simulation for the performance for a multi-channel heat exchanger in terms of overall heat transfer was conducted. The simulation was based on its application which was the cooling of electronic chips. Two parameters that were considered for the simulation was the weight concentration of nanofluids and inlet water temperature. From the results, overall heat transfer coefficient ratios were higher as the weight concentration increased because under high concentration, collision between nanoparticles and heat exchanger wall was possibly higher. However, the study states that the increase in overall heat transfer ratio is not solely due to the increase in nanoparticle concentration. Other factors such as temperature of working fluid, surface structure of the heat exchanger must be taken into consideration. Finally, the best overall heat transfer coefficient ratio was achieved at higher mass flow rate, a lower inlet water temperature and higher nanoparticle weight concentration [11].

1.2 Nanoparticle parameters for heat transfer enhancement

The enhancement in thermal conductivity for nanofluids can be attributed to several factors involving the nanoparticle such as particle material, volume fraction, size, and shape. Numerous studies have been conducted to determine the effects of these parameters on the enhancement in thermal conductivity of nanofluids [12, 13].

Considering the first parameter for nanoparticle which is the particle material, studies have shown that suspension of nanoparticle material which has higher thermal conductivity relative to the base fluid significantly increases the thermal conductivity of the nanofluids. The nanoparticle can be of metallic or non-metallic materials [14]. Table 1.1 shows the thermal conductivity values of various metallic and non-metallic materials commonly used as nanoparticles. The increase in nanofluid thermal conductivity varies with respect to the nanoparticle material used where materials with better thermophysical properties added to the base fluid will result in better heat transfer enhancement.

Table 1.1

Thermal conductivities for metallic and non-metallic materials [14].

Material	Element	Thermal conductivity (W/m K)
Metallic (solids)	Silver	429
	Copper	401
	Aluminium	237
Non-metallic (solids)	Diamond	3300
	Carbon nanotubes	3000
	Silicon	148
	Alumina (Al_2O_3)	40
Metallic (liquid)	Sodium @ 644K	72.3
Non-metallic (liquids)	Water	0.613
	Ethylene glycol	0.253
	Engine oil	0.145

This parameter is closely related to the second parameter which is the volume fraction. The volume fraction of nanoparticle materials added to the conventional basefluid is usually stated in terms of percentage (i.e. 1% nanoparticle volume fraction). Several literatures have reported that the increase in thermal conductivity of nanofluids varies from a small percentage increase to a significant percentage increase per volume fraction of nanoparticle material added. The increase in thermal conductivity is seen to increase linearly with respect to the nanoparticle volume fraction used [15, 16].

Although increase in thermal conductivity was seen for both metallic and non-metallic nanoparticles, metallic particles are able to increase the thermal conductivity of nanofluids at lower volume fraction compared to non-metallic nanoparticles. However, preventing the metallic nanoparticles from oxidizing during the production process is a concern [4].

Another parameter which contributes to the potential increase in thermal conductivity of nanofluids is the size of nanoparticle used which is defined as the surface to volume ratio of the nanoparticles. The area of solid/liquid interface is higher for smaller particles within the same volume fraction of a suspension [13]. The viscosity of the nanofluid will also be affected by the size of the nanoparticles. As volume fraction of the nanoparticle increases, the viscosity of the nanofluid will also increases.

Several studies conducted by researchers found that when volume fraction of nanoparticles were kept constant with variation in nanoparticle sizes [17, 18] viscosity of the nanofluids were higher at smaller nanoparticle sizes. Ideally, heat transfer is superior for nanofluids with larger nanoparticles hence lower viscosity. However, this may cause instability to the nanofluid as a result of increase in settling velocity rate using the Stokes law equation. Therefore, some researchers have suggested that better heat transfer enhancement can be achieved by using nanofluids with uniform distribution of smaller nanoparticles [4].

The final parameter with respect to the nanoparticle is the shape of the nanoparticle. Several studies reported that elongated particles which gives higher aspect ratio with regards to total area between solid/liquid interface results in better heat transfer enhancement when compared to spherically shaped nanoparticles. The drawback is that, using non-spherical nanoparticles will result in the increase in viscosity of the nanofluid [13]. Several shapes of nanoparticles which have been studied are such as cylindrical [16], rods [19], and shuttle-like shape [20].

1.3 Objectives of study

Heat transfer characteristic can be improved with the use of nanofluids. Increase in heat transfer characteristics is important for process related industries as it improves performance of the devices that requires efficient heat transfer. The use of nanofluid as the cooling medium for waste heat recovery can also be improved as a result of better heat transfer especially involving heat exchanger devices. Therefore, the main objectives of this research project are:

1. To calculate the effect of different nanoparticle shapes on heat transfer characteristics for nanofluids (i.e. heat transfer coefficient, and overall heat transfer coefficient)
2. To determine the effect of different nanoparticle shapes based on the heat transfer characteristics on thermodynamic performances of a shell and tube heat exchanger (i.e. convective heat transfer rate, and entropy generation)
3. To compare the results for both heat transfer characteristics and thermodynamic performances of the best nanoparticle shape with conventional nanoparticle shape (spherical), and best performing nanoparticle shape without considering the size factor.

1.4 Organisation of the report

This report is organized into five main chapters. Chapter 1 gives a brief introduction of why devices involving cooling of liquids needs to be improve and how it can be achieved through the use of nanofluids stating examples of previous studies which have been conducted. This chapter also touched on the nanoparticle parameters which affect the heat transfer enhancement of nanofluids and the objectives of the research project.

Chapter 2 begins with a brief review of theoretical models that have been used to determine the thermal conductivity enhancement for nanofluids containing spherical shape nanoparticles stating its advantages and limitations. This is followed with a brief review on the theoretical model that is used to determine the thermal conductivity enhancement of nanofluids for non-spherical shape nanoparticles underlining the relationship between shape factor, n and the sphericity value, ψ of the nanoparticle. Several studies highlighting the effects of different nanoparticle shape factor on thermal conductivity enhancement of nanofluids were reviewed at the end of the chapter.

Chapter 3 describes the research methodology used to achieve the objectives of the research project. The shell and tube heat exchanger design and operating parameters were presented along with the thermophysical properties for particle material, conventional basefluid, and particle shape effects. Obtained from various literatures and books, the required mathematical formulations used for this study are also listed down in this chapter.

Chapter 4 discuss on the results obtained by solving the mathematical formulation stated in the previous chapter. This chapter is divided into three aspects. The first aspect discuss on the effect of different particle shape on heat transfer characteristics and thermodynamic performances of a shell and tube heat exchanger. The second part compares the performance of the best performing particle shape with the conventional (spherical) particle shape and the third part compares the performance of the best performing particle shape with or without considering the size factor. The results from all three aspects were then related or compared to results obtained from previous studies to determine their similarities and validity.

Chapter 5 summarizes the research project in terms of best performing particle shape, performance comparison between conventional particle shape and best particle shape without size factor. The chapter concludes with some recommendations on how to further enhance the performance of nanofluids and shell and tube heat exchangers plus possible future studies related to this research project.

CHAPTER 2

LITERATURE REVIEW

2.0 Literature Review

The increase in thermal conductivity of nanofluids has been studied through various experimental and theoretical approaches. For experimental studies, thermal conductivity of nanofluids mostly depends on the parameters that have been discussed in the previous chapter. During the preparation of nanofluids, spherical shaped particles are the most commonly used. Meanwhile for theoretical studies measurement for thermal conductivity of spherical shaped particle, the earliest model used was the Maxwell model [21]. Unfortunately, results obtained using this model was appropriate for micro/mini particles and low volume concentration.

To overcome the limitation of this model, another model was developed by Bruggeman [22] where results obtained for particles at low volume concentration were similar to the results obtained using the Maxwell model. Unlike the Maxwell model, for particles at high volume concentration, results obtained using the Bruggeman model were in agreement with the results obtained from experimental investigations [14]. Nevertheless, the Maxwell model is frequently used for comparison purposes with experimental findings due to its simplicity to determine the thermal conductivity of nanofluids [23].

Although spherical shaped particles are commonly used during nanofluid preparations, researchers have also studied on particles with different shapes. Examples of different shape particles that have been studied are cylindrical, disk, etc. The next section will discuss on the model that has been developed to determine the thermal conductivity of nanofluids for non-spherical particles.

2.1 Relationship between particle shape factor and spherical value for nanofluids

The Maxwell model which is commonly used to determine the thermal conductivity of nanofluids for theoretical studies does not take into consideration the shape of the particle. An extended version of the Maxwell model was proposed by Hamilton and Crosser [24] to include a variable known as the shape factor, *n* to account for the shape of the particle. The Hamilton and Crosser model for thermal conductivity of nanofluids is governed by the equation:

$$k_{eff} = \frac{k_p+(n-1)k_b-(n-1)(k_b-k_p)\emptyset}{k_p+(n-1)k_b+(k_b-k_p)\emptyset} k_b \quad (2.1)$$

where, k_p and k_b are the thermal conductivities of the particle and base fluid respectively. The volume fraction of the particle is denoted by $\emptyset$. The shape factor, n is governed by the equation

$$n=3/\psi \quad (2.2)$$

where ψ is the particle sphericity, which is defined as the ratio between surface areas of a spherical particle with equal volume, to the surface area of the non-spherical particle.

For comparison, the Hamilton and Crosser model is reduced to the Maxwell model when the shape factor, n equals to 3 or sphericity, ψ equals to 1 [2].

Using the reduced Hamilton and Crosser model for spherical particle, the results obtained for thermal conductivity were in agreement with experimental studies for volume fraction below 30%. As long as the ratio between thermal conductivity of particle is greater than thermal conductivity of the base fluid by a factor of 100 (k_p/k_b >100), the Hamilton and Crosser model is valid for non-spherical particles. A study regarding [4] the range for sphericity value, using Al_2O_3-water nanofluids, Xuan and Li [25] found that the range for sphericity was between 0.3-1 using the Hamilton and Crosser model. However, there was no reference to the shape which the sphericity value represents. Several researchers agreed that for cylindrical particle, shape factor, n was found to be 6 corresponding to sphericity, ψ value of 0.5 [3].

An experimental study on the effect of particle shape on thermal conductivity and viscosity of alumina nanofluids was conducted in 2009 [26]. Different particle shapes (i.e. blades, platelets, cylinders, and bricks) were used during the experiment. The sphericity, ψ values for each of these shapes were 0.36, 0.52, 0.62, and 0.81 respectively. The empirical shape factor, *n* corresponding to the sphericity values were 8.6, 5.7, 4.9, and 3.7. This shows that as the sphericity, ψ value increases, the empirical shape factor, *n* decreases. From the results obtained, the shape which recorded the highest increases in thermal conductivity was the cylinder shape particle. The thermal conductivity and viscosity of alumina nanofluid increased as the volume concentration increased. Unlike the thermal conductivity, the increase in viscosity recorded by the blade shape particle was the lowest as volume concentration increased.

2.2 Effect of different nanoparticle shapes on thermal conductivity enhancement of nanofluids

The first recorded experimental study for thermal conductivity enhancement due size and shape of the added nanoparticles suspension were reported by H. Xie et al. [27]. Using the transient hot-wire method, the thermal conductivity of a nano sized SiC suspension were recorded. The particle shape that was used for the experiment were sphere and cylinder shape. When compared to conventional base fluid, the results showed that by adding nanoparticles to the base fluid (i.e. spherical and cylinder) the thermal conductivity increased by 15.8% and 22.9% respectively. Comparing the results based on the shape of the particle, the results clearly show that thermal conductivity of the cylinder shape particle nanofluid is superior to the spherical shape particle nanofluid.

Another experimental study using cylinder-like (rod) shape particle was conducted by Murshed et al. [19]. The nanoparticle material that was used for this experimental study was TiO_2 with deionized water as the base fluid. Similarly, using spherical and rod shape particles enhanced nanofluids, the recorded thermal conductivities were compared to thermal conductivity of conventional base fluid showing an enhancement of 30% for spherical particle and 33% for rod particles. Compared in terms of particle shape, rod shaped particle produces larger increase in thermal conductivity compared to spherical shaped particle nanofluid. Results from both of these experimental studies were then compared with results obtained by applying the Hamilton and Crosser Model and upon comparison found that the increased in the thermal conductivity of cylinder shaped particle nanofluid compared to spherical shaped particle nanofluid was attributed to the higher shape factor, *n* of the cylinder shaped particle.

In an experimental study by H.T. Zhu et al. [20], nanofluid containing CuO nanoparticles with ethylene glycol (EG) as its basefluid was conducted to determine the thermal conductivity enhancement. The nanoparticles were prepared using the ultrasonic vibration and microwave irradiation technique. The outcome of the preparation stage was a shuttle-like shape particle. The thermal conductivity of the shuttle-like shaped nanofluid was recorded at room temperature. An increase of 18-31% was recorded corresponding to 1-5% increase in volume fraction. The results were then compared to results obtained from different studies that had been conducted where the base fluids were suspended with quasi-spherical shaped CuO particles. Comparing results under similar room temperature conditions, nanofluids with shuttle-like shaped particles have higher thermal conductivity enhancement. This is attributed to the good dispersion nature of the shuttle-like particle via the method of preparation and of the particle shape itself.

A study on thermal conductivity enhancement using graphene nanofluid was conducted using the transient hot wire method [28]. Flat sheet shaped graphene particles ranging from 5nm to 1500nm were suspended in water without any surfactant as additives. Comparing thermal conductivity for graphene nanofluids with other nanofluids at same temperature (30°C) showed that increase in thermal conductivity of graphene nanofluids was very much similar to carbon nanotubes (CNT) nanofluids. When compared to metallic and non-metallic nanofluids containing spherical shaped particles, thermal conductivity enhancement in much superior for the latter. The high enhancement was explained by a study conducted by Venkata Sastry et al. [29] with respect to the percolation model.

The effect on thermal conductivity enhancement and mechanical properties of silicon carbide (SiC) nanoparticle shaped like a disk or platelet dispersed uniformly in water was studied in 2008 [30]. The volume fraction of nanoparticle was between 1 to 7%, and maximum enhancement was 28% higher compared to thermal conductivity of conventional base fluid. Using the Hamilton and Crosser model, the experimental result was then compared with cylinder and spherical shaped particles. Although thermal conductivity enhancement using disk/platelet shaped particles were lower than cylinder shaped particles, the results were higher compared to spherical shaped particles which were normally used during nanofluid preparation.

Besides experimental investigations on effect of particle shape on thermal conductivity enhancement of nanofluids, studies based on theoretical or numerical studies have also been used. Using a differential effective medium theory, a theoretical study was conducted by X. Feng Zhou and L. Gao [31] to estimate the thermal conductivity for non-spherical particles in nanofluids. Based on the theory, the results showed that higher thermal conductivity can be achieved by using non-spherical shaped particles and that the results obtained were in good agreement with data collected from recent experimental studies on nanofluids.

Using numerical analysis, the heat transfer performance and pressure drop of nanofluids flowing through a pipe were investigated for carbon and titanate nanotubes dispersed in both water and ethylene glycol/water mixture as base fluid. The investigation was carried out to determine the effect of particle parameters i.e. particle concentration, size, particle material, etc. Results obtained based on the effect of particle shape showed that, heat transfer coefficient for carbon nanotubes (CNT) dispersed in water were higher than other nanofluids. Larger aspect ratio and higher thermal conductivity of CNTs were attributed as the factors of the significant improvement.

While for titanate nanotubes (TNT), even though the heat transfer coefficient were lower compared to other nanofluids, heat transfer coefficient of TNT/water nanofluid were approximately the same at lower concentration (0.6%) with Al_2O_3/water (2%) nanofluid. This shows the significant impact of particle shape on the heat transfer characteristics of nanofluids [32].

2.3 Summary of literature review

The use of nanofluids as a cooling medium to further improve performance of devices which involves cooling of liquid has been widely studied and published as literatures in recent years. However, most of these studies and literatures only cover performance enhancement for nanofluids containing spherical shaped nanoparticles. The study of nanofluids containing non-spherical nanoparticles for such devices are still limited for the simple reason that non-spherical nanoparticles are more difficult to produce compared to spherical shape nanoparticles. Therefore, studies on the effect of different nanoparticle shapes on heat transfer characteristics and thermodynamic performances of cooling devices (i.e. heat exchangers) should be pursued further as recent studies had shown that thermal conductivity enhancement of nanofluids containing non-spherical shaped nanoparticles are higher compared to conventional shaped nanoparticles. These studies involving different nanoparticle shapes can be done theoretically using mathematical formulations obtained from literatures and books or by numerical analysis using computational fluid dynamics (CFD) software as it might be costly to conduct these studies experimentally.

CHAPTER 3

METHODOLOGY

3.0 Methodology

To achieve the objectives of this study, the thermodynamic performance for a shell and tube heat exchanger will be evaluated. The application of this type of heat exchanger is for waste heat recovery in biomass power plants. The heat transfer process that takes place in this shell and tube heat exchanger is between the flue gas and nanofluids. The calculation aspect of this study is divided into three sections. The sections involved are the calculation for flue gas (shell side), nanofluids (tube side), and the thermodynamic performance for the shell and tube heat exchanger (STHX). The mathematical formulations used for this study was obtained from various references [33-37].

The effect of different particle shape on nanofluids heat transfer characteristics will also be correlated with the increase in percentage volume fraction from 0% to 1%. For this study, the mass flow rate of the flue gas flowing through the shell side of the heat exchanger was kept a constant value of 26.3 kg/s as mentioned in Table 3.3.

Mass flow rate of nanofluid flowing through the tube side of the heat exchanger was kept at a constant value of 35 kg/s. This is to ensure that nanofluid flow inside the tube was always laminar as a recent theoretical study by K.Y. Leong [38] using similar shell and tube heat exchanger design and operating conditions found that under turbulent conditions, as a result of nanofluid flowing too fast, it was unable to absorb enough heat from the flue gas to produce heat transfer improvement. The nanofluid mass flow rate value of 35kg/s was the maximum possible value ensuring that flow was always laminar for this theoretical study.

Based on the flue gas composition obtained from Chen et al. [39] the thermal properties for the flue gas composition were obtained using an online flue gas properties calculator [40]. The flue gas composition and thermal properties are shown in Table 3.1 and Table 3.2.

Table 3.1

Composition of flue gas from biomass heating plant [39]

Types of gases	Percentage
CO_2	12.1
H_2O	24.4
O_2	3.2
N_2	60.3
Flue gas dew point	64.3 °C

Table 3.2

Thermal properties of flue gas [40]

Specific heat (kJ/kg K)	Thermal conductivity (W/m K)	Dynamic viscosity (Ns/m^2)
1.170	3.29 x 10^{-2}	1.9 x 10^{-5}

3.1 Flue gas side calculation (shell side)

The design specifications and operating parameters for shell and tube heat exchanger that was analysed for this study was obtained from Chen et al. [39]. These parameters are shown in Table 3.3. Using these parameters, the cross flow area (A_{cf}) and equivalent diameter (D_e) for the heat exchanger were obtained using Eqns (3.1)-(3.2). Subsequently, the Reynolds number, Prandtl number, and convective heat transfer coefficient for flue gas were obtained using Eqns (3.3)-(3.5).

Table 3.3

Shell and tube heat exchanger design and operating parameters for flue gas and nanofluids [39]

Parameter	Type/dimension/rate
Type of heat exchanger	Single tube pass, type E shell and tube heat exchanger
Tube outside diameter, d_o (mm)	25.4
Tube inner diameter, d_i (mm)	22.9
Pitch, p_t/d_o	1.75
Total tube number, N	1024
Tube layout	Rotated square
Shell inner diameter, D_s (mm)	2090
Shell thickness, δ_s (mm)	14
Baffle type	Single-segmental
Baffle spacing, B (mm)	1776
Baffle cut	25%
Nanofluids mass flow rate (kg/s)	35
Flue gas mass flow rate (kg/s)	26.3
Nanofluids inlet temperature, (°C)	30
Flue gas temperature, (°C)	150

(a) Eq. (3.1) is used to determine the cross flow area, A_{cf}:

$$A_{cf} = (D_s - N_{TC} d_o)B \tag{3.1}$$

Where,

$$N_{TC} = \frac{D_s}{P_t}$$

(b) Eq. (3.2) is used to determine the equivalent diameter, D_e:

$$D_e = \frac{4\left(P_t^2 - \frac{\pi d_o{}^2}{4}\right)}{\pi d_o} \tag{3.2}$$

(c) Eq. (3.3) is used to determine the flue gas Reynolds number, Re_{fg}:

$$Re_{fg} = \left(\frac{\dot{m}_{fg}}{A_{cf}}\right)\left(\frac{D_e}{\mu_{fg}}\right) \tag{3.3}$$

(d) Eq. (3.4) is used to determine the flue gas Prandtl number, Pr_{fg}:

$$Pr_{fg} = \frac{c_{p,fg}\mu_{fg}}{k_{fg}} \tag{3.4}$$

(e) Eq. (3.5) is used to determine the flue gas convective heat transfer coefficient, h_{fg}:

$$h_{fg} = \frac{0.36k}{D_e} Re_{fg}^{0.55} Pr_{fg}^{\frac{1}{3}} \tag{3.5}$$

3.2 Nanofluids side calculation (tube side)

To determine the effect of different particle shapes of heat transfer characteristics of nanofluids, the thermophysical properties of the nanofluids used for this study must be determined and this is shown is the following sections.

3.2.1 Thermal conductivity of nanofluid

The nanoparticle material that is considered for this study was boehmite alumina (γ-AlOOH). The properties for the nanoparticle material were taken from references [26, 41] and are shown in Table 3.4. The conventional basefluid that is used for this type of shell and tube heat exchanger is a 50/50 mixture of ethylene glycol/water (EG/H_2O). The thermal properties for this basefluid are shown in Table 3.5.

Table 3.4

Properties of alumina boehmite (γ-AlOOH)

Properties	Value
Density, kg/m^3 [26]	3.05
Molar mass, g/mol	60
Molar heat capacity, J/mol K [41]	37.19
Specific heat, C_p (kJ/kg K)	0.6183

Table 3.5

Thermal properties of ethylene glycol and water 50/50 mixture [42]

Ethylene glycol-H_2O (50/50)				
Temperature	Thermal conductivity (W/m K)	Density (kg/m^3)	Dynamic viscosity (Ns/m^2)	Specific heat (kJ/kg K)
365	466.7×10^{-3}	1022.0	8.284×10^{-4}	3.428

The nanoparticle shapes that are considered for this study are platelets, blades, cylinders, and bricks. The shape effect and surface resistance to thermal conductivity of EG/H_2O-AlOOH nanofluid for the nanoparticles are shown Table 3.6. These properties are used to evaluate the thermal conductivity increase of EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes.

Table 3.6

Alumina boehmite particle shape effect and surface resistance thermal conductivity ratio of nanofluids [26]

	Aspect ratio	Sphericity, ψ	Shape factor, $n = \frac{3}{\psi}$	C_k	C_k^{shape}	$C_k^{surface} = C_k - C_k^{shape}$
Platelets	1:1/8	0.52	5.7	2.61	5.72	-3.11
Blades	1:6:1/12	0.36	8.6	2.74	8.26	-5.52
Cylinders	1:8	0.62	4.9	3.95	4.82	-0.87
Bricks	1:1:1	0.81	3.7	3.37	3.72	-0.35

The thermal conductivity of different nanoparticle shapes was determined using the mathematical formulation from Eq. (3.6). The thermal conductivity of EG/H_2O-AlOOH nanofluids was calculated for percentage nanoparticle volume fraction ranging from 0 to 1%.

(a) Eq. (3.6) is used to determine the thermal conductivity of nanofluids, k_{eff}:

$$\frac{k_{eff}}{k_0} = 1 + \left(C_k^{shape} + C_k^{surface}\right)\emptyset = 1 + C_k\emptyset \tag{3.6}$$

From Eqn 3.6, C_k is the thermal conductivity enhancement coefficient ratio for the nanofluid. The values of C_k varies for different shapes and were obtained from the experimental thermal conductivity ratios obtained from the reference [26].

3.2.2 Heat transfer characteristics of nanofluids

Using the available data that were provided from tables [3.4-3.6], the thermophysical properties of EG/H_2O-AlOOH nanofluids (i.e. density, specific heat, viscosity, and Prandtl number) were determined using the mathematical formulations from Eqs (3.7)-(3.10). The thermophysical properties of nanofluids were calculated for percentage volume fraction ranging from 0 to 1%.

(a) Eq. (3.7) is used to determine the nanofluids density, ρ_{nf}:

$$\rho_{nf} = (1-\emptyset)\rho_f + \emptyset\rho_p \tag{3.7}$$

(b) Eq. (3.8) is used to determine the nanofluids specific heat, $C_{p,nf}$:

$$C_{p,nf} = \frac{(1-\emptyset)\rho_f C_{p,f} + \emptyset\rho_p C_{p,p}}{\rho_{nf}} \tag{3.8}$$

(c) Eq. (3.9) is used to determine the nanofluids viscosity, μ_{nf}:

$$\mu_{nf} = \frac{1}{(1-\emptyset)^{2.5}}\mu_f \tag{3.9}$$

(d) Eq. (3.10) is used to determine the nanofluids Prandtl number, Pr_{nf}:

$$Pr_{nf} = \frac{C_{p,nf}\mu_{nf}}{k_{nf}} \tag{3.10}$$

Using the thermophysical properties of nanofluids obtained for percentage volume fraction 0 to 1% above, the heat transfer and overall heat transfer coefficients can be determined using Eqs (3.11)-(3.17).

(e) Eq. (3.11) is used to determine the number of tube per pass, $N_{t,p}$:

$$N_{t,p} = N_T \tag{3.11}$$

In order to simplify the calculation aspect of this study, only flow in a single tube (one pass per tube) is considered.

(f) Eq. (3.12) is used to determine the tube side flow area per pass, $A_{o,t}$:

$$A_{o,t} = \frac{\pi}{4}d_i^2 N_{t,p} \tag{3.12}$$

(g) Eq. (3.13) is used to determine the nanofluids Reynolds number, Re_{nf}:

$$Re_{nf} = \left(\frac{\dot{m}_{nf}}{A_{o,t}}\right)\left(\frac{d_i}{\mu_{nf}}\right) \tag{3.13}$$

(h) Eq. (3.14) and Eq. (3.15) are used to determine the nanofluids Nusselt number, Nu_{nf}:

$$Nu_{nf} = 3.66 \text{ for laminar flow} \tag{3.14}$$

$$Nu_{nf} = 0.024 Re_{nf}^{0.8} Pr_{nf}^{0.4} \text{ for turbulent flow} \tag{3.15}$$

(i) Eq. (3.16) is used to determine the nanofluids heat transfer coefficient, h_{nf} :

$$h_{nf} = \frac{Nu_{nf} k_{nf}}{d_i} \tag{3.16}$$

(j) Eq. (3.17) is used to determine the overall heat transfer coefficient, U_o:

$$\frac{1}{U_o} = \frac{1}{h_{fg}} + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2k_w} + \frac{1}{h_{nf}} \frac{d_o}{d_i} \tag{3.17}$$

The tube material for the heat exchanger is made from copper. The value for thermal conductivity of copper wall of the tube, k_w required to solve Eq. 3.17 was obtained from a heat transfer book [43]. From the book, it was determine that thermal conductivity for copper material, k_w is $401\, W/m\, K$.

3.2.3 Thermodynamic performance of STHX

The thermodynamic performance of EG/H_2O-AlOOH nanofluid containing different nanoparticle shapes for the studied application can determined using Eqs (3.18)-(3.27). The thermodynamic performances studied were the convective heat transfer rate and entropy generation for the shell and tube heat exchanger (STHX).

(a) Eqn. (3.18) is used to determine the total tube outside heat transfer area, A_s:

$$A_s = \pi L d_o N_t \tag{3.18}$$

(b) Eqn (3.19) is used to determine the number of heat transfer units, NTU:

$$NTU = \frac{U_o A_s}{C_{min}} \tag{3.19}$$

(c) Eqns (3.20) and (3.21) are used to determine the minimum ($C_{\min}$) and maximum (C_{max}) capacity rate:

$$C_{min} = \left(\dot{m}C_p\right)_{fg} \tag{3.20}$$

$$C_{max} = \left(\dot{m}C_p\right)_{nf} \tag{3.21}$$

(d) Eq. (3.22) is used to determine the heat exchanger effectiveness, ε (assuming single pass, both fluids unmixed):

$$\varepsilon = 1 - exp\left[\left(\frac{1}{C^*}\right)(NTU)^{0.22}\{exp[-C^*(NTU)^{0.78}] - 1\}\right] \tag{3.22}$$

(e) Eq. (3.23) is used to determine the capacity heat ratio, C^*:

$$C^* = \frac{C_{min}}{C_{max}} \tag{3.23}$$

(f) Eq. (3.24) is used to determine the heat transfer rate, q:

$$q = \varepsilon C_{min}\left(T_{fg,i} - T_{nf,i}\right) \tag{3.24}$$

(g) Eq. (3.25) is used to determine the rate of entropy generation, $\dot{S}_{gen}$:

$$\dot{S}_{gen,\Delta T} = \left(\dot{m}_{fg}C_{p,fg}\right)ln\frac{T_{h,o,fg}}{T_{h,i,fg}} + \left(\dot{m}_{nf}C_{p,nf}\right)ln\frac{T_{c,o,nf}}{T_{c,i,nf}} \tag{3.25}$$

(h) Eq. (3.26) and Eq. (3.27) are used to determine the hot and cold outlet temperatures for flue gas ($T_{h,o,fg}$) and nanofluid ($T_{c,o,nf}$) respectively:

$$T_{h,o,fg} = T_{h,i,fg} - \varepsilon\left(T_{h,i,fg} - T_{c,i,nf}\right)C^* \tag{3.26}$$

$$T_{c,o,nf} = T_{c,i,nf} + \varepsilon\left(T_{h,i,fg} - T_{c,i,nf}\right) \tag{3.27}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Results and Discussion

In this section, results obtained using the mathematical formulations discussed from the previous chapter will be analysed. The effect of Ethylene glycol/water-alumina boehmite (EG/H_2O-AlOOH) nanofluids containing different nanoparticle shapes on heat transfer characteristics and thermodynamic performance will be discussed. A comparison study between spherical shaped nanoparticles commonly used in conventional nanofluids and effect of nanoparticle size factor will be discussed at the end of the chapter.

4.1 Effect of different particle shapes on thermal conductivity of nanofluid

Using the mathematical formulation obtained from the literature mentioned before, the thermal conductivity enhancement of EG/H_2O-AlOOH nanofluids containing different particle shapes were obtained. The nanoparticle shapes being studied were platelets, blades, cylinders, and bricks. The thermal conductivity enhancement was for nanofluids containing nanoparticle volume fraction ranging from 0 to 1%. The results are shown in Figure 4.1.

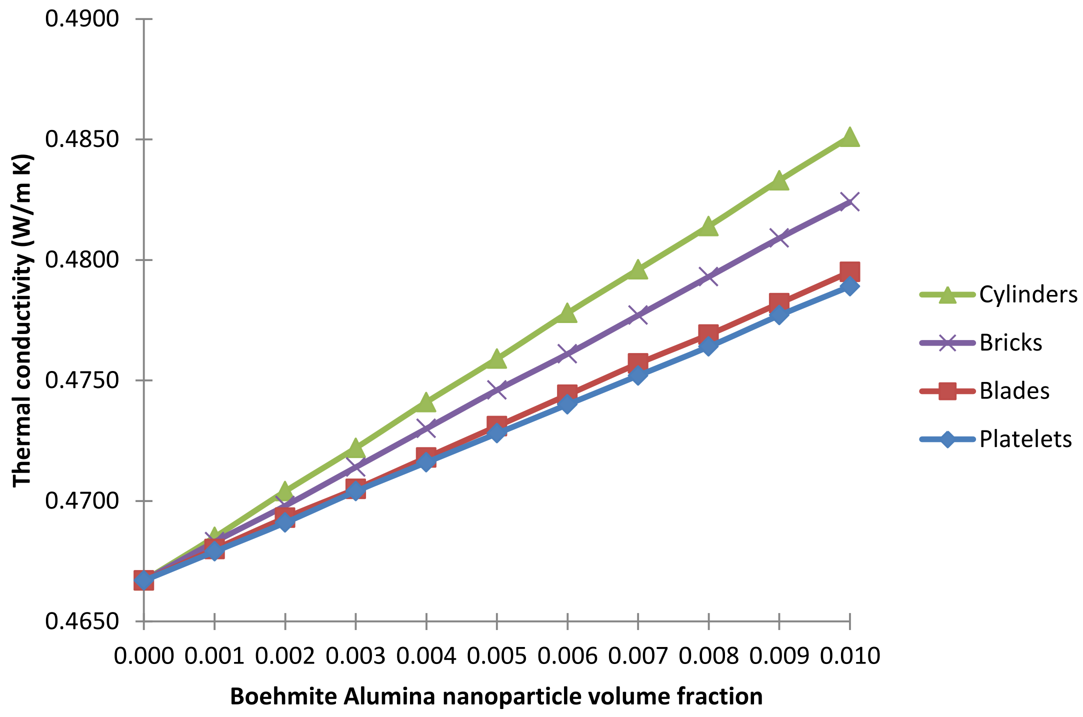

Figure 4.1 Effect of different particle shapes on thermal conductivity of nanofluids

Figure 4.1 shows the thermal conductivity enhancement of EG/H_2O-AlOOH nanofluids containing cylinders, bricks, blades, and platelets nanoparticle shapes. The thermal conductivity enhancement of these EG/H_2O-AlOOH nanofluids increased with the increase in nanoparticle volume fraction. The improvement for EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes were linear with the increase in nanoparticle volume fraction because the range for nanoparticle volume fraction involved in this study is relatively small (between 0 to 1%). Percentage increase of thermal conductivity enhancement for EG/H_2O-AlOOH nanofluids containing different shape nanoparticles at 1% nanoparticle volume fraction compared to conventional EG/H_2O basefluid is shown in Table 4.1.

Table 4.1

Effect of different particle shapes on thermal conductivity of nanofluids containing 1% of boehmite nanoparticle compared to EG/H_2O basefluid.

Parameter	Basefluid	Shape			
		Platelets	Blades	Cylinders	Bricks
$k, W/m\ K$	0.4667	0.4789	0.4795	0.4851	0.4824
$\%_{increase}$	-	2.6	2.7	3.9	3.4

The results showed that for EG/H_2O-AlOOH nanofluids containing 1% boehmite alumina nanoparticle volume fraction, EG/H_2O-AlOOH nanofluids containing cylinder shaped nanoparticles produced the highest increase in nanofluid thermal conductivity enhancement (3.9%) when compared to EG/H_2O basefluid. The lowest thermal conductivity enhancement obtained was for nanofluid containing platelet shaped nanoparticles (2.6%).

EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles produces the highest thermal conductivity enhancement because from the particle shape effect and surface resistance parameter table (Table 3.6), cylinder shaped nanoparticle had the highest thermal conductivity enhancement coefficient (C_k) compared to the other nanoparticle shapes. The value for thermal conductivity enhancement coefficient (C_k) plays an important factor because as it increases with the increased in volume fraction so does the thermal conductivity enhancement for EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes.

4.2 Effect of different particle shapes on heat transfer characteristics of nanofluid

4.2.1 Heat transfer coefficient of nanofluid

The effect of different nanoparticle shapes on heat transfer coefficient of EG/H_2O-AlOOH nanofluids were obtained using the mathematical formulation stated in the previous chapter (Chapter 3). The results obtained for nanoparticle volume fraction ranging from 0 to 1% are shown in Figure 4.2.

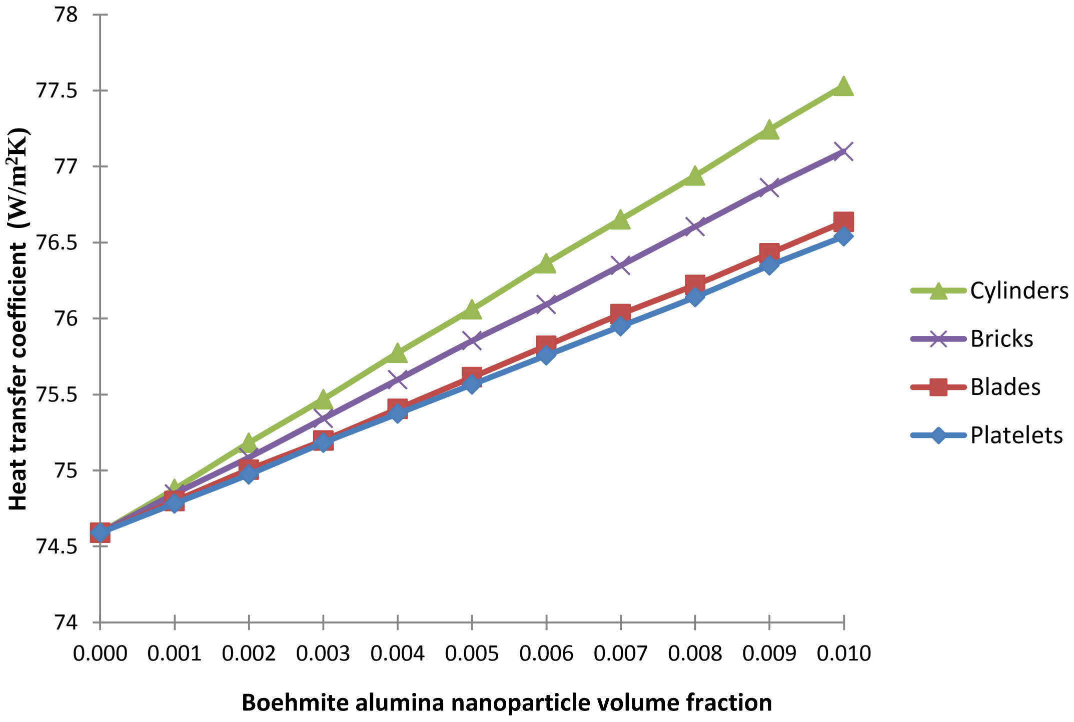

Figure 4.2 Effect of different particle shapes on heat transfer coefficient of nanofluids

Figure 4.2 shows the heat transfer coefficient improvement of EG/H_2O-AlOOH nanofluids containing cylinders, bricks, blades, and platelets nanoparticle shapes. The heat transfer coefficient improvement of these EG/H_2O-AlOOH nanofluids increased as nanoparticle volume fraction increases. Since the range for nanoparticle volume fraction involved in this study was relatively small (between 0 to 1%), the improvement for EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes were linear with the increase in nanoparticle volume fraction. Percentage increase of heat transfer coefficient for EG/H_2O-AlOOH nanofluids containing different shape nanoparticles at 1% nanoparticle volume fraction compared to conventional basefluid is shown in Table 4.2.

Table 4.2

Effect of different particle shapes on heat transfer coefficient of nanofluids containing 1% of boehmite nanoparticle compared to EG/H_2O basefluid.

Parameter	Basefluid	Shape			
		Platelets	Blades	Cylinders	Bricks
$h, W/m^2\ K$	74.59	76.54	76.64	77.53	77.10
$\%_{increase}$	-	2.6	2.7	3.9	3.4

The increase in heat transfer coefficent is directly related to the increase in thermal conductivity as it is one of the main parameters that is required in the calculation of heat transfer coefficient as in Eq (3.16). The results obtained showed that EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles produced the highest increase in heat transfer coefficient with an increase of 3.9%. While EG/H_2O-AlOOH nanofluid containing platelet shaped nanoparticles was the least performing nanofluid with an increase of only 2.6%.

4.2.2 Overall heat transfer coefficient of nanofluid

The effect of different nanoparticle shapes for EG/H_2O-AlOOH nanofluids on the overall heat transfer coefficient is shown in Figure 4.3. The result obtained was for EG/H_2O-AlOOH nanofluids containing different boehmite alumina nanoparticles shapes with nanoparticle volume fraction ranging from 0 to 1%.

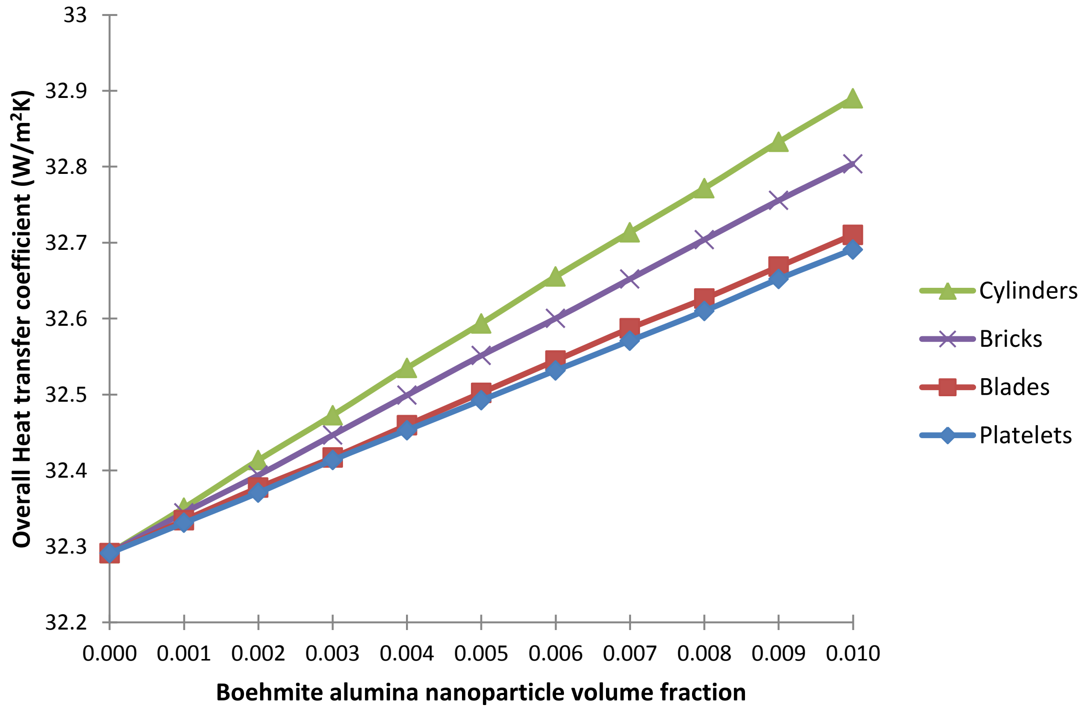

Figure 4.3 Effect of different particle shapes on overall heat transfer coefficient of nanofluids

Figure 4.3 shows overall heat transfer coefficient improvement of EG/H_2O-AlOOH nanofluids containing cylinders, bricks, blades, and platelets nanoparticle shapes. The overall heat transfer coefficient improvement of these EG/H_2O-AlOOH nanofluids increased with the increase in nanoparticle volume fraction. The improvement for EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes were linear with the increase in nanoparticle volume fraction because the range for nanoparticle volume fraction was relatively small (between 0 to 1%). Percentage increase of overall heat transfer coefficient for EG/H_2O-AlOOH nanofluids containing different shape nanoparticles at 1% nanoparticle volume fraction compared to conventional EG/H_2O basefluid is shown in Table 4.3.

Table 4.3

Effect of different particle shapes on overall heat transfer coefficient of nanofluids containing 1% of boehmite nanoparticle compared to EG/H_2O basefluid.

Parameter	Basefluid	Shape			
		Platelets	Blades	Cylinders	Bricks
$U_o, W/m^2\,K$	32.29	32.69	32.71	32.89	32.80
$\%_{increase}$	-	1.2	1.3	1.9	1.6

The results obtained for overall heat transfer coefficient improvement showed that EG/H_2O-AlOOH nanofluid containing cylinder shape nanoparticles produced the highest increase in overall heat transfer coefficient with an increase of 1.9% compared to the remaining nanoparticle shapes. EG/H_2O-AlOOH nanofluid containing platelet shaped nanoparticle was the least improved nanofluid with only an improvement of 1.2%. The result for heat transfer coeffient improvement obtained previously played an important role when evaluating the overall heat transfer coefficient for EG/H_2O-AlOOH nanofluids. Since EG/H_2O-AlOOH nanofluid containing cylinder shape nanoparticles showed the highest improvement in heat transfer coefficient, the overall heat transfer coefficient obtained also show similar superiority.

From the theoretical study, it can be seen that different nanoparticle shapes result in different heat transfer characteristics. Improvements in heat transfer coefficient and overall heat transfer coefficient can be achieved with the use of nanofluids containing different nanoparticle shapes.

Based on literatures, nanoparticles aspect ratio plays an important role in the enhancement of heat transfer characteristics. From the particle shape effect and surface resistance parameter table (Table 3.6) obtained from the literature [26] used in this study showed that the cylinder shaped nanoparticles has the highest aspect ratio compared to the other nanoparticle shapes.

Hence, the increase in heat transfer characteristic for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles was higher compared to other nanoparticle shapes. The results obtained from this study is supported by a study by A.S. Cherkasova and J.W. Shan [44] which deals with effect of different silicon carbide (SiC) nanoparticle aspect ratio and the results from the study showed that as the aspect ratio increases, from 4.8 to 9.6, thermal conductivity of the suspension increased from 16.5% up to 39.5 %.

4.3 Effect of nanofluids with different particle shapes on thermodynamic performance of shell and tube heat exchanger

4.3.1 Convective heat transfer rate

The first thermodynamic performance for the shell and tube heat exchanger application evaluated for this study was the convective heat transfer rate. This was done by applying the previously mentioned mathematical formulations in Chapter 3. Figure 4.4 shows the effect of EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes on the convective heat transfer rate of a shell and tube heat exchanger application for nanoparticle volume fraction ranging from 0 to 1%.

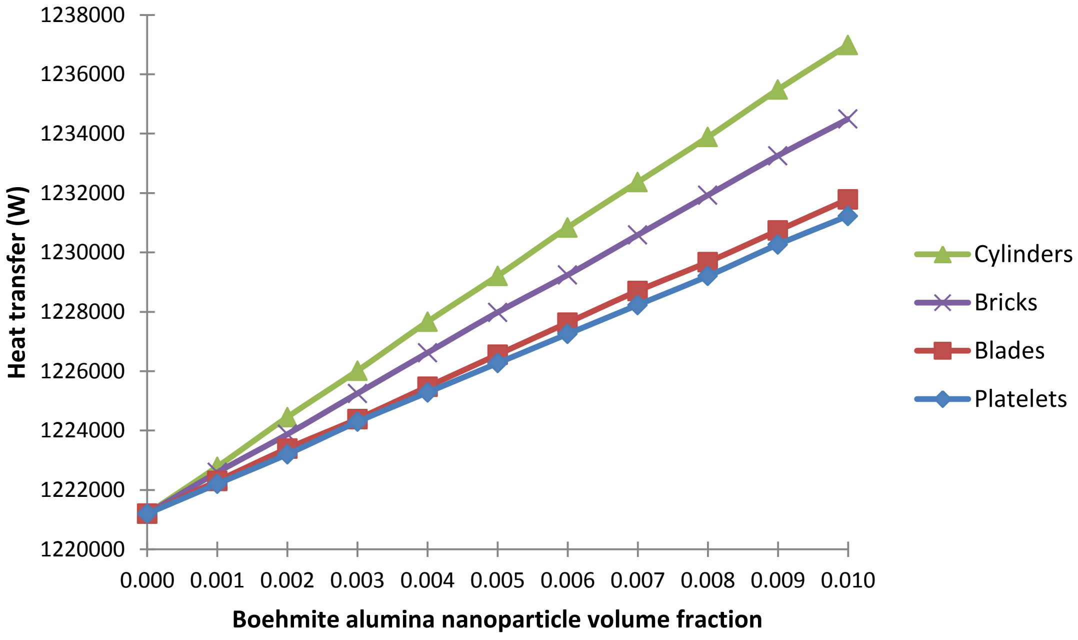

Figure 4.4 Effect of different particle shapes on heat transfer rate of nanofluids

Figure 4.4 shows the convective heat transfer rate improvement of EG/H_2O-AlOOH nanofluids containing cylinders, bricks, blades, and platelets nanoparticle shapes. The convective heat transfer rate improvement of these EG/H_2O-AlOOH nanofluids increased with the increase in nanoparticle volume fraction. The improvement for EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes weree linear with the increase in nanoparticle volume fraction because the range for nanoparticle volume fraction was relatively small (between 0 to 1%). Percentage increase of convective heat transfer rate for EG/H_2O-AlOOH nanofluids containing different shape nanoparticles at 1% nanoparticle volume fraction compared to conventional basefluid is shown in Table 4.4.

Table 4.4

Effect of different particle shapes on heat transfer rate of nanofluids containing 1% of boehmite nanoparticle compared to EG/H_2O basefluid.

Parameter	Basefluid	Shape			
		Platelets	Blades	Cylinders	Bricks
q, kW	1221.200	1231.231	1231.792	1236.987	1234.492
$\%_{increase}$	-	0.82	0.88	1.3	1.1

Results obtained in Figure 4.4 shows that convective heat transfer can be enhanced by adding different nanoparticles shapes with the conventional EG/H_2O basefluid. At 1% nanoparticle volume fraction, the increase in convective heat transfer rate was highest for EG/H_2O-AlOOH nanofluid containing cylinder shape nanoparticles with a percentage increase of 1.3% when compared to conventional EG/H_2O basefluid. This was followed by EG/H_2O-AlOOH nanofluids containing bricks (1.1%), blades (0.88%) , and platelets (0.82%) nanoparticle shapes respectively.

4.3.2 Entropy generation

The second thermodynamic performance that was analysed was the entropy generation as a result of using nanofluids containing different nanoparticle. The results were obtained using the mathematical formulation for entropy generation mentioned in the previous chapter (Chapter 3). The result obtained was for EG/H_2O-AlOOH nanofluids containing different boehmite alumina nanoparticles shapes with nanoparticle volume fraction ranging from 0 to 1%.

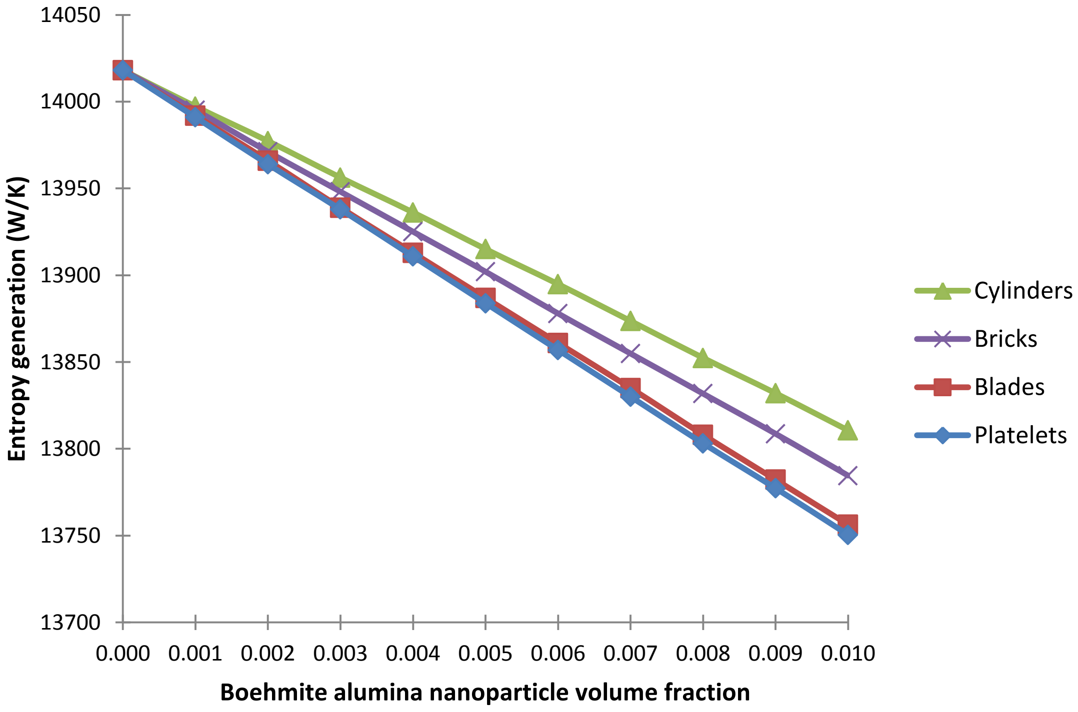

Figure 4.5 Effect of different particle shapes on entropy generation of nanofluids

Figure 4.5 shows the results for entropy generation of EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes. From the results obtained, it can be seen that entropy generation can be reduced by adding different nanoparticles shapes to the conventional EG/H_2O basefluid. Entropy generation minimization was achieved for all EG/H_2O-AlOOH nanofluids as volume fraction increase. Although entropy generation minimization occurs for all nanoparticle shapes, different nanoparticle shapes results in different entropy generation reduction. For EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes at 1% nanoparticle volume fraction, the percentage reduction in entropy generation for different nanoparticle shapes compared to conventional EG/H_2O basefluid is shown in Table 4.5.

Table 4.5

Effect of different particle shapes on entropy generation of nanofluids containing 1% of boehmite nanoparticle compared to EG/H_2O basefluid.

Parameter	Basefluid	Shape			
		Platelets	Blades	Cylinders	Bricks
$\dot{S}_{gen}, W/K$	14018.13	13750.44	13756.31	13810.61	13784.53
$\%_{reduction}$	-	1.91	1.88	1.48	1.67

From Table 4.5, the results obtained show that at 1% nanoparticle volume fraction EG/H_2O-AlOOH nanofluid containing platelet nanoparticle shape achieved the highest reduction in entropy generation compared to the remaining nanoparticle shapes with a reduction of 1.91%. This is followed by EG/H_2O-AlOOH nanofluids containing blades (1.88%), bricks (1.67%), and cylinder (1.48%) nanoparticle shapes respectively. This result was different from the results obtained for heat transfer characteristics and convective heat transfer rate which showed that EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles. Eventhough, EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles produces the least reduction in entropy generation, percentage difference between the remaining nanoparticles were relatively small (less than 0.5%).

The increase in heat transfer performance as a result of using nanofluid containing different nanoparticle shapes was also confirmed in a study conducted by Yulong Li et al. [45] using similar nanoparticle shapes where the effects of nanoparticle shapes on heat transfer performance for a six-turn oscillating heat pipe were determined. The study showed that under laminar conditions, heat transfer performance for the oscillating heat pipe was enhanced for all the studied nanoparticle shapes. The study also showed that nanofluid containing cylinder-like shaped nanoparticles achieved the best heat transfer performance with an increase in performance efficiency of 75.8% at nanoparticle volume fraction of 0.3% when compared to the other nanoparticle shapes.

Minimization of entropy generation from the use of nanofluids is fore mostly because of its superior thermal properties compared to conventional basefluid. Using the required mathematical formulation, it is observed that as boehmite alumina nanoparticle volume fraction increases, entropy generation, $\dot{S}_{gen}$ for EG/H_2O-AlOOH nanofluids containing different nanoparticle shapes were reduced. This is because, according to a study V. Bianco et al. [46] at higher nanoparticle volume concentration, the improvement of heat transfer rate between wall and fluid contributes to the reduction in difference between wall and bulk temperatures. Nevertheless, this also resulted in the increase in dynamic viscosity of the nanofluid which in subsequently leads to the increase in shear stress. The increased in dynamic viscosity and shear stress will result in higher pumping power required to pump the nanofluid through the heat exchanger.

The theoretical results show that, EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles produces the highest increase for both heat transfer characteristics and for thermodynamic performance for the selected shell and tube heat exchanger application, EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticle produced the highest convective heat transfer rate. This is followed by EG/H_2O-AlOOH nanofluids containing bricks, blades and platelets shaped nanoparticles respectively.

However, in terms of entropy generation minimization, EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticle was the least performing nanofluid when compared to the remaining EG/H_2O-AlOOH nanofluids containing different shaped nanoparticles. EG/H_2O-AlOOH nanofluid containing platelet shaped nanoparticles produced the highest reduction in entropy generation, followed by EG/H_2O-AlOOH nanofluids containing blades, and bricks shaped nanoparticles respectively. The percentage increase in entropy generation for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticle when compared to EG/H_2O-AlOOH nanofluids containing the other three nanoparticle shapes was relatively low (less than 0.5%).

The improved performance for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles when compared to conventional EG/H_2O basefluid and other EG/H_2O-AlOOH nanofluids containing different nanoparticles is summarized in Table 4.6.

Table 4.6

Summary for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles at 1% volume fraction improvement compared to EG/H_2O basefluid and EG/H_2O-AlOOH nanofluids containing the remaining nanoparticle shapes.

Parameters	Basefluid	Shape		
		Platelets	Blades	Bricks
Thermal conductivity, $k, W/m\ K$	3.9%	1.3%	1.15%	0.55%
Heat transfer coefficient, $h, W/m^2\ K$	3.9%	1.3%	1.1%	0.56%
Overall heat transfer coefficient, $U_o, W/m^2\ K$	1.9%	0.6%	0.55%	0.3%
Heat transfer, q, kW	1.3%	0.47%	0.43%	0.20%
Entropy generation increase, $\dot{S}_{gen}, W/K$	1.48% (reduction)	0.44%	0.39%	0.19%

4.4 Comparison study with conventional nanoparticle shape for nanofluid

In Chapter 2 it was stated that most literatures agree that spherical shape was the most common nanoparticle shape used in nanofluids. For comparison purposes, similar theoretical analysis was conducted for nanofluids with spherical shaped nanoparticles. The parameters used for this analysis were also similar to the previous analysis. Subsequently heat transfer characteristics and heat exchanger performance were obtained.

4.4.1 Thermal conductivity of nanofluids

Using the Maxwell Model or the Hamilton and Crosser Model (*n*=3) thermal conductivity enhancement for EG/H_2O-AlOOH nanofluid containing spherical shaped nanoparticles was obtained for boehmite alumina nanoparticle volume fraction ranging from 0 to 1%. The result for EG/H_2O-AlOOH nanofluid containing spherical shaped nanoparticles is shown in Figure 4.6.

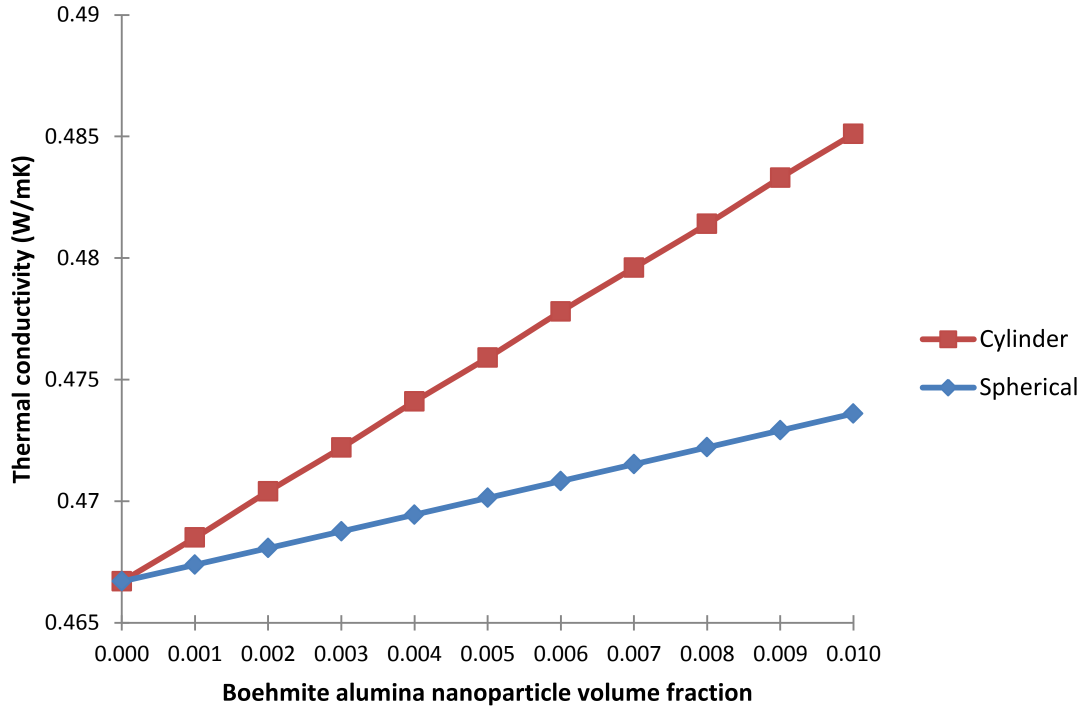

Figure 4.6 Thermal conductivity comparison between nanofluids containing spherical and cylinder shaped nanoparticles

Figure 4.6 shows the result for thermal conductivity enhancement for EG/H_2O-AlOOH nanofluids containing spherical shaped nanoparticles. The result obtained was then compared with thermal conductivity enhancement for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles which is also shown in Figure 4.6. From the comparison, EG/H_2O-AlOOH nanofluid containing cylinder shape nanoparticles showed higher thermal conductivity enhancement. Where at 1% nanoparticle volume fraction, the percentage increased in thermal conductivity enhancement was 2.4%.

4.4.2 Heat transfer characteristics and thermodynamic performances

Using the same mathematical formulation as before, the results for heat transfer coefficient, overall heat transfer coefficient, heat transfer rate, and entropy generation was obtained for EG/H_2O-AlOOH nanofluid containing spherical shaped nanoparticles.

The graph comparison results for EG/H_2O-AlOOH nanofluids containing spherical and cylinder shaped nanoparticles for heat transfer characteristics and heat exchanger thermodynamic performances are shown from Figures 4.7 to 4.10.

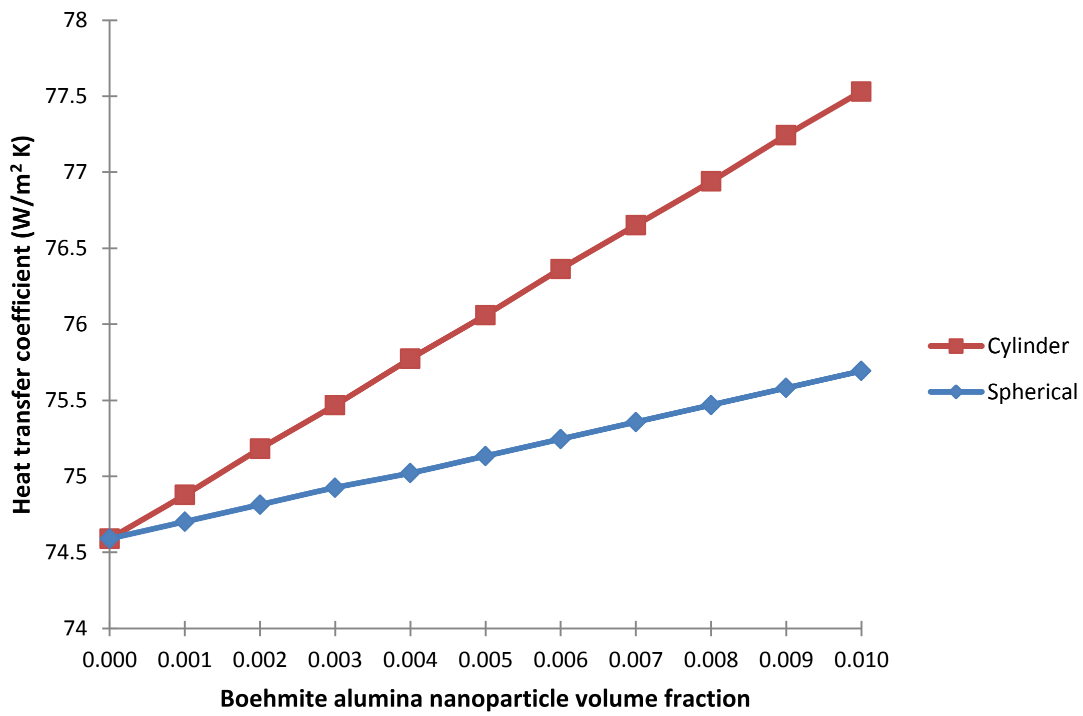

Figure 4.7 Heat transfer coefficient comparison between nanofluids containing spherical and cylinder shaped nanoparticles

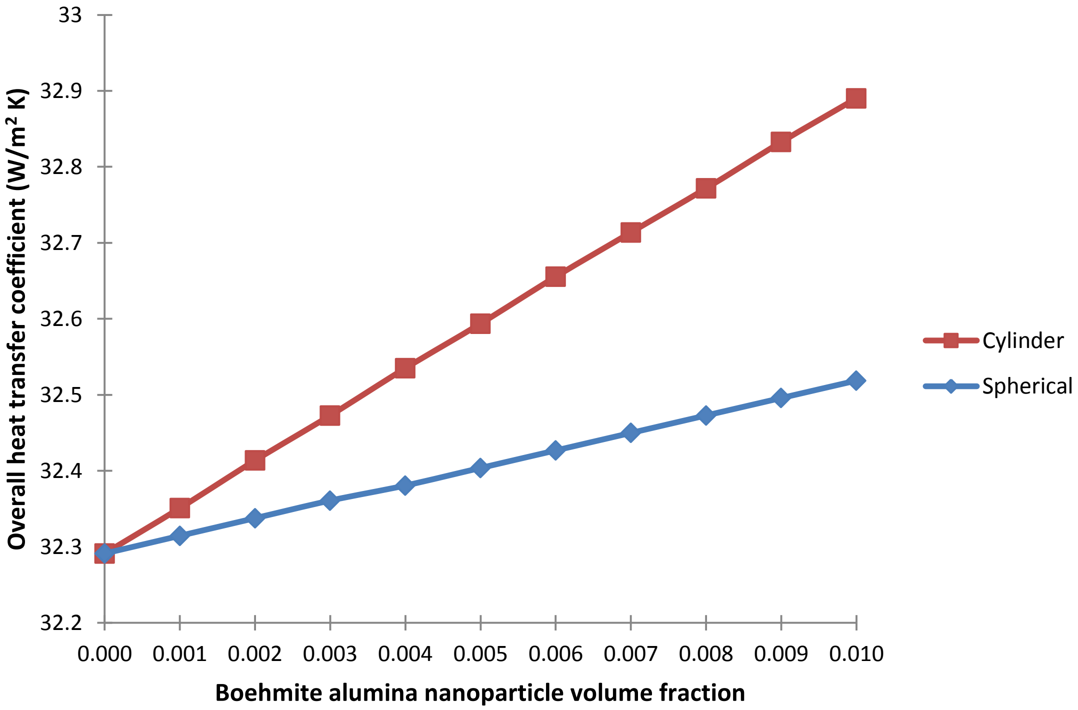

Figure 4.8 Overall heat transfer coefficient comparison between nanofluids containing spherical and cylinder shaped nanoparticles

The figures 4.7 and 4.8 shows the comparison for heat transfer characteristics between EG/H_2O-AlOOH nanofluids containing cylinder and spherical shaped nanoparticles. For heat transfer coefficient (Figure 4.7), result at 1% nanoparticle volume fraction shows an increase of 2.4% for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles when compared to EG/H_2O nanofluid containing spherical shaped nanoparticles.

In terms of overall heat transfer coefficient (Figure 4.8), an increase of approximately 1.14% was obtained for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles when compared to EG/H_2O-AlOOH nanofluid containing spherical shaped nanoparticles corresponding to 1% nanoparticle volume fraction.

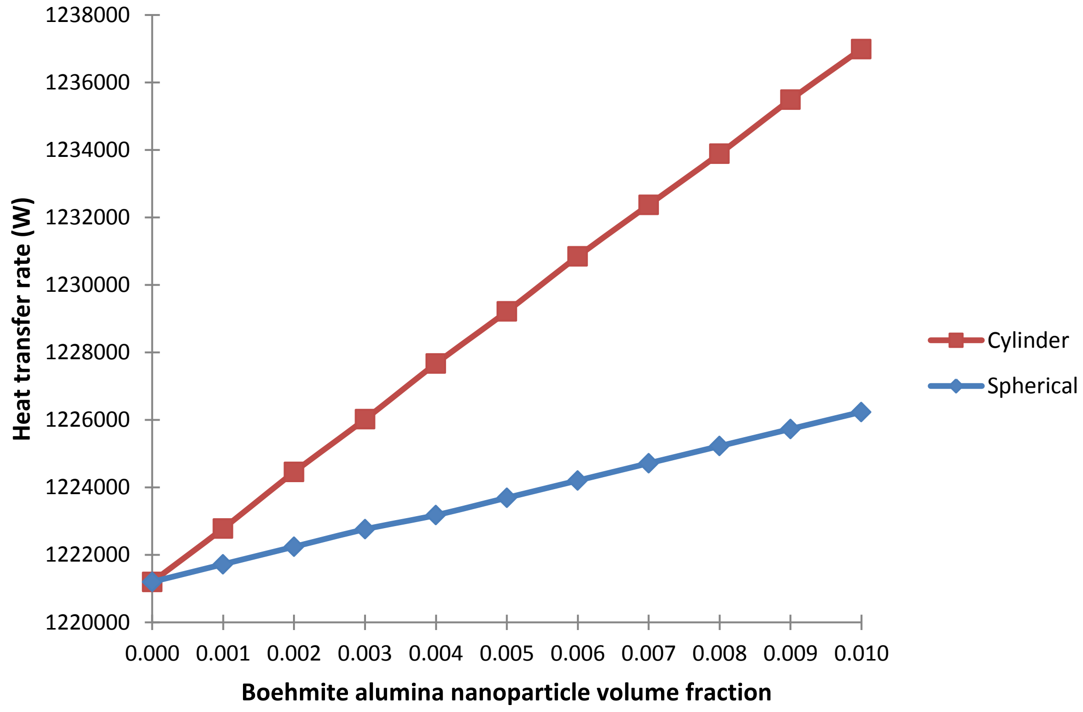

Figure 4.9 Heat transfer rate comparison between nanofluids containing spherical and cylinder shaped nanoparticles

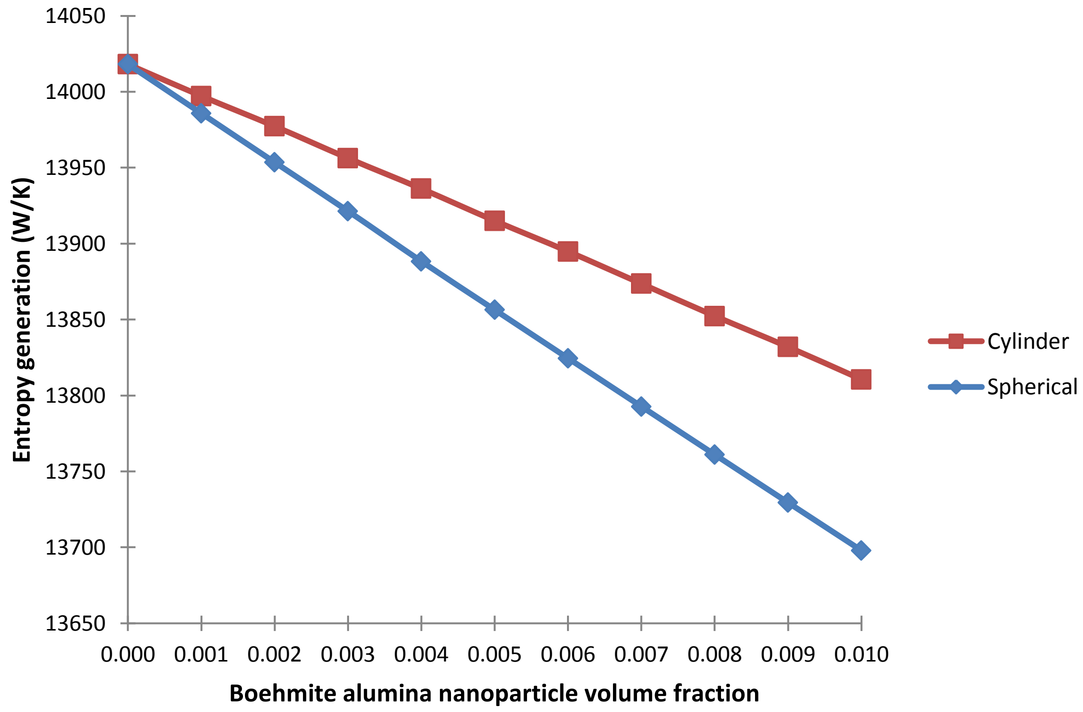

Figure 4.10 Entropy generation comparison between nanofluids containing spherical and cylinder shaped nanoparticles

Figures 4.9 and 4.10 shows the comparison for thermodynamic performances between EG/H_2O-AlOOH nanofluids containing cylinder and spherical shaped nanoparticles. At 1% nanoparticle volume fraction, comparison for the first thermodynamic performance (Figure 4.9), EG/H_2O-AlOOH containing cylinder shaped nanoparticles showed an increase of approximately 0.88% in convective heat transfer rate when compared to EG/H_2O-AlOOH nanofluid containing spherical shaped nanoparticles. Similarly, for the second thermodynamic performance involving entropy generation (Figure 4.10), EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles showed a slight increase of approximately 0.82% when compared to EG/H_2O-AlOOH nanofluid containing spherical shaped nanoparticles.

The overall comparison between results obtained for EG/H_2O-AlOOH nanofluids containing cylinder and spherical nanoparticles at 1% volume fraction is presented in tabulated form in Table 4.7.

Table 4.7

Comparison between heat transfer characteristics and thermodynamic performance for nanofluids containing cylinder and spherical shaped nanoparticles.

Parameters	Spherical shape	Cylinder shape	$\%increase_{cylinder}$
Thermal conductivity, $k, W/m\ K$	0.4736	0.4851	2.4
Heat transfer coefficient, $h, W/m^2\ K$	75.69	77.53	2.4
Overall heat transfer coefficient, $U_o, W/m^2\ K$	32.52	32.89	1.14
Heat transfer, q, kW	1226.234	1236.987	0.88
Entropy generation, $\dot{S}_{gen}, W/K$	13697.96	13810.61	0.82

From the table, the results obtained from this comparison study clearly shows that EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles performed better when compared to EG/H_2O-AlOOH nanofluid containing conventional (spherical) shaped nanoparticles albeit a slight increase in terms of entropy generation for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles.

The increase in thermal conductivity and convective heat transfer for cylinder shaped nanoparticle was also recorded in a study by L. Yu et al. [47] where alumina-polyalphaolefin (PAO) nanofluids were used. In the study, performance of a rod-shaped nanoparticle was compared to a spherical-shaped nanoparticle and similar with the results obtained in this study, cylinder-like shaped nanoparticle produced better heat transfer characteristics especially in terms of heat transfer coefficient compared to spherical shaped nanoparticle. This was because the thermal conductivity ratio $\frac{k_{eff}}{k_f}$ for the cylinder-like nanoparticle was slightly higher than the spherical shaped nanoparticle. The researchers, L. Yu et al., states that besides the normal parameters that effect the enhancement of nanofluids by non-spherical nanoparticles, in order to correctly understand experimental data for nanofluids containing non-spherical nanoparticles consideration for convective flow must also include shear-induced alignment and orientational motion caused by the nanoparticles.

4.5 Effect of nanoparticle size factor for nanofluids containing cylinder shaped nanoparticles

The thermal conductivity enhancement of EG/H_2O-AlOOH nanofluids used for the heat transfer characteristics and thermodynamic performances calculation in Section 4.1 previously involved both the shape and size factor of the nanoparticle. The results obtained as illustrated from Figures 4.2 to 4.4 showed that performance of EG/H_2O-AlOOH containing cylinder shaped nanoparticle was much more superior compared to the other nanoparticle shapes.

In this section, the performance between the results obtained for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticle previously have been compared with EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles but without taking into consideration the size factor of the nanoparticle. Similarly to the results obtained previously, comparison has been made for boehmite alumina nanoparticle volume fraction ranging from 0 to 1%.

Performance comparison between both types of EG/H_2O-AlOOH nanofluids will be represented in graphical form. In the comparison figures from 4.11 to 4.15, results for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles without considering the size factor was represented by the continuous line graphs, while the results for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles when both (shape and size) factor were taken into consideration was represented by the dashed line graphs.

4.5.1 Effect of nanoparticle size factor on thermal conductivity enhancement for nanofluids

The thermal conductivity enhancement for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles without taking the size factor into consideration was obtained using Eqn. (4.1).

$$\frac{k_{eff}}{k_0} = 1 + \left(C_k^{shape}\right)\emptyset \tag{4.1}$$

In equation 4.1, the value for C_k^{shape} was obtained from Table 3.6 in Chapter 3. From this equation, it clearly shows that only the thermal conductivity ratio in terms of shape factor is taken into consideration. The size factor, defined as the surface to volume ratio of a nanoparticle represented by the thermal conductivity ratio, $C_k^{surface}$ was omitted from the equation.

The comparison for thermal conductivity enhancement of EG/H_2O-AlOOH nanofluids containing cylinder shaped nanoparticles with and without considering the size factor of the nanoparticle is shown in Figure 4.11. The results obtained were for nanofluids containing boehmite alumina nanoparticle volume fraction ranging from 0 to 1%.

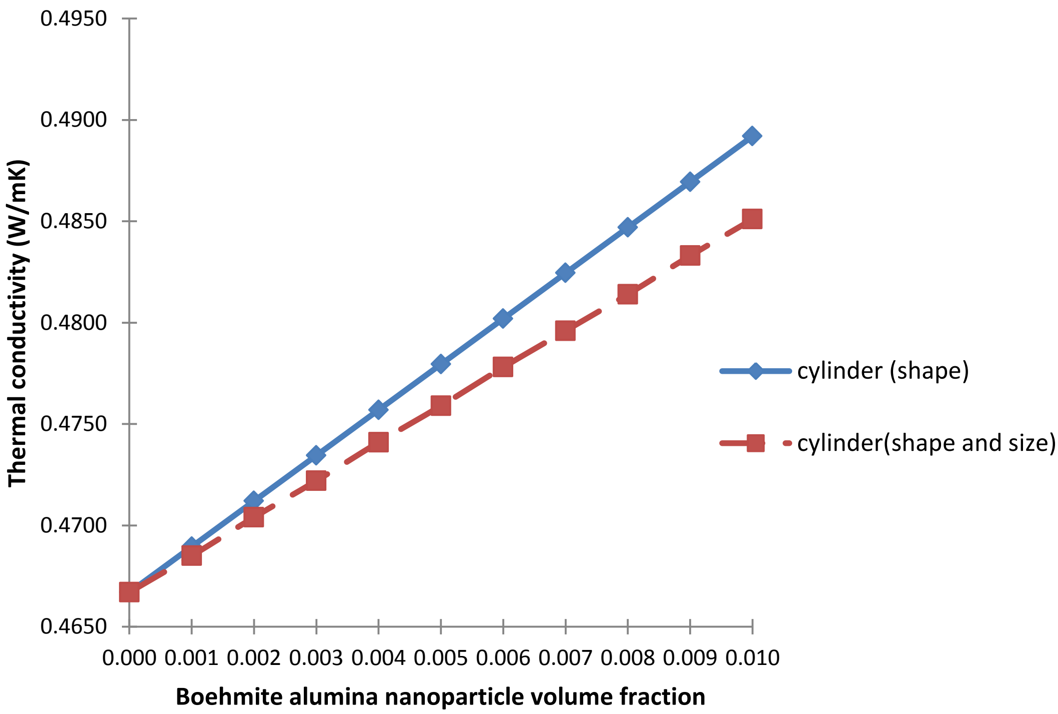

Figure 4.11 Comparison between thermal conductivity enhancements of nanofluids

Figure 4.11 shows the thermal conductivity enhancement comparison for both EG/H_2O-AlOOH nanofluids. The results obtained showed that, when size factor for cylinder shaped nanoparticle was not taken into consideration the thermal conductivity enhancement for EG/H_2O-AlOOH nanofluid calculated using the mathematical formulation mentioned previously was higher compared to the thermal conductivity enhancement of EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles when both factors (shape and size) were taken into consideration.

The reason why thermal conductivity enhancement of EG/H_2O-AlOOH nanofluid containing cylinder shape nanoparticles was higher when nanoparticle size factor was not taken into consideration is because the interfacial effects between the nanoparticles and base liquid interface were neglected. For nanofluids suspension within the same range of volume concentration, stronger interfacial effects are seen with smaller nanoparticles sizes.

The manifestation of interfacial thermal resistance or Kapitza resistance which increases as a result of interactions between nanoparticles and base liquid interface restricts the heat flow resulting in the decrease of the thermal conductivity of the nanofluid [48]. That is why the thermal conductivity enhancement of EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles was lower when nanoparticle size factor was taken into consideration.

4.5.2 Effect of nanoparticle size factor on heat transfer characteristics and thermodynamic performances

Using similar mathematical formulations the comparison between heat transfer coefficient, overall heat transfer coefficient, heat transfer rate, and entropy generation were made for both EG/H_2O-AlOOH nanofluids containing cylinder shaped nanoparticles. The heat transfer characteristics and thermodynamic performance comparison for both types of nanofluids are shown from Figure 4.12 to 4.15.

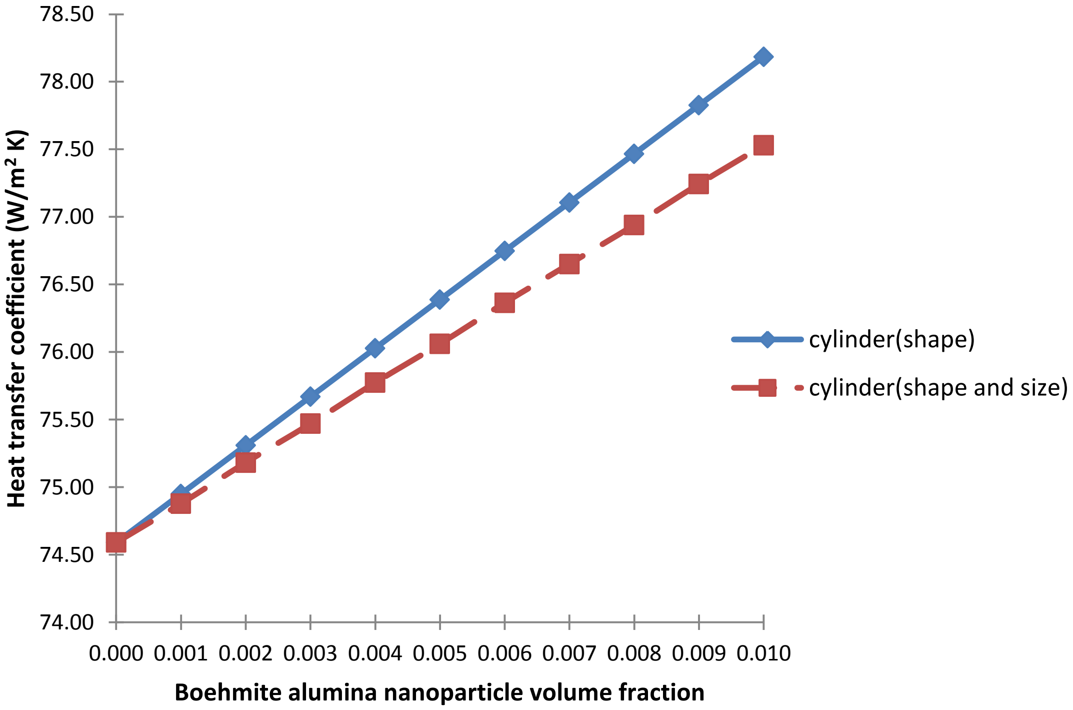

Figure 4.12 Heat transfer coefficient comparison of nanofluids

For the first heat transfer characteristic parameter, the results for heat transfer coefficient comparison is shown in Figure 4.12. The result shows that heat transfer coefficient for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles was higher when size factor of nanoparticle was not taken into consideration. The mathematical formulation used to determine the heat transfer coefficient shows the influence of thermal conductivity enhancement for nanofluids on the increase in this parameter. Higher thermal conductivity enhancement of EG/H_2O-AlOOH nanofluids results in improved heat transfer coefficient performance for nanofluids.

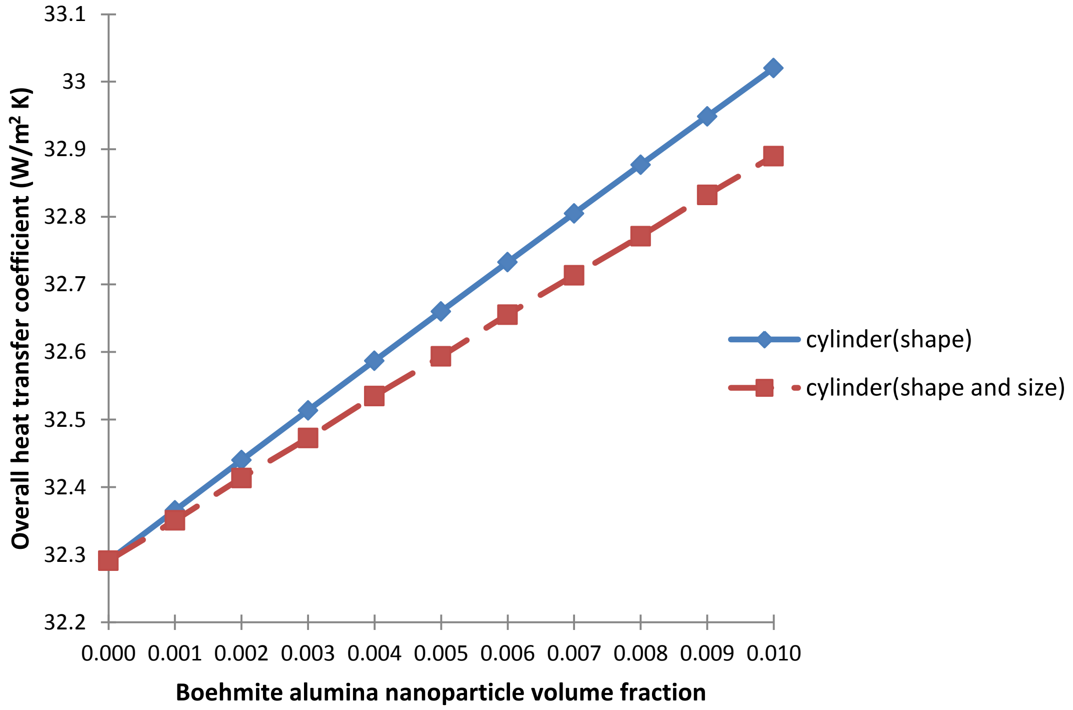

Figure 4.13 Overall heat transfer coefficient comparison of nanofluids

For the second heat transfer characteristic parameter, the result for overall heat transfer coefficient comparison is shown in Figure 4.13. Similar to the first heat transfer characteristic, the result shows that overall heat transfer coefficient for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles was higher when size factor of nanoparticle was not taken into consideration. The mathematical formulation used to determine the overall heat transfer coefficient shows that higher value heat transfer coefficient results in the increase of overall heat transfer coefficient because heat transfer is greater between the nanofluid and the tube wall.

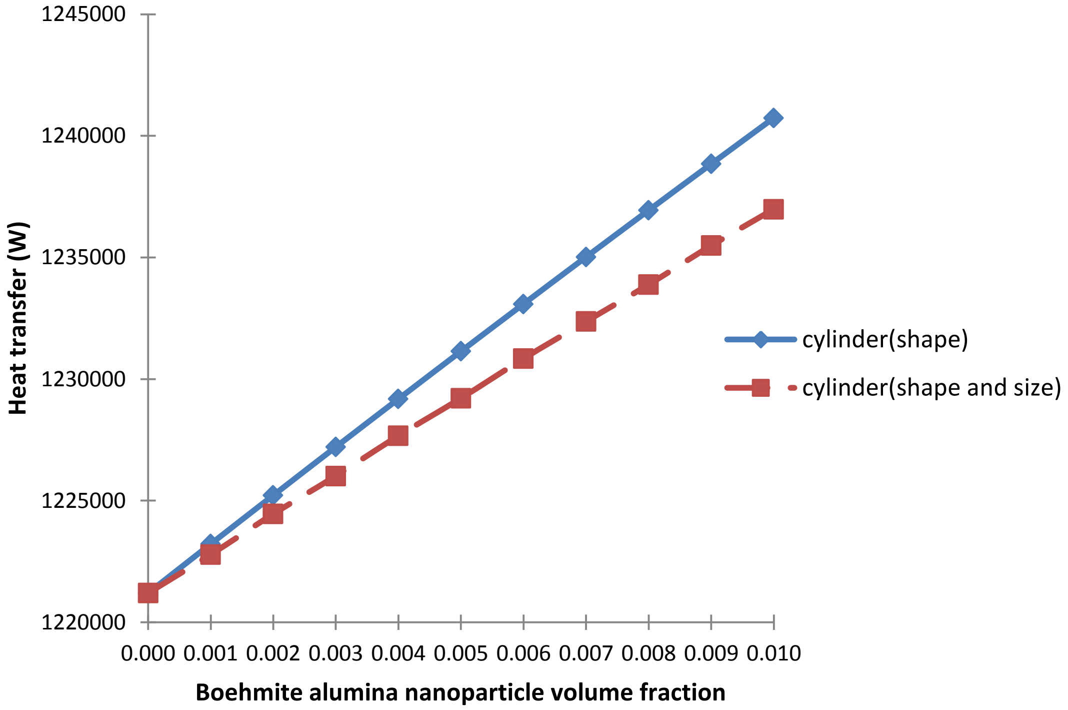

Figure 4.14 Heat transfer comparison of nanofluids

In terms of thermodynamic performance, the result comparison for the convective heat transfer rate for both EG/H_2O-AlOOH nanofluids containing cylinder shaped nanoparticles is shown in Figure 4.14. From the comparison, convective heat transfer rate for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles without considering the size factor of the nanoparticle was higher than EG/H_2O-AlOOH nanofluid containing similar shaped nanoparticles but both (shape and size) factor were considered.

The reason behind this is directly related with the results for the heat transfer characteristics (Figure 4.12 and Figure 4.13) obtained previously. In terms of mathematical formulation convective heat transfer rate is a product of both heat transfer coefficient and overall heat transfer coefficient and since heat transfer characteristic parameters obtained for nanofluids were higher when size factor of nanoparticle was not taken into consideration, convective heat transfer rate also showed the similar trend.

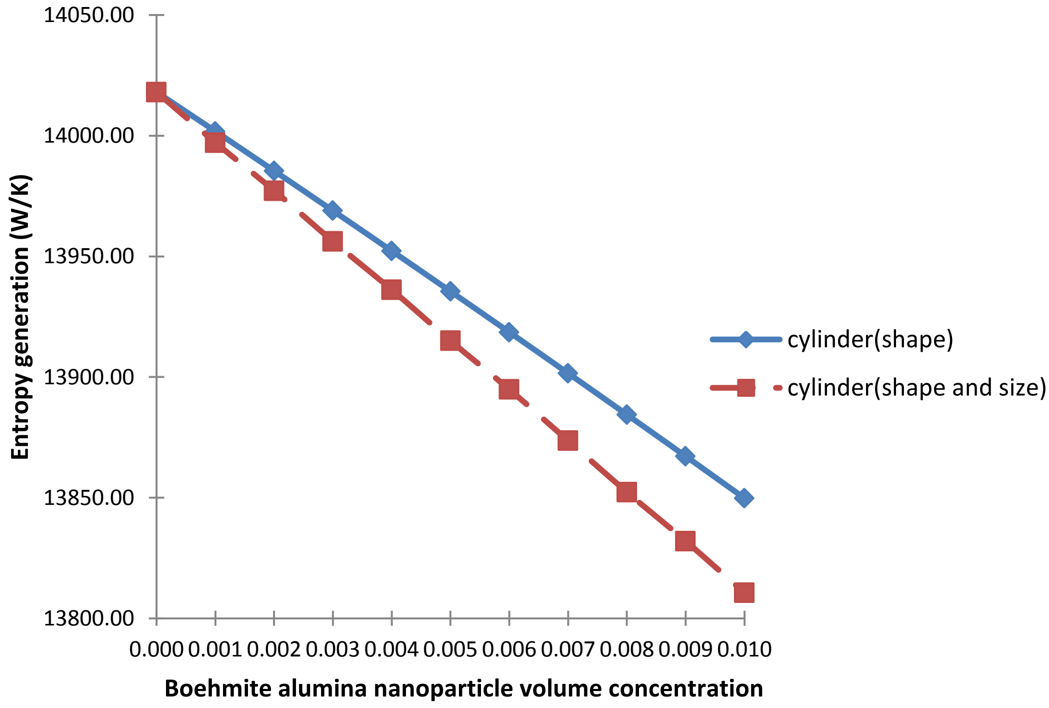

Figure 4.15 Entropy generation comparison of nanofluids

For the second thermodynamic performance, comparison result on entropy generation for both EG/H_2O-AlOOH nanofluids containing cylinder shaped nanoparticles is shown in Figure 4.15. Unlike the results for heat transfer characteristics and the first thermodynamic performance, EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles when size factor of nanoparticle was not taken into consideration showed a decrease in performance.

From Figure 4.15, the results showed that although entropy generation minimization occurs as nanoparticle volume fraction increases, entropy generation for EG/H_2O-AlOOH nanofluid without considering the nanoparticle size factor was higher compared to EG/H_2O-AlOOH nanofluid containing similar shaped nanoparticles but both (shape and size) factors were taken into consideration. This is because the dynamic viscosity for EG/H_2O-AlOOH nanofluid containing cylinder shape nanoparticles without considering size factor was higher compared to when both (size and shape) factors are taken into consideration.

From the results shown in Figures 4.12 to 4.15, similar to the results obtained previously, both types of EG/H_2O-AlOOH nanofluids showed an increase in performance when compared to the conventional basefluid, ethylene-glycol/water (EG/H_2O) mixture. The results showed from Figures 4.12 to 4.15 also revealed that performance for EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles was better when the thermal conductivity enhancement of nanofluid does not take into consideration the size factor of the nanoparticle. Results for both heat transfer characteristics and thermodynamic performance showed a slight increase in comparison. The performance comparison for both types of EG/H_2O-AlOOH nanofluids containing 1% boehmite nanoparticle fraction is summarized in Table 4.8.

Table 4.8

Comparison between heat transfer characteristics and thermodynamic performance for nanofluids containing cylinder shaped nanoparticles with and without size factor

Parameters	Cylinder shaped (shape factor)	Cylinder shaped (shape and size factor)	$\%_{increase}$
Thermal conductivity, $k, W/m\ K$	0.4892	0.4851	0.85
Heat transfer coefficient, $h, W/m^2\ K$	78.19	77.53	0.85
Overall heat transfer coefficient, $U_o, W/m^2\ K$	33.02	32.89	0.40
Heat transfer, q, kW	1240.736	1236.987	0.30
Entropy generation, $\dot{S}_{gen}, W/K$	13849.80	13810.61	0.28

From the results summarized in Table 4.8, results obtained for both EG/H_2O-AlOOH nanofluids containing 1% boehmite nanoparticle volume fraction showed that there was only a slight increase in performance percentage when the size factor of nanoparticle was not taken into consideration. All performance parameters showed an increase of less than 1% under similar working conditions. However, it is important that when conducting theoretical analysis, every aspect that is available has to be taken into consideration to ensure that the results obtained from the theoretical study is as close as possible to the actual performance.

CHAPTER 5

CONCLUSION

5.0 Conclusion

A theoretical study was conducted to investigate the effect of nanoparticle shapes on heat transfer characteristics and thermodynamic performance of a shell and tube heat exchanger. The results obtained from this study were calculated and determined using the mathematical formulations from various literatures and books. Subsequently, the results were compared with several existing literatures to determine its similarity and validity. From the study, it can be concluded that:

1. EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles produced the highest heat transfer characteristic enhancement compared to EG/H_2O-AlOOH nanofluids containing the remaining particle shapes (i.e. platelets, bricks, and bricks) and also with the conventional particle shape (spherical).

2. For thermodynamic performance, EG/H_2O-AlOOH nanofluid containing cylinder shaped nanoparticles produce the highest increase in convective heat transfer rate when compared with EG/H_2O-AlOOH nanofluid containing remaining particle shapes (i.e. platelets, blades, and bricks) and also with the conventional particle shape (spherical).
3. For entropy generation, EG/H_2O-AlOOH nanofluids for all nanoparticle shapes resulted in the minimization of entropy generation when compared to conventional EG/H_2O basefluid. EG/H_2O-AlOOH nanofluid containing platelet shaped nanoparticles produced the least amount of entropy followed by EG/H_2O-AlOOH nanofluids containing brick, blade, and cylinder shaped nanoparticles respectively.

From the conclusion above, it was established that cylinder shaped nanoparticles was the best performing particle shape albeit a slight increase in entropy generation when compared to the remaining particle shapes (i.e. platelets, blades, and bricks). However the percentage increase in entropy generation when compared to the remaining particle shapes were less 0.5%.

When nanoparticle size factor was not taken into consideration, results for EG/H_2O-AlOOH nanofluid containing the best performing particle shape (cylinder) obtained previously for heat transfer characteristics and convective heat transfer was lower compared to results when size factor was not taken into consideration. However, in terms of entropy generation, not considering the particle size factor resulted in higher amount entropy generated for the EG/H_2O-AlOOH nanofluid. To ensure results obtained from this study are as close as possible to actual conditions, every factor has to be considered and taken into consideration during the analysis. This is because, similar to nanoparticle materials, and volume concentration, size and, shapes are also important parameters for application of nanofluids.

The enhanced performance as a result of nanoparticle shapes can be further improved with extensive studies on the major factors influencing the performance for non-spherical nanofluids suspensions. Other key issues which would help improve the use of nanofluids are to lower its viscosity, because a major drawback of using nanofluids is the increase in fluid viscosity which results in increasing the pumping power.

Recommendations on how to further improve the performance of nanofluids are such as by adding additives to the nanofluids. Because adding additives such as oleic acid (OA) [49] in nanofluids has shown increased in thermal performance when compared to conventional base fluid and non-additive nanofluid. From the study, and increase of up to 50% for heat flux was achieved for nanofluid containing oleic acid additives compared to conventional nanofluid. The effectiveness of the thermosyphon economizer (TPEC) also increased to 0.3 compared to when using conventional silver nanofluid which gave an effectiveness of 0.2. The reason behind the improve performance was that the additive helps stabilize and uniformly distributes the nanoparticles which cause the thermal conductivity of the liquid to increase.

Although studies have shown that the use of nanofluids enhances convective heat transfer for the given application with the addition of nanoparticles up to 1% by significantly improving the heat transfer performance, several studies have found that further addition of nanoparticle concentration tends to decrease the heat transfer performance.

Therefore, in addition to using nanofluids to enhance the thermal performance of the system another recommendation is to make modification to the system design in order to further increase the performance of the system. Taking the system studied in this research as an example, the tube side of the heat exchanger where the nanofluids are being channelled through can be improved further by using passive methods such as modified tubes, and tube inserts. The study of nanofluids flowing through these types of improvements have been conducted and results show that thermal performance of the system can be further enhanced when compared to conventional systems. The use of tube inserts, for example have been conducted using numerical analysis by Sasmito et al. [50] to investigate the heat transfer performance of a square section tube under laminar flow conditions. Results showed that for all tube insert configurations, significant increase for the convective heat transfer in the tube section, which subsequently increases the overall thermal performance of the system.

With respect to future studies, the study on effect of nanoparticle shapes for heat transfer characteristics and thermodynamic performances of a shell and tube heat exchanger can be research further by varying the flue gas and nanofluid mass flow rates. By studying with different mass flow rates, it is possible to determine the most optimum flow rates which will result in the best operating condition for the heat exchanger.

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