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Computational Investigation of Heat Transfer of Nanofluids in Domestic Water Heat Exchanger

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ABSTRACT

Recent development of nanotechnology led to the concept of using suspended nanoparticles in the heat transfer fluids to improve the heat transfer properties of the base fluids. The heat transfer enhancement by nanofluids is the significant concern in the efficiency of domestic water heat exchanger system. A computational investigation of the heat transfer in a domestic water heat exchanger was conducted on the water and water-based nanofluids. Copper (Cu) and Alumina (Al_2O_3) nanoparticles were selected in the water-based nanofluids. Volume fraction of nanoparticle in the nanofluids was set at 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 %, respectively. Heat exchanger was invented for the heat transfer from one medium to another in many heat transfer systems. Domestic water heat exchanger can be used in a heat pump domestic water heating system. The density, thermal conductivity and dynamic viscosity of the water-based fluid were increased while the specific heat capacity of the water base fluid, reduced with the addition of Cu as well as Al_2O_3 nanoparticles. Addition of Cu nanoparticle into the water-based heat transfer fluid significantly increased the domestic hot water temperature. The efficiency of domestic water heat exchanger system was optimum when 1.5 % Cu or Al_2O_3 nanoparticles was added into the water-based heat transfer fluid.

1. Introduction

The recent development of nanotechnology led to the concept of using suspended nanoparticles in the heat transfer fluids to improve the heat transfer coefficient of the base fluids. Most researches that were done on the nanofluids supports the concept of nanofluids in improving the heat transfer of the system. Most studies done on the nanofluids in the heat transfer systems such as the heat exchangers recently have reported that the presence of the nanoparticles in the heat transfer fluids increased the effective thermal conductivity of the heat transfer fluids and consequently enhanced the heat transfer characteristics of the heat transfer system. Since the metals in solid form have much higher thermal conductivity than the fluids, it has then been proposed that the idea of using metallic particles to increase the thermal properties of the heat transfer fluids be highlighted. Nanofluids with appropriate selection of the base fluid type as well as appropriate selection of the nanoparticles in terms of material, size, shape and concentration in the base fluid can perform much better cooling

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properties than the conventional heat transfer fluids.

The heat transfer phenomena of the nanofluids in the heat exchanger is still not fully understood. Thus, the nanofluids are the plausible solution for the heating challenge in the domestic water heat exchanger system. Nanofluids consisting of metallic particles in the fluids are considered to have great potential for the heat transfer enhancement. Hence, the nanofluids are considered to have high suitability to the application in the practical heat transfer processes. The heat transfer enhancement by nanofluids is the significant concern in the efficiency of domestic water heat exchanger system in the present study.

The main objective in the present study was to conduct a computational investigation of the heat transfer in a domestic water heat exchanger. Therefore the heat transfer enhancement by different type of water-based nanofluids was to be investigated. This research was aimed to compare the computational results and the heat transfer capabilities of the water and the water-based nanofluids in the domestic water heat exchanger system. Hence, the efficiency of the domestic water heat exchanger system was also to be analyzed in this research.

This present study was limited to the water-based nanofluids with single-phase model. Due to the extreme size and the low concentration of the suspended nanoparticles, the nanoparticles are assumed to move with same velocity as the base fluid. The wall of the domestic water heat exchanger tank was insulated and therefore the wall conditions were assumed in an adiabatic boundary condition. The wall of the domestic water heat exchanger tank was assumed smooth and the roughness of the wall considered negligible. The nanofluids proposed in the domestic water heat exchanger system of this present study were Newtonian. The heat transfer of the computational models is considered as steady state process. Both the radiative and the gravitational effects were considered as negligible in the computational models. By considering the local thermal equilibrium, the nanoparticle–liquid mixture may then be approximately considered to behave as a conventional single-phase homogenous fluid with properties that are to be evaluated as the function of those of the constituents. Water was selected as the base fluid in the domestic water heat exchanger system. Copper (Cu) and Alumina (Al_2O_3) nanoparticles were selected in the water-based nanofluid. Volume fraction of nanoparticle in the nanofluid was set at 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 % respectively in the domestic water heat exchanger system.

2. Literature Review

Heat exchanger has been invented for the heat transfer from one medium to another in many heat transfer systems but was not limited to the air-conditioning condensers, refrigeration evaporators, power plant combustion engines, petroleum refineries and car radiators. Heat exchanger is also applicable in the domestic water heaters. Shell and tube heat exchanger is the most common type of the heat exchanger which is widely used in the industry. Shell and tube heat exchanger consists of a shell with a bundle of tubes. The shell is a large pressure vessel where it comprises a bundle of tubes inside it. Parallel-flow arrangement can be designed for the shell and tube heat exchanger in which the two fluids enter the heat exchanger at the same end and travel in parallel to one another to the other side of the heat exchanger. A circulating fluid flows through the tubes while another circulating fluid flows through the shell to transfer heat between the two fluids, either from the tube to shell side or *vice versa*. The fluids can be either in liquid or gas form on either the shell or the tube side of the heat exchanger.

Domestic water heating system using heat pump is a promising technology in both residential and commercial applications due to the use the same mechanical principles as the refrigerators and air conditioners (Figure 1). Heat pump take heat from the environment and concentrate it to heat the domestic water to be used in either the domestic hot water or the space heating applications [1]. Heat pump domestic water heating system consists of domestic water heat exchanger, heat pump, circulator, piping and valves. The domestic water heat exchanger absorbs the heat from the heat pump and then transfers the heat into the domestic water system. Heat pump is one of the energy sources which can be collected from the waste heat by the refrigeration cycle or the ambient air. Various heat pumps are available to be used for the domestic water heating system, e.g. the air-source, ground-source, solar-assisted, direct-expansion solar-assisted, integrated solar-assisted, gas engine driven and the multi-function heat pumps [2]. The domestic water is drawn from the water main and then flows into the heat exchanger coil. Heat transfer fluid was drawn from the heat pump and then is circulated in the heat exchanger tank. The domestic water is then transferred from lower temperature to higher temperature. On the other hand, the heat transfer fluid is transferred from higher temperature to lower temperature. The heat transfer process happened between the domestic water and the heat transfer fluid in the heat pump domestic water heating system.

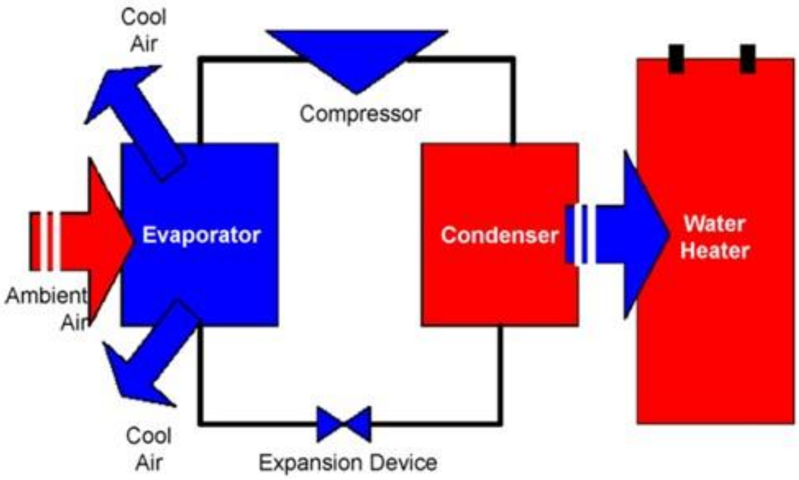

Fig. 1. Schematic of a domestic water heating system [1]

Maxwell in 1873 was the one who originally proposed the idea of using the metallic particles to increase the thermal properties of the heat transfer fluids by knowing the fact that metals in solid form have much higher thermal conductivity than the base fluids [3].

The concept of the nanofluids is the idea of using the nanometer-sized particles to create a stable and highly conductive suspensions, primarily for suspension stability. Nanofluids are the solid-liquid composite materials in which the engineered fluids (i.e. composite) consisting of the suspended nanoparticles (i.e. solid) with average size below 100 nm in the conventional heat transfer fluids (i.e. liquid). Nanofluids are the dilute suspensions of the nanoparticles so that have superior properties like high thermal conductivity, minimal clogging in the flow passage, reduced pumping power, long term stability and homogeneity [10]. Therefore the nanofluids have a wide range of potential application where improved in heat transfer was required. The two important elements of the nanofluids are the nanoparticle material and the base fluid types. Nanoparticles used in the nanofluids have been made of various materials such as the oxide ceramics (Al_2O_3, CuO), the metals (Cu) and the semiconductors (TiO_2). The thermophysical properties of the solid particles are shown in Table 1. The common base fluids include water, ethylene glycol and oil. The thermal conductivity of the nanoparticle materials, either metallic or non-metallic are typically higher than the base fluids result in the significant increase in the heat transfer coefficient. Hence, the effective thermal conductivity of nanofluids is expected to be higher than the base fluids. The thermophysical properties of the base fluids are shown in Table 2.

Table 1
Schematic of a domestic water heating system [13]

	Al_2O_3	CuO	Cu	TiO_2
Specific heat capacity, cp (J/kgK)	773	551	385	692
Density, ρ (kg/m3)	3,960	6,000	8,940	4,250
Thermal conductivity, k (W/mK)	40	33	401	8.4

Table 2
Thermophysical properties of base fluids [14]

	Water	Ethylene Glycol
Specific heat capacity, c_p (J/kgK)	4,179	2,090
Density, ρ (kg/m3)	997.1	1,113.2
Thermal conductivity, k (W/mK)	0.613	0.253

Mapa and Mazhar [4] tested the effect of nanofluids in the mini heat exchanger and they concluded that the nanofluids enhance the heat transfer rate of the mini heat exchanger, and stated that the presence of the nanoparticles reduced the thermal boundary layer thickness. Pawel *et al*., [5] concluded that experiments on the nanofluids have indicated significant increases in the thermal conductivity compared to the liquids without nanoparticles or larger particles, and the extent of thermal conductivity enhancement sometimes greatly exceeds the predictions of well-established theories. They also reported that the increment of thermal conductivity was greatly dependent on the features of nanoparticles such as the high particle mobility and the large surface-to-volume ratio [5].

Choi and Zhang [6] reported that the nanofluid technology has been studied and developed by many research groups worldwide. The effects of the particle volume concentration, particle material, particle size, particle shape, base fluid material, temperature, additive and the acidity on the heat transfer enhancement were investigated experimentally by multiple research groups. In an experimental analysis done by Heris *et al*., [7], the heat transfer coefficient increased with an increasing Peclet number as well as an increasing volume fraction and the Al_2O_3 water-based nanofluids showed larger enhancement than the copper oxide water-based nanofluids. In another study, Heris [8] reported that more heat transfer enhancement as high as 40 % with Al_2O_3 particles while the thermal conductivity enhancement was less than 15 %. Heris also concluded his experimental investigation that the heat transfer enhancement by the nanofluids depends on the increment of the thermal conductivity.

In another experimental analysis done by Farajollahi *et al*., [9] for nanofluids in a shell and tube heat exchanger, the addition of the nanoparticles to the base fluid enhances the heat transfer performance and increases the heat transfer coefficient of the base fluid. Farajollahi *et al*., [9] also concluded that the γ–Al_2O_3/water and TiO_2/water nanofluids were proven that the heat transfer characteristics of the nanofluids improved significantly while the addition of nanoparticles to the base fluid enhances the heat transfer performance and results in a larger heat transfer coefficient than that of the base fluid. Saidur *et al*., [10] reported that the use of the nanofluids in the heat exchanger, which operates under the laminar conditions will be more advantageous than which operates under the turbulent conditions. Huminic [11] investigated the heat transfer characteristics in the double tube helical heat exchangers using the nanofluids and reported that the use of CuO and TiO_2 nanoparticles as the dispersed in water can significantly enhance the convective heat transfer in the laminar flow regime, and the enhancement increases with the Dean Number, as well as the particle concentration level. Soleimani *et al*., [12] reported that the velocity components increase with an increase of the nanoparticles volume fraction, which enhances the energy transport within the nanofluids. They also explained that the addition of the high thermal conductivity nanoparticles increased the conduction and the effectiveness of a heat transfer enhancement.

3. Methodology

Nanofluids can be produced by either the single-step or the two-step production methods. The single-step production method involves condensing the nano-powders from the vapour phase directly into a flowing low-vapour-pressure liquid. As such, the nanoparticles were made by either using the physical vapour deposition (PVD) technique or the liquid chemical method and then dispersed in liquid simultaneously [15,16]. The two-step production method involves the nanoparticles to be produced first and then mixed with the base fluids. In the two-step production method, the nanoparticles can be produced either using the inert gas condensation (IGC), mechanical grinding, chemical vapour deposition (CVD), chemical precipitation, micro emulsions, thermal spray or the spray pyrolysis [15,16].

Due to the nano-powders are commercially available nowadays, the two-step production method is more extensively used to produce the nanofluids. Nevertheless, the issue of stabilization of the nanoparticle suspensions in the base liquid is still a concern in the production of the nanofluids. The stability of the nanofluids can be determined using the sedimentation photograph method and the zeta potential analysis method. The most important factors in determining the stability of the nanoparticle suspensions are its concentration, dispersant, viscosity of base fluid, pH value, diameter, density and the duration of ultrasonic vibration [17]. The addition of the surface active agents and the control of the liquid pH were used to overcome this issue of stabilization of the nanoparticle suspensions in the base liquid. Salt and oleic acid were used as the stabilizers to increase the stability of the copper oil-based nanofluids and the copper water-based nanofluids [17].

In this paper, the heat transfer enhancement by the different type of water-based nanofluids as the heat transfer fluids was investigated and reported. The computational results, heat transfer capabilities of the water and the water-based nanofluids in the domestic water heat exchanger system, and the efficiency of the domestic water heat exchanger system was analyzed and compared. A domestic water heat exchanger was modeled by a 3D modeling software, Solidworks version 2012. A domestic water heat exchanger was then analyzed by an add-ins of flow simulation of Solidworks version 2012. The research parameters are selected to establish the measurement of the temperature of the hot water produced by the domestic water heat exchanger.

The temperature dependency of the different physical properties of the heat transfer fluids has been considered to improve the accuracy of the calculations. There are a number of well-known correlations for calculating the thermophysical properties of the nanofluids are often cited by many researchers. The density and effective specific heat capacity of the nanofluid can be calculated based on the volume fraction of the nanoparticle and the heat capacity concept [3,18]. The properties such as thermal expansion coefficient and thermal diffusivity of the nanofluid can be calculated as following equations,

$$\rho_{nf} = (1 - \emptyset)\rho_{bf} + \emptyset\rho_{np} \tag{1}$$

$$\left(\rho C_p\right)_{nf} = (1 - \emptyset)\left(\rho C_p\right)_{bf} + \emptyset\left(\rho C_p\right)_{np} \tag{2}$$

$$(\rho\beta)_{nf} = (1 - \emptyset)(\rho\beta)_{bf} + \emptyset(\rho\beta)_{np} \tag{3}$$

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}} \quad (4)$$

The effective dynamic viscosity of the nanofluid can be calculated from the following equation [12]. The selected model of effective dynamic viscosity of the nanofluid is referenced from the Brinkman's model, which is one of the earliest models used to obtain the dynamic viscosity for the nanofluid [19],

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\emptyset)^{2.5}} \quad (5)$$

The effective thermal conductivity of the nanofluid can be calculated from the following equation [3,19]. The effective thermal conductivity of the nanofluid can be calculated using the Maxwell model as above because the effective thermal conductivity of the nanofluid relies on the thermal conductivity of the nanoparticles, the base fluid and the volume fraction of the nanoparticles.

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np}+2k_{bf}-2\emptyset(k_{bf}-k_{np})}{k_{np}+2k_{bf}+\emptyset(k_{bf}-k_{np})} \quad (6)$$

The thermal conductivity of the common heat transfer liquids and solids of the metal and the metal oxide was compared and is shown in the Figure 2. Due to high thermal conductivity, water, Cu and Al_2O_3 are selected in the present study.

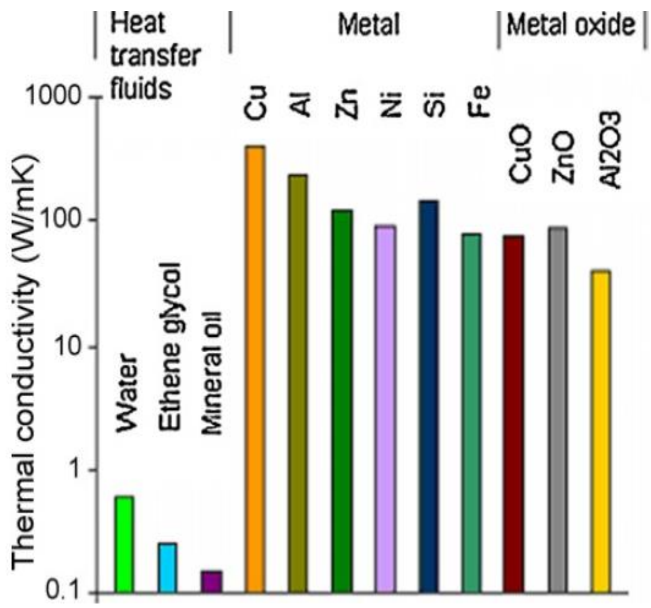

Fig. 2. Comparison of the thermal conductivity of common heat transfer liquids and solids of metal and metal oxide [15]

The boundary conditions of the domestic water heat exchanger tank are identified as the temperature of the water inlet and the refrigerant inlet as well as the volumetric flow rate of the water outlet and the refrigerant outlet from the domestic water heat exchanger tank. The water inlet and the water outlet are the boundaries of the domestic water heat exchanger coil. The domestic water heat exchanger coil was designed for draw the domestic water gravitationally from the domestic water storage tank at a working temperature of 300.15 K. On the other hand, the refrigerant inlet and the refrigerant outlet are the boundaries of the domestic water heat exchanger tank. The domestic water heat exchanger tank however was designed to draw the refrigerant from the heat pump at a working temperature of 60 ºC (or 333.15 K). The volumetric flow rate of the water outlet and the refrigerant outlet is also part of the boundary conditions of the domestic water heat exchanger tank. The water outlet and refrigerant outlet was set at a volumetric flow rate of 0.02 m^3/s and 0.03 m^3/s, respectively.

The data of the boundary conditions defined in this computational analysis was referred to the current plumbing design practiced in the building industry of Malaysia and Singapore. The domestic water heat exchanger was designed to produce the hot water of 333.15 K from a normal water supply of 330.15 K by the heat recovery process or the thermal stratification process. The computational analysis of the water outlet and the refrigerant outlet temperatures modeled by Solidworks was verified against the current plumbing design used in the building industry. The accuracy of the hot water temperature analyzed by Solidworks model was approximately ± 3.23 K or 99.03 %.

4. Results and Discussion

The Solidworks modeling software computes the water and the refrigerant leaving temperatures from the domestic water heat exchanger. The results of the water and the refrigerant leaving temperatures as well as the effects of the different base fluids, the different nanoparticles and the concentration of nanoparticle was discussed. The water, Cu and Al_2O_3 water-based nanofluids have been focused in this computational investigation. Furthermore, this computational investigation focuses on the different volume fraction of the nanoparticle, which were 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 %, respectively of the nanoparticle within the base fluids.

The flow simulation of the different heat transfer fluids used as the refrigerant in the domestic water heat exchanger was carried out by the Solidworks. The results of the refrigerant outlet and the water outlet temperature by the different heat transfer fluids used in the domestic water heat exchanger are tabulated in the Table 3 and 4 respectively.

Table 3
Temperature of the heat transfer fluids at the refrigerant outlet

Type of Heat Transfer Fluids	Temperature (K)
1. Water	325.8451
2. 0.5 % Cu Water-based Nanofluid	325.7977
3. 1.0 % Cu Water-based Nanofluid	325.9387
4. 1.5 % Cu Water-based Nanofluid	326.3259
5. 2.0 % Cu Water-based Nanofluid	326.0117
6. 2.5 % Cu Water-based Nanofluid	325.5986
7. 3.0 % Cu Water-based Nanofluid	325.3945
8. 0.5 % Al_2O_3 Water-based Nanofluid	326.0040
9. 1.0 % Al_2O_3 Water-based Nanofluid	326.1586
10. 1.5 % Al_2O_3 Water-based Nanofluid	326.4523
11. 2.0 % Al_2O_3 Water-based Nanofluid	326.1867
12. 2.5 % Al_2O_3 Water-based Nanofluid	325.8864
13. 3.0 % Al_2O_3 Water-based Nanofluid	325.6777

Table 4
Temperature of the domestic water at the water outlet

Type of Heat Transfer Fluids	Temperature (K)
1. Water	336.3835
2. 0.5 % Cu Water-based Nanofluid	336.6924
3. 1.0 % Cu Water-based Nanofluid	337.4153
4. 1.5 % Cu Water-based Nanofluid	337.8081
5. 2.0 % Cu Water-based Nanofluid	338.1677
6. 2.5 % Cu Water-based Nanofluid	338.7352
7. 3.0 % Cu Water-based Nanofluid	338.8775
8. 0.5 % Al_2O_3 Water-based Nanofluid	336.1640
9. 1.0 % Al_2O_3 Water-based Nanofluid	336.5309
10. 1.5 % Al_2O_3 Water-based Nanofluid	336.5874
11. 2.0 % Al_2O_3 Water-based Nanofluid	336.6474
12. 2.5 % Al_2O_3 Water-based Nanofluid	336.9254
13. 3.0 % Al_2O_3 Water-based Nanofluid	337.0106

The density, specific heat capacity, dynamic viscosity, thermal conductivity and mass flow rate of the nanofluids are compared against the base fluid and are illustrated in the Figure 3 - 7.

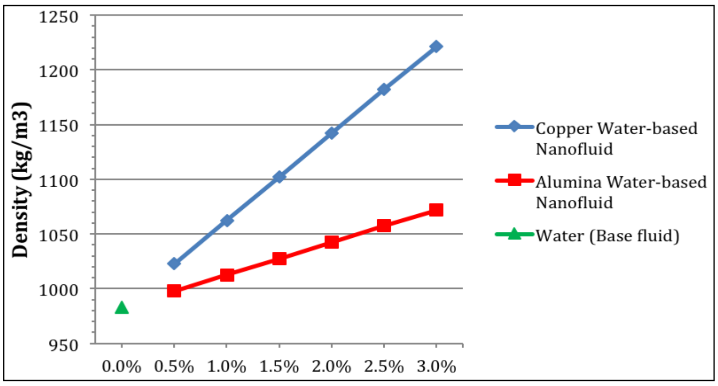

Fig. 3. Density of heat transfer fluid

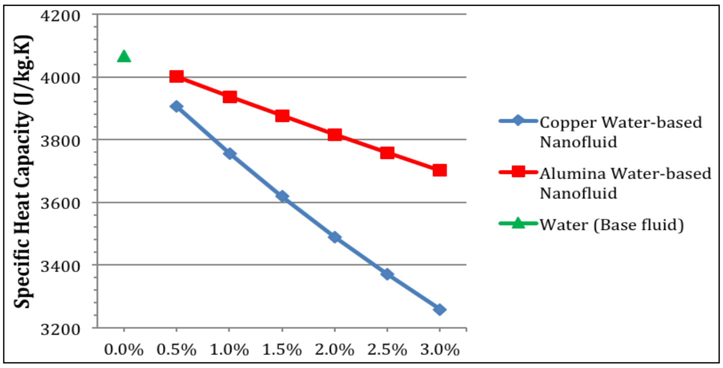

Fig. 4. Specific heat capacity of heat transfer fluid

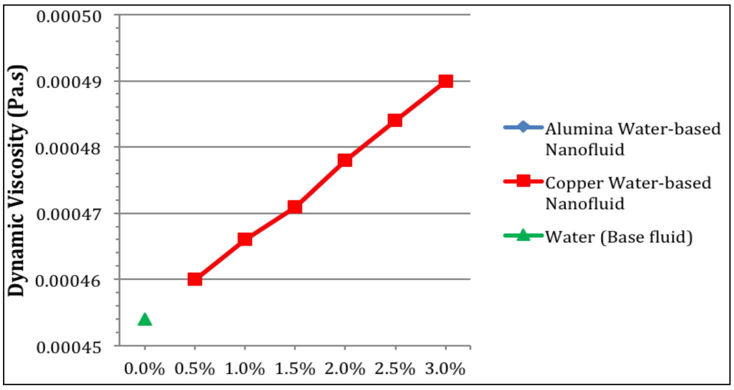

Fig. 5. Dynamic viscosity of heat transfer fluid

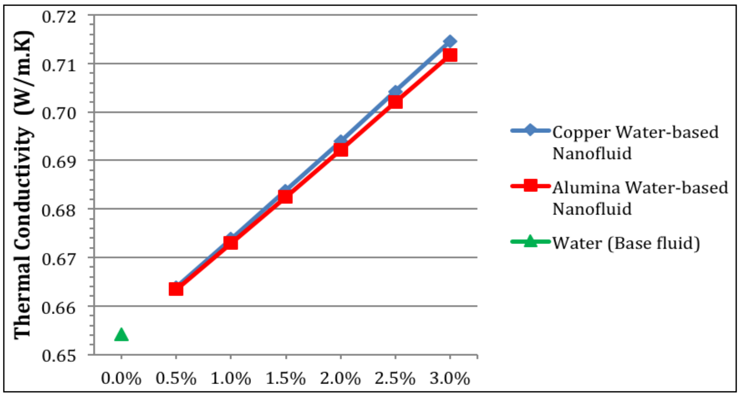

Fig. 6. Thermal conductivity of heat transfer fluid

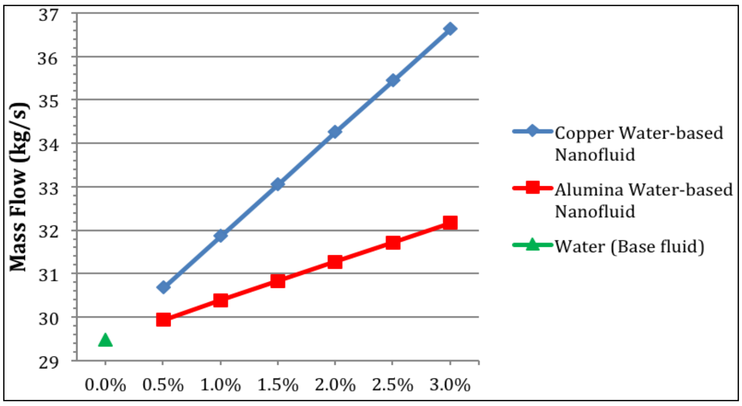

Fig. 7. Mass flow of heat transfer fluid

The addition of the Cu or the Al_2O_3 nanoparticles in the water-based fluid leads to the increment of the density, dynamic viscosity and the thermal conductivity of the heat transfer fluid. However, the specific heat capacity of the water-based fluid was reduced with the addition of Cu as well as Al_2O_3 nanoparticles.

The efficiency of the domestic water heat exchanger is illustrated in Figure 8. The graph shows that the efficiency of domestic water heat exchanger is optimum when 1.5 % Cu or Al_2O_3 nanoparticles was added into the water-based heat transfer fluid.

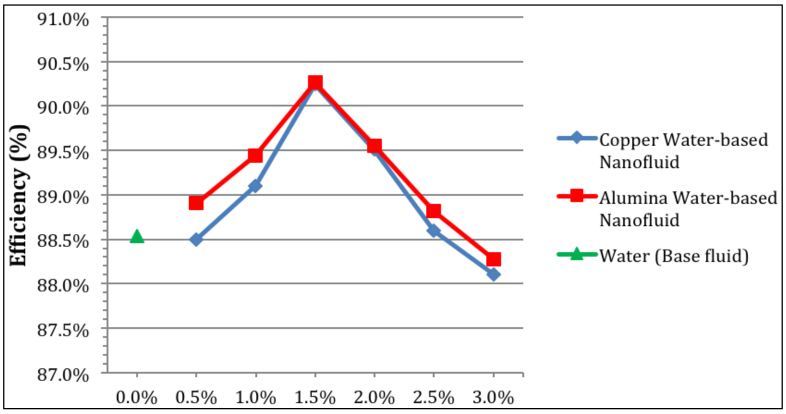

Fig. 8. Efficiency of domenstic water heat exchanger

5. Conclusions

The results from this computational investigation shown that the efficiency of domestic water heat exchanger was optimum when 1.5 % Cu or Al_2O_3 nanoparticle is added into the water-based heat transfer fluid. The results also shown that the addition of Cu or Al_2O_3 nanoparticle into the water-based heat transfer fluid increases the domestic hot water temperature. The Cu nanoparticle significantly increased the domestic hot water temperature. The application of nanofluids as a strong potential for enhancing the heat transfer in the domestic water heating system was found in the present study. A further research work for the same area was required to analyze the overall system effectiveness using nanofluids in the domestic water heat exchanger. Therefore, it is recommended that the overall heat pump domestic water heating system to be investigated in future. The heat pumps, in-line heaters or any possible heat source is also recommended to be included in the computational model for system simulation.

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