Numerical Simulation of an Al_2O_3-H_2O Nanofluid as a Heat Transfer Agent for a Flat-Plate Solar Collector

Eman Abdel-Hakim Tora*; Tarek Moustafa

Abstract— This work introduces a model to numerically simulate the heat transfer performance of an Al_2O_3-water based nanofluid as the working fluid for flat-plate solar collectors. A numerical model is developed by considering the features and the performance of the collector using water as the reference system. Then, the model is modified to consider the thermophysical properties of the nanofluid (μ, ρ, k, C_p) and the potential consequent impact on the convective heat transfer inside the tubes in terms of the Nusselt number to compare the efficiency of the collector when using a nanofluid in the case when only water is used. An alumina-water nanofluid with variable volumetric concentrations of nanoparticles is simulated to demonstrate the applicability of the model. The calculated convective heat transfer coefficient, the enhanced efficiency, the altered mass flow rate, the collector heat removal factor and the heat loss coefficient are in good agreement with the trend of the available experimental data..

Index Terms— nanofluids, heat transfer, modeling and simulation, solar collector

1 Introduction

Industrial processes require heating at different temperature levels. Low quality heat, at temperatures less than 150^{o}C, can be provided via flat-plate solar collectors. Flat-plate solar collectors are used broadly to increase the working fluid temperature in the range of 30^o to 100^{o}C above the ambient temperature. Its operation depends on the absorption of solar radiation; the absorbed energy is conducted to a working fluid circulating inside the tubes of the collector [1]. This working fluid may be water, ethylene glycol or a mixture of water and propylene glycol [2-3], but these fluids have low thermal conductivities. For instance, the thermal conductivity of water is 0.685 W/m K at 120^{o}C while that of ethylene glycol is 0.236 W/m K at 100^{o}C.

Since the emergence of nanofluids [2], which show higher thermal conductivities than the corresponding base fluids, research work has investigated the potential of nanofluids as the working fluids of collectors, whereas and this research can be classified mainly into two categories: direct absorption solar radiation [3,4] that requires design changes and regular collectors that employ nanofluids as the working fluids [5].

Nanofluids have attracted attention as a working fluid for solar collectors because of their predicted capability to enhance the thermal performance of collectors, and thus energy and cost savings can be achieved [6]. A nanofluid refers to a suspension of nanoparticles in a base fluid. These nanoparticles must be composed of material with a very high thermal conductivity, such as metals (e.g., silver, which has a thermal conductivity of 429 W/m K), non metals (e.g., alumina oxide, which has a thermal conductivity of 39 W/m K), semiconductors (e.g., TiO_2, which has a thermal conductivity of 11.4 W/m K) and carbon (e.g., nanotubes (CNT), which have a thermal conductivity of 3300 W/m K) [7]. The base fluid can be one of the above mentioned conventional working fluids, either water or organic liquids [8]. A stable CNT-H_2O based nanofluid was prepared and tested as a solar collector working fluid [9]. The study indicated that the prepared nanofluid enhanced the water heater performance. The application of a nanofluid in solar collectors leads to a homogeneous temperature distribution inside the receiver. In addition, greater light absorption, a high absorption at visible wavelengths and a low emissivity at infrared wavelengths can be achieved, and sunlight can be directly converted into useful heat. Otanicar et al. [10] showed that tuning the size and the shape of the nanoparticles to go well with applications is fundamental to enhance the thermal

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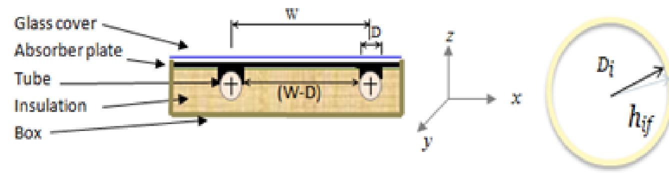
behavior of solar collectors using nanofluids. They concluded that using nanofluids increases the efficiency of low temperature (<100^{o}C) solar collectors; their conclusion is further supported by the results of other studies [11]. The improved efficiency and the reduced size of the solar energy system due to the application of nanofluids favors the cost and environmental aspects of the solar systems [12]; another preceding study indicated that economical benefits may be attained if the useful life cycle energy savings are considered [13]. Recently, the flat-plate solar collector using Al_2O_3-H_2O nanofluid was investigated experimentally. This experimental study demonstrated an increase in the collector efficiency of 28.3% at a 0.2 wt. % nanoparticle concentration [5]. Similarly, a 0.4 wt. % water-multi wall carbon nanotube (MWCNT) nanofluid improved the flat-plate solar collector efficiency [9].

From the preceding discussion, it is very evident that using nanofluids as the working fluids of solar collectors has the potential to increase the thermal efficiency of the collector subject to good preparation and operation of the nanoparticles and the base fluid. Thus, this study introduces an approach to numerically illustrate and predict the change in the efficiency due to the application of a nanofluid in *conventional* flat-plate solar collectors. The model developed can be used to compare the technical performance and the operation features of employing nanofluids with water as the working fluid of the collector.

2 System description

Figure 1 depicts a sheet and a tube flat-plate solar collector (FP SC) using a liquid as the working fluid. The FP SC consists mainly of (i) a glass cover or two glass covers on top of the absorber plate to reduce the convection and the radiation thermal loss, (ii) an absorber plate, which is a black surface with a high absorption for the global solar radiation-beam and diffuse light, (iii) tubes where the liquid working fluid, such as water, is circulated to gain the energy from the absorber, (iv) insulation located at the back and edges of the collector to decrease the conduction heat transfer loss between the tubes and the box and (v) a collector box to enclose the different components.



(a) Front View of the FPSC (b) Cross Section of a Tube

Fig. 1. Schematic of a flat-plate solar collector [18].

3 Modelling

A model was developed to numerically simulate the impact of using a nanofluid as the working fluid of the flat-plate solar collector. The model is designated to introduce a general approach that is capable of predicting the change in the collector efficiency, the heat removal factor, and the heat loss coefficient. The model assumes that the properties of the nanofluids are based on the concentration, size, and shape of the suspended nanoparticles in addition to the operating temperature and the fluid mass flow rate. The model is solved with an alumina-water nanofluid to demonstrate its applicability under the following assumptions [14],[15],[16],[17]:

1. Quasi-steady state condition: thus, calculations are performed on an hourly basis.
2. Constant wall temperature: the inlet and exit solar collector temperatures of the working fluid are controlled at certain designated temperatures, and the temperature difference between the fluid bulk temperature and the inner wall temperature of the tubes of the collector are similarly controlled.
3. Forced circulation with a fully developed regime: the entrance region is small and can be neglected.
4. Nanofluids are well prepared with an adequate stability; the nanofluid acts as a single phase.

To develop a model representing the FPSC performance under the influence of nanofluids, the model of Duffie & Beckman [18] to evaluate the FPSC performance was used as the basis for this study. Then, this model was adopted and extended herein to reflect the application of nanofluids via compiling correlations that represent nanofluid properties and the likely thermal and flow alterations. The model of Duffie and Beckman is used broadly and successfully to predict the FPSC performance in terms of the absorbed solar energy (the energy gained after optical loss), the thermal loss, and finally the net useful solar energy. The thermophysical properties of the nanofluid are assessed as functions of the concentrations, size, and shape of the nanoparticles, the fluid temperature and the mass flow rate via well known correlations that are adequate for engineering applications [19]. The convective heat transfer coefficient h_{if} of the nanofluid and the inner wall of the tubes is estimated from the Nusselt number (Nu), which is calculated using a correlation especially developed for water-based nanofluids [20].

- The total incident solar radiation is a function of the location (latitude Θ, longitude Φ) and time Γ.

$$I_T = f(\Phi, \Theta, \Gamma) \quad (1)$$

- Part of the incident radiation is lost due to the optical properties of the materials of the collectors. The energy absorbed after the optical loss is calculated by

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \ (1+\cos\beta/2) + \rho_g \ I(\tau\alpha)_g (1-\cos\beta/2) \quad (2)$$

- The equation adds the three incident solar radiation spectra: the beam radiation (denoted by the subscript b), the diffuse radiation (subscript d), and the ground-reflected radiation (subscript g). By using the average transmittance-absorptance factor ($\tau\alpha$), the previous equation can be simplified to

$$S = (\tau\alpha)_{av} \ I_T \quad (3)$$

where (I_T) is the total incident solar radiation, β is the collector is tilt angle, θ is the beam radiation incident angle, and $(1 \pm \cos\beta)/2$ is the view factor, which is positive for a view factor from the collector to the sky and negative for a view factor from the collector to the ground.

- Not all of the absorbed solar energy is beneficially transferred to the working fluid due to thermal loss. Thus, the net useful solar energy after eliminating the thermal loss is equal to

$$Q_u = A_{Sc} \, F_R \, (I_T (\tau\alpha)_{av} - U_L \, (T_i - T_a)) \quad (4)$$

where A_{Sc} is the area of the solar collector, U_L is the overall loss coefficient of the collector, T_i is the working fluid temperature at the inlet of the collector, and T_a is the ambient temperature.

The term F_R is the collector heat removal factor, which is defined as the ratio between the actual heat transfer and the maximum value. Its value is attained from

$$F_R = F^{'} \, F^{''} \quad (5)$$

F" is collector flow factor and refers to the collector capacitance factor $(\dot{m} C_p / A_{Sc} \, U_L \, F^{'})$ which is given as

$$F^{''} = \frac{\dot{m} \, C_p}{A_c \, U_L \, F^{'}} [1 - \exp(\frac{-A_c \, U_L \, F^{'}}{\dot{m} \, C_p})] \quad (6)$$

$F^{'}$ is the collector efficiency factor. It depends on the convective heat transfer coefficient h_{if} in addition to the collector dimensions as follows:

$$F^{'} = \frac{1/U_L}{W[\frac{1}{U_L[D+(W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i \, h_{fi}}]} \quad (7)$$

The term F refers to the fin efficiency – the area (W-D)/2 given in Fig.1 - and is calculated as

$$F = \frac{\tanh[\Psi \ (W-D)/2]}{\Psi \, (W)/2} \quad (8)$$

$$\Psi = \sqrt{\frac{U_L}{\delta \ k_b}} \quad (9)$$

With reference to Fig. 1, W is the distance between the two parallel tubes, D is the tube outer diameter, and C_b is the bond conductance pre-unit-length basis, which is given by

$$C_b = \frac{k_b \ b}{\gamma} \quad (10)$$

where k_b is the thermal conductivity of the bond, b is the bond width, and γ is the bond thickness.

The net useful solar energy gained is exchanged to the working fluid circulating in the tubes; this heat transfer occurs via convection over the tube wall. The useful energy equals the net heat absorbed by the working fluid, which can be calculated by

$$Q_u = \dot{m} \ C_p \ (\mathrm{T_{co}} - \mathrm{T_{ci}}) \quad (11)$$

$$Q_u = h_{if} \ \ A_{tbi} (T_w - T_b) \quad (12)$$

According to this equation, the mass flow rate of the working fluid needed to achieve a certain heat duty can be calculated as long as the inlet and exit temperatures of the working fluids are known. Alternatively, the fluid outlet temperature can be estimated for a

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specified mass flow rate.

C_p is the specific heat of the working fluid, $\dot{m}$ is its mass flow rate and T_{co} is the temperature of the working fluid at the exit of the solar collector. T_w is the tube inner wall temperature, T_b is the bulk temperature, and h_{if} is the convective heat transfer coefficient. The value of the convective heat transfer coefficient h_{if} is required to solve Equation 13 and Equation 7. Furthermore, h_{if} reflects the influence of the nanofluids on the thermal performance. The heat transfer coefficient of any fluid can be estimated from the Nusselt number due to the direct proportionality, which is given as

$$h_{if} = Nu\ k\ / D_i \qquad (13)$$

The Nusselt number can generally be calculated via certain correlations that depend on the fluid properties, the conductor geometry, and the flow regime, but the properties of nanofluids depend additionally on the nanoparticle concentration. For nanofluids, special correlations have been developed to evaluate the Nusselt number; a review of these correlations is given by Vajjha and Das [21]. For a water-based nanofluid flowing inside a pipe, the formula of Xuan and Li [22] is used herein to consider the type of the flow regime, as follows:

For $Re < 2300$,

$$Nu=0.4328\,(1+11.285\,\phi^{0.754}\,Pe^{0.218})\,Re^{0.333}\,Pr^{0.4}; \qquad (14a)$$

For $2300 < Re < 25000$,

$$Nu=0.0059\,(1+7.628\,\phi^{0.6886}\,Pe^{0.001})\,Re^{0.9238}\,Pr^{0.4}; \qquad (14b)$$

General, formulas for the Re number and the Pr number for a flow in a tube are given by

$$\mathrm{Re} = \frac{\rho D u}{\mu} \qquad (15)$$

$$\mathrm{Pr} = \frac{\mu C_p}{k} \qquad (16)$$

Apparently, both the Re number and the Pr number are functions of the physical properties of the working fluid. For conventional fluids, these properties can be attained from standard tables or equations [23]. However, for nanofluids, the properties depend on parameters such as the nanoparticle concentration [24]. Herein, the properties are considered temperature dependent, and the correlations given by Azmi et al. [25] can be used. The model target is to compare the performance of the collector using a nanofluid to one using water under the same temperature conditions.

Viscosity of the nanofluid:

$$\mu_{nf} = \mu_w\ (0.9042 + 0.1245\phi - 0.08445\frac{T_b}{72} + 0.6436\frac{d_p}{70}) \qquad (17)$$

Thermal conductivity of the nanofluid:

$$k_{nf} = k_w\,(0.9809 + 0.142\phi + 0.2718\frac{T_b}{70} - 0.102\frac{d_p}{150}) \qquad (18)$$

Specific heat of the nanofluid:

$$Cp_{nf} = Cp_w\ (1.036 - 0.0298\phi - 0.07261\frac{T_b}{70}) \qquad (19)$$

where *dp* is the nanoparticle size, Tb is the fluid bulk temperature ($20^oC < T_b < 70^oC$), *k* is the thermal conductivity of water, μ is the viscosity, ϕ is the nanoparticle volumetric concentration, *w* denotes water and *nf* denotes nanofluid.

- The density of the nanofluid can be calculated according to the mixing theory as developed by Pak and Cho [26]. The experimental results of Sommer and Yerkes [27] demonstrate the applicability of the formula.

$$\rho_{nf} = (1-\varphi)\,\rho_f + \phi\,\rho_p \qquad (20)$$

- The kinematic viscosity:

$$\nu_{nf} = \frac{\mu_{nf}}{\rho_{nf}} \qquad (21)$$

- The viscosity of nanofluid is calculated as

$$\mu_{nf} = (1 + 2.5\phi)\,\mu_f \qquad (22)$$

The formula was developed by Eistein [28], but it was recommended recently to approximately evaluate the viscosity of nanofluids [29].

The thermal conductivity of a nanofluid can be estimated through different formulas [30,31,32]. Each formula can determine the impact of one or two of the variables but not all.

$$n = 3/\Im$$

$$k_{nf} = k_f\,(\frac{k_p + (n-1)*k_f - (n-1)\phi(k_f - k_p)}{k_p + (n-1)k_f + \phi(k_f - k_p)}) \qquad (23)$$

$\Im$ is the nanoparticle sphericity, which is the ratio of the surface area of a sphere with a volume equal to that of the particle to the surface area of the particles. Choi and Eastman [35] recommend using the HCM [33] to approximately calculate the thermal conductivity of a nanofluid. With the assumption of using spherical nanoparticles, Maxwell's relation [34] is attained as

$$k_{nf} = [\frac{k_p + 2k_f - 2(k_f - k_p)\phi}{k_p + 2k_f - (k_f - k_p)\phi}]\,k_f \qquad (24)$$

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To incorporate the effect of the nanoparticle size on the thermal conductivity, the formula developed by Beck et al. [36] is used, where the particle sizes are interrelated to the thermal conductivity as follows:

$$k_{nf} = k_w (1 + 4.4134\ \phi\ (1 - e^{-0.025 d_p})) \quad (25)$$

where d_p is the nanoparticle size in nm.

In all equations, ϕ refers to the volume concentration of the nanoparticles, which is defined as follows:

$$\phi = \frac{V_{NP}}{V_T} \quad (26)$$

where the volume of the nanoparticles is (VNP) and the total volume is VT.

The required mass of the nanoparticles equivalent to the specific volume concentration can be calculated from [37]

$$m_{NP} = 0.001\ \phi\ \ \rho_{NP} \quad (27)$$

The volume fraction related to the mass fraction of nanoparticles ϕ_{wt} was given by Zhang et al. [38] as follows:

$$\phi = \frac{\phi_{wt}\ \rho_f}{\rho_p + \rho_f\ \phi_w - \phi_w\ \rho_p} \quad (28)$$

4 Results and Discussion

The model is solved first with water, and the results are counted as a basis for comparison of the results for a nanofluid. Then, the model is solved with an alumina-water nanofluid as the collector working fluid.

4.1 Solution Procedure

This model was solved using computer software called LINGO (the program is given in an appendix placed at the end of the paper). It can be used efficiently to solve mathematical models and optimization problems. The sequence of calculations and the solution is depicted in Fig. 2.

To solve the model, the input data are the mass flow rate of the working fluid and the inlet and exit temperatures of the collector while varying both the temperature difference (0 – 5 – 10)^{o}C between the inlet temperature of the fluid and the ambient air temperature and the nanoparticles concentration (0.01vol% - 0.5vol%). The nanoparticle sizes of 15 nm, 30 nm, 60 nm, and 90 nm were analyzed to indicate the impact of the nanoparticle size on the collector performance. The model tackles the prediction of the efficiency of the collector under different operating conditions while recognizing the differences due to using nanoparticles. At the end, the results are validated via comparison with some well-cited experimental data.

4.2 Results and Discussion

4.2.1 Collector efficiency

First, the model was solved using 15 nm Al_2O_3 as the nanoparticles and the other properties listed in Table 1. The mass flow rate is 0.07 kg/s, and the area of the solar collector is 2 m^2. The temperature dependence of the physical properties of the nanofluid is considered.

TABLE 1
PROPERTIES OF THE AL_2O_3 PARTICLES USED IN THE SIMULATION

Specific Heat (J/kg K)	*Thermal Conductivity (W/m ^{o}C)*	*Density (kg/m^3)*
775	*39*	*3970*

The efficiency of the FPSC was calculated by the model for various Al_2O_3 volumetric concentrations with maintaining temperature difference ((T_i-T_a)/G_t) between the ambient air and the fluid temperature at the collector inlet equal to 0.005. The results are listed in Table 2. The efficiency increases by 14.7% at a nanoparticle concentration of 0.01 vol% and by 37.44% at a nanoparticle concentration of 0.5 vol%. The same trend was experimentally attained by Yousefi et al. [5] and is primarily attributed to the enhanced thermal properties of the nanofluid, which increases with the nanoparticles. In addition, this efficiency enhancement can be explained in detail in terms of the heat removal factor and the heat loss factor given in the next section.

TABLE 2
EFFECT OF THE NANOPARTICLE CONCENTRATION ON THE COLLECTOR EFFICIENCY.

ϕ	0	0.0001	0.0005	0.001	0.005
η	0.585	0.671	0.69	0.708	0.804
$\Delta\eta$	0	14.70	17.95	21.03	37.44

4.2.2 Heat removal factor and heat loss coefficient

For different temperature differences (T_i-T_a), Fig. 3 shows that the collector efficiency increases with increasing nanoparticle concentration. In addition, by decreasing the difference between the ambient air temperature and the fluid temperature entering the collector, the efficiency increases at a given nanoparticle concentration. The heat removal factor F_R ($\tau\alpha$) and the heat loss coefficient ($F_R U_L$) can be calculated from the correlations derived from Fig. 3, where the intercept of each line represents F_R ($\tau\alpha$) and the slope represents $F_R U_L$. Table 3 lists the values of F_R ($\tau\alpha$) and ($F_R U_L$) at different nanoparticle concentrations.

Within each temperature difference (Ti-Ta), there is a constant value of ($F_R U_L$) and F_R ($\tau\alpha$). At a given temperature difference, F_R ($\tau\alpha$) increases and ($F_R U_L$) decreases with increasing nanoparticle concentration.

These results agree with the experimental results of Yousefi et al. [5]; the same trend was achieved, which validates the model results. With all of the nanoparticle concentrations investigated, the collector has higher efficiencies with a nanoparticle fluid than with water.

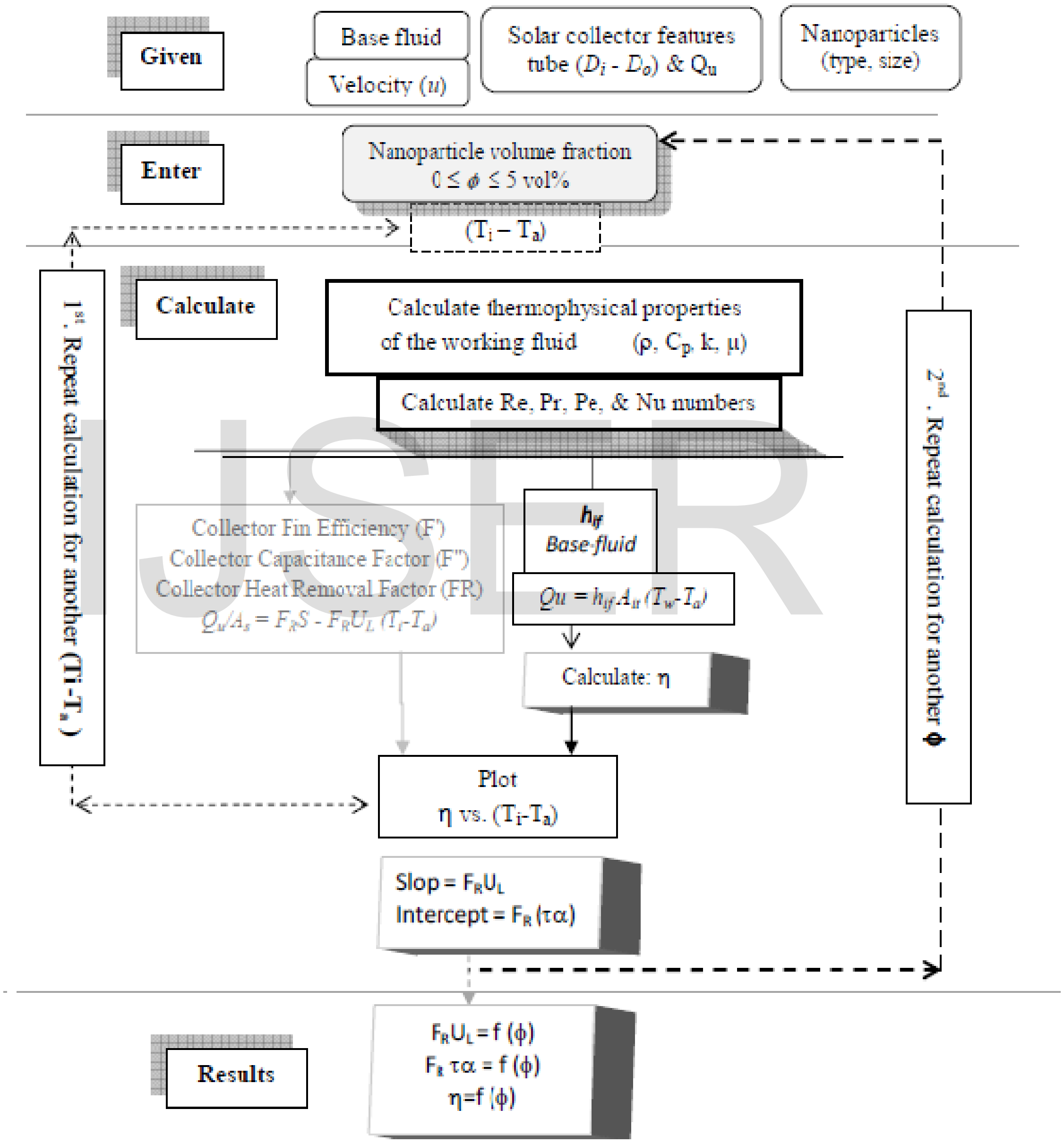

Fig. 2. Solution procedure.

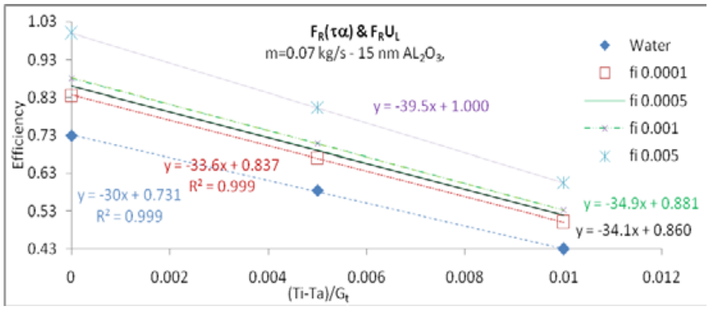

Fig. 3. Efficiency of the FPSC at variable nanoparticle concentrations and temperature differences.

TABLE 3
EFFECT OF THE VOLUMETRIC CONCENTRATION OF NANOPARTICLES ON THE HEAT REMOVAL FACTOR AND THE HEAT LOSS FACTOR

ϕ	*Equation*	*Slop* $-F_R\ \tau\alpha$	*Intercept* F_RU_L
0	$\eta = 0.731 - 30(T_i - T_a)$	*0.731*	*30*
0.0001	$\eta = 0.837 - 33.6(T_i - T_a)$	*0.837*	*33.6*
0.0005	$\eta = 0.86 - 34.1(T_i - T_a)$	*0.86*	*34.1*
0.001	$\eta = 0.881 - 34.9(T_i - T_a)$	*0.881*	*34.9*

This increase in efficiency can be attributed to the enhanced thermal conductivity in addition to increasing the convective heat transfer coefficient, as shown in the next figure. Over the three temperature differences investigated and all of the nanoparticles concentrations, the convective heat transfer coefficient h_i is higher than the value attained when using water.

This increase in the convective heat transfer coefficient may be attributed to the increasing thermal conductivity, where the effective thermal conductivity is equal to 1.5 at a nanoparticle concentration of 0.5 vol%.

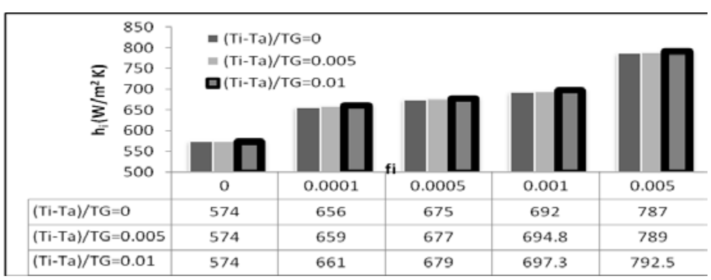

Fig.4. Thermal conductivity enhancement with nanoparticle concentration.

4.2.3 Mass flow rate

The influence of the working fluid mass flow rate was analyzed using the model developed. The model was solved for Al_2O_3 nanoparticle concentrations of 0.01 vol% to 0.5 vol% while maintaining the fluid inlet and outlet temperatures equal to 35°C and 55°C, respectively. The collector efficiency at mass flow rates of 0.005 kg/s, 0.006 kg/s, and 0.007 kg/s were calculated. The results are shown in Fig. 4 to indicate that the mass flow rate has a favorable influence on the collector efficiency. This result can be represented as $Q_u = \dot{m}\, C_p\ (T_i - T_o)$; thus, the useful solar energy is directly proportional to the mass flow rate for a certain temperature increase.

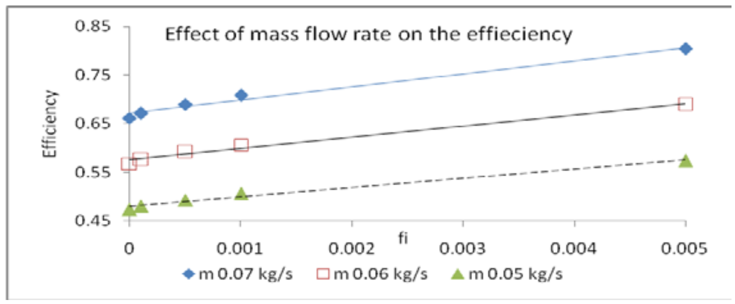

Fig. 5. Effect of the fluid mass flow rate on the collector efficiency for variable volumetric concentrations of nanoparticles.

This current model result matches the outcomes of the experiments of Yousefi et al. [5]; it has been concluded that the collector efficiency increases with the nanoparticle concentration at (Ti-Ta)/Gt > 0.0015. They attributed this result to the increase in the Reynolds number. The Reynolds numbers at mass flow rates of the fluid of 0.007, 0.006, and 0.005 kg/s are given in Fig. 6.

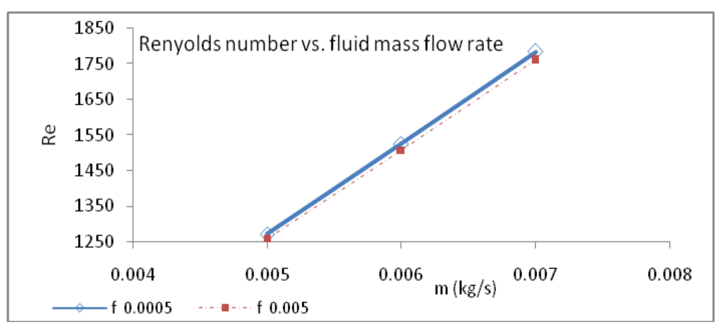

Fig. 6. Reynolds numbers at different mass flow rates of the working fluid

4.2.4 Particle size

The impact of the nanoparticle size is simulated using the thermal conductivity formula developed by Beck et al. [36]. Figure 7 shows that increasing the nanoparticle size enhances the collector efficiency due to the increase in the thermal conductivity. However, at concentrations of 1.8 vol%, no further benefit can be obtained by increasing the size of the particles. In addition, there is a nanoparticle concentration, conservatively 2 vol%, where the maximum increase can be attained, which may explain why Yousefi et al. [5] limited the experimental work to 0.4 wt% of Al_2O_3 nanoparticles during the examining of the flat plate solar collector efficiency when using Al_2O_3-H_2O as the working fluid.

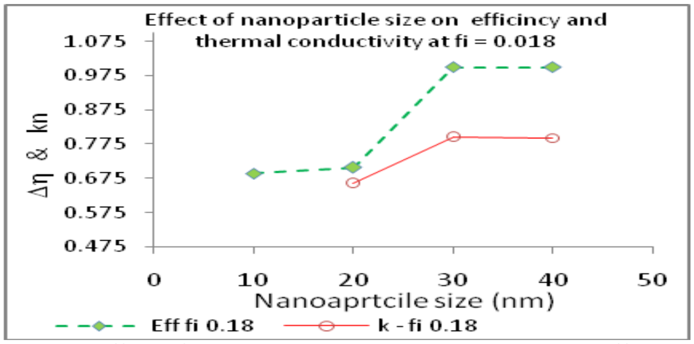

Fig. 7a. Effect of the nanoparticle size on the collector efficiency increase Δη and the fluid thermal conductivity k at fi of 0.018

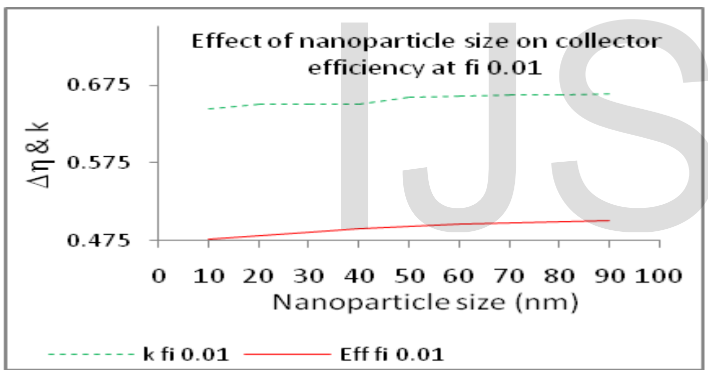

Fig. 7b. Effect of the nanoparticle size on the collector efficiency increase Δη and the fluid thermal conductivity k at fi of 0.01

4.2.5 Particle shape

The impact of different shapes of the nanoparticles was investigated using the HCM. Four shapes (spherical, tetrahedral, hexahedral, and octahedral) were analyzed; Table 4 lists the shape factors for the shapes considered [39]. The collector efficiency was calculated at a nanoparticle concentration of 0.3 vol %, a fluid mass flow rate of 0.07 kg/s, inlet and exit temperatures of the working fluids of 33^{o}C and 50^{o}C, respectively, and a nanoparticle size of 20 nm. The viscosity was calculated using the Einstein model to keep the nanoparticle shape as the sole variable.

TABLE 4
SHAPE FACTOR OF NANOPARTICLES WITH DIFFERENT SHAPES

Shape	*Shape Factor (n)*
Spherical	*1*
Octahedral	*1.18*
Hexahedral	*1.24*
Tetrahedral	*1.49*

The simulation results show that nanoparticle size starts to have an apparent impact on the collector performance at high concentrations (> 1 vol %); at lower concentrations, the shape of the nanoparticle has no effect. This behavior may be attributed to a similar impact of the nanoparticle shape on the thermal conductivity, as depicted in Fig. 8. Meanwhile, nanoparticles with a higher shape factor (≥2) show a higher enhancement in the thermal conductivity and the efficiency at any concentration. Thus, using nanoparticles with a disk-like shape or a quadrangular shape may be more useful than using spherical particles.

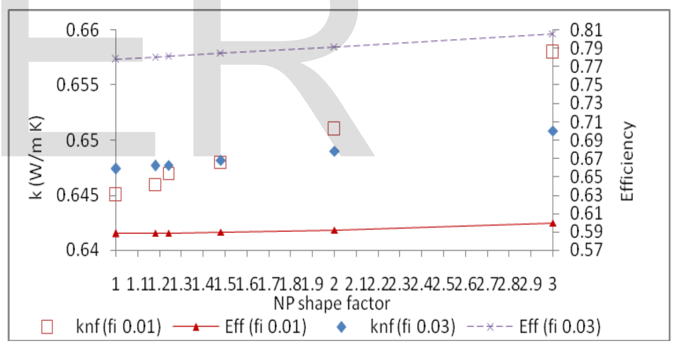

Fig. 8. Effect of the nanoparticle shape on the solar collector efficiency

5 Conclusion

A model was developed to numerically predict the performance of a typical flat plate solar collector with a sheet and tube geometry by using a nanofluid as the working fluid. The model was solved with an alumina-water nanofluid as a case study to demonstrate the applicability of the model. The model was validated via a comparison with published experimental results on the behavior of nanofluids as a heat transfer agent. The model results show a trend similar to that of the experimental data. The model considers the performance of the collector itself under regular conditions to provide hot water. The main point is to modify an ordinary model of a FPSC to recognize the impact of using a nanofluid when evaluating the performance of the collector. The influence of the nanoparticle concentration (ϕ), size (d_p) and shape (ℑ) are considered in conjunction with the mass flow rate (*m*) of the working fluid, the effect of the temperature on the collector efficiency (η), the heat removal factor ($F_R\tau\alpha$), and the heat loss coefficient (F_RU_L).

The following concluding remarks are derived about the model from the results:

1. The collector using an alumina-water nanofluid has higher efficiency than one using water.
2. The nanoparticle concentration is directly proportional to the collector efficiency. For a given temperature range, linear relations were determined to represent the collector efficiency enhancement.
3. The temperature difference between the ambient air and the working fluid inlet temperature to the collector has direct impact on the collector performance:
   i. The lower this difference, the higher the efficiency that is attained.
   ii. The heat transfer loss (U_L) is almost constant for the same temperature difference.
4. The nanoparticle size has a noticeable impact at concentrations higher than 1 vol %. The thermal conductively of the nanofluid and the collector efficiency have better values with higher particle sizes.
5. The impact of the nanoparticle shape appears at high concentrations only. The higher the shape factors of the nanoparticles, the more obvious the efficiency enhancement.

APPENDIX

LINGO program

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EfficiencyW=QuW/It;
Efficiency_increase=(QuNF- QuW)/QuW EfficiencyNF=QuNF/IT;;!the unit is W;
!!!! with NF usage starting from 1vol% NP; f=0.001;
! Also I fix in both cases heating the working fluid from 65oC to 95oC;
DT=Tfo-Tfi;
Tfo=55;
Tfi=35;
Tw-Tb=5;Tb=(Tfi+Tfo)/2;
Di=0.01;
W=0.15;
! Also fix the inner tube wall temperature above that of the bulk temperature by 5K; !Thus (Tw-Tb)=5;
!QuW=1;! 1 kw;
!Part (I): use WATER as the working fluid;! f subsribt refers to the working fluid;
mW=0.007;QuW=Mw*CpW*DT;IT=1;Asc=2;Lt=2;
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!;
! cp water at the bulk temperature of 50oC is .... kJ/kg K);
! Now I need to determine hi from the mass flow rate and the physical properties of the working fluid under the operating conditions give above;
!here are water properties at the bulk temperature, (w) REFERS TO WATER;
DW=989;
CPW=4.18135;
KVW=0.568*10^(-6);!KW means Kinematic Visocity;
KW=0.639;! THE UINT IS wat NOT kw;
PrW=1000*CPW*MIOW/KW;! i MULTILPY BY 1000 TO UNIFORM THE UNITS, TO MAKE THE UNITS OF cP IN (w) INSTEAD OF KW TO MATCH THE UNITS OF (K) IN THE BOTTOM TERM;
MIOW=DW*KVW;
u=V/Ac;
Ac=3.14*DI^2/4;
V=MW/DW;
ReW=DW*u*DI/MIOW;
NuW=0.0059*(1+7.6286*f^0.6886*PeW^0.001)*ReW^0.9238*PrW^0.4; PeW=0;
Hi=KW*NuW/DI;! the unit here is (watt) since KW unit is w/m2 oC;
 ! nOW WE KNOW Hi THUS WE CAN DETERMINE THE NEADED (area);
! This energy gained by the fluid equal to the absorbed by the collector tubes by CONVECTION;
n*Ait=QuW/((hi/1000)*(Tw-Tb));!I divide hi by 1000 to convert the unit to kW to match QuW units;Ait=3.14*Di*Lt;
!!!!!!;!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!QuNF=M_nf*CPNF*DT;!Ait is the surface area of the collector tube;
!t=Ait/(3.14*Di);!Lt is the tube length and given in cm;
Di=0.01;
! By knowing Lt we determine the Asc, inah Allah;
!So far, the hi is calculated for the collector tube using water............In the next part (part II) Insh Allah I will calculate hi for that of NF;
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Part (II)
! Nanofluid (Al2O3)
DTnf=Qu/(CPnf*m);
CPnf=CpW*(1.036-0.0298*f-0.07261*Tb/70);
Dnf=(1-f)*DW+f*Dp;
Mionf=MioW*(0.9042+0.1245*f-0.0844*T/72+0.6436*nmp/170);
Knf=KW*(0.9808+0.0142*f+0.2718*Tb/80-0.102*nmp/150);
Dp=3880;
CPp=0.773;
Kp=36;
Prnf=1000*CPnf*MIOnf/Knf;
!above I multiplied by 1000 since cnf unit is kW however knf unit is wat, so to make kw into w;
Vnf=V;!M_nf/Dnf;
unf=u;
Renf=Di*Dnf*unf/Mionf;
Prnf=1000*Mionf*cpnf/knf;
!!!Nunf=(Prnf^0.4)*(Renf^0.8)*0.023;NuNF=0.0059*(1+7.6286*f^0.6886*Penf^0.001)*Renf^0.9238*Prnf^0.4;
Penf=unf*nmP/TD; nmP=15*10^(-9);
TD=knf/(Dnf*1000*CPnf); ! nmP is nm or size of nanoparticles in nanometer - TD is the Thermal Diffisivity;
hinf=Nunf*knf/Di;
QuNF=n*Ait*(HiNF/1000)*(Tw-Tb);! I divide hi by 1000 to convert its unit from W to kW to match QuNF units (kW);
! I use (Ait) as we use the same collector to study the change due to JUST replacing the working fluid;!!!!!!!!!!!!!!!;
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!Ait1=QuNF1/((HiNF1/1000)*(Tw-Tb));!PDNF=(ff*Lt*Dnf*unf^2)/(2*gc*DI);! PD means Pressure Drop;
PressDrop=ff*(Lt/Di)*Dnf*(u^2)/2;
!PD=(ff*Lt*DW*u^2)/(2*gc*DI);
gc=1;
ff=64/Renf;
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!So far , the model calculate hi and Qu using hi value.................;
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!Now, add the (Ti-Ta) to get FR and FR UL by plotting Qu vs (Ti-Ta);
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REFERENCES

[1] S. Kalogirou, Solar thermal collectors and applications, Progress Energy Combustion 30 (2004) 231–295.

[2] S.U.Choi, Enhancing thermal conductivity of fluids with nanoparticles, ASME FED 231 (1995) 99–103.

[3] R. Prasher, P. Bhattacharya, P. Phelan, Thermal conductivity of nanoscale colloidal solutions (nanofluids). Physics Review Letters 94 (2005) 025901.

[4] O. Mahian, A. Kianifa, S. Kalogirou, I. Pop, S. Wongwises, A review of the applications of nanofluids in solar energy, International Journal of Heat and Mass Transfer 57(2013) 582-594.

[5] T. Yousefi, F. Veysi, E. Shojaeizadeh, S. Zinadini, An experimental investigation on the effect of Al2O3-H2O nanofluid on the efficiency of flat-plate solar collectors, Renewable Energy 39(2012) 293-298.

[6] E. Natarajan, R. Sathish, Role of nanofluids in solar water heater. International Journal of Advanced Manufacturing Technology 43 (2009) 6082-6087.

[7] J. Buongiorno, Convective transport in nanofluids, Journal of Heat Transfer 128(2006) 240-250.

[8] C. Pang,Y. Kang, Stability and thermal conductivity characteristics of nanofluids (H2O/CH3OH+NaCl+Al2O3 nanoparticles) for CO2 absorption application. International Refrigeration AC Conference, Purdue. July 16-19, 2012.

[9] T. Yousefi, E. Shojaeizadeh, F. Veysi, S. Zinadini, An experimental investigation on the effect of pH variation of MWCNT-H2O nanofluid on the efficiency of a flat-plate solar collector, Solar Energy 86 (2012)771-779.

[10] T. Otanicar, P. Phelan, R.S. Prasher, G. Rosengarten, R.A.Taylor, Nanofluid-based direct absorption solar collector. JRSE (2010) 033102-1.

[11] H. Tyagi, P.E. Phelan, R. Prasher, Applicability of nanofluids in high flux solar collectors, Journal of Solar Energy Engineering 3 (2009) 023104.

[12] E. Sani, L. Mercatelli, S. Barison, C. Pagura, F. Agresti, L. Colla, P. Sansoni, Potential of carbon nanohorn-based suspensions for solar thermal collectors, Soarl Energy Material and Solar Cells 95 (2011) 2994–3000.

[13] T. Otanicar, J.S. Golden, Comparative environmental and economic analysis of conventional and national solar hot water technologies, Environmental Science Technology 43(2009) 6082-6087.

[14] E.A. Tora, "Computer Simulation of Nanofluids Applications in Processes Thermal Energy Systems", Presented in 1st International Conference Advanced Basic and applied Science, 6 – 9 Nov. 2012, Hurghada, Egypt

[15] E.A. Tora, "Aspen plus preliminary simulation of nanofluids", Journal of American Science 2012; 8(12):391-397.

[16] E. A. Tora, T. M. Moustaf; Water-Based Nanofluid as a Working Fluid for Flat-Plate Solar Collector: Heat and Flow Behaviours; The 16th International Conference on Petroleum, Mineral Resources and Development; 10-12 Feb., 2013; Cairo, Egypt

[17] E.A. Tora; Nanofluids as a Cooling Agent for Rankine Power Cycle; 2nd International Conference on Energy Systems & Technology (ICEST 2013); 18-21 Feb. 2013; AfaqScientific, Cairo, Egypt

[18] J.A.Duffie, W.A. Beckma, Solar engineering of thermal processes, 3rd ed. New Jersy: John Wiley & Sons 2006.

[19] S. Hosseini, A. Shahrjerdi, Y. Vazifeshenas, A review of relations for physical properties of nanofluids, Australian Journal Basic and Appled Science 5 (2011) 417-435.

[20] S.K. Das, S.U. Choi, H.E. Patel, Heat transfer in nanofluids: a review, Heat Transfer Engineering 27 (2006) 3–19.

[21] R.S. Vajjha, D.K. Das, P.K.Namburu, Numerical study of fluid dynamic and heat transfer performance of Al2O3 and CuO nanofluids in the flat tubes of a radiator, International Journal of Heat and Fluid Flow 31 (2010) 613–621.

[22] Y. Xuan, Q. Li, Investigation of convective heat transfer and flow features of nanofluids, Journal of Heat Transfer 125 (2003)151–155.

[23] R. Darby, Chemical engineering fluid mechanics, 2nd ed. New York: Marcel Dekker, Inc; 2001.

[24] S.M. Murshed, K.C. Leong, C. Yang, Investigations of thermal conductivity and viscosity of Nanofluids, International Journal Thermal Science 47(2008) 560–568.

[25] W.H. Azmi, K.V. Sharma, P.K. Sarma, R. Mamat, Influence of certain thermo- physical properties on prandtl number of water based nanofluids. National conference in mechanical engineering research and postgraduate students (1st NCMER 2010) 26-27. MAY 2010, FKM Conference Hall, UMP, Kuantan, Pahang, Malaysia; pp. 502-515 ISBN: 978-967-5080-9501 (CD ROM); Editors: M.M. Rahman, M.M. Noor and K. Kadirgama, Universiti Malaysia Pahang.

[26] B.C. Pak, Y.I. Cho, Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles, Experimental Heat Transfer 11(1998)151-170.

[27] A.D. Sommers, K.L.Yerkes, Experimental investigation into the convective heat transfer and system level effects of Al2O3-propanol nanofluids, Journal of Nanoparticle Research 12 (2010)1003- 1014.

[28] A. Einstein, Eine neue bestimmung der molekuldimensionen. Annalen der Physik, Leipzig 19 (1906) 289–306.

[29] D.A. Drew, S.L.Passman, Theory of multi component fluids. Berlin: Springer; 1999.

[30] S. Özerinç, S. Kakaç, A.G. Yazıcıoğlu, Enhanced thermal conductivity of nanofluids: a state of the art review, Journal of Microfluid and Nanofluid 8(2010)145-170.

[31] C. Kleinstreuer, Y. Feng, Experimental and theoretical studies of nanofluid thermal Conductivity enhancement: a review. Nanoscale Research Letters 6(2011) 229.

[32] K. Oğuz, Numerical forced convection heat transfer analysis of nanofluids considering performance criteria, MSc, (2012), Middel East Technical University.

[33] R.L. Hamilton, O.K. Crosser, Thermal conductivity of heterogeneous two- component systems, Journal of Industrial Engineering and Chemistry 3(962)187-191.

[34] J.C. Maxwell, A Treatise on electricity and magnetism. Oxford: Clarendon Press; 1873.

[35] S.U. Choi, J.A. Eastman, Enhancing thermal conductivity of fluids with nanoparticles, ASM Mechanical Engineering Congress & Exhibition, November 12-17, 1995, San Francisco, CA.

[36] M.P. Beck, Y. Yuan, P. Warrier, A.S. Teja, The effect of particle size on the thermal conductivity of alumina nanofluids, Journal of Nanoparticles Research 11(2009) 1129-1136.

[37] H.S. Zeinali, M.E.Nasr, S.G.Etemad, Experimental investigation of convective heat transfer of Al2O3/water nanofluid in circu-

lar tube, International Journal of Heat and Fluid Flow 28 (2007) 203–210.

[38] X. Zhang, H. Gu, M. Fujii, Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles, Experimental Thermal and Fluid Science 31 (2007) 593-599

[39] W.H. Qi, M.P. Wang, Q.H. Liu, Shape factor of non spherical particles, Journal of Material Science 40(2005) 2737-2739