Investigating the Thermal Performance of a Nano-fluid Based Flat - plate solar Collector

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Solar thermal energy is a renewable, convenient source and environmentally benign energy resource. Flat-plate solar collectors are the most common and cost-effective devices for exploiting and converting solar energy into heat and transfer the heat to a medium. However, the efficiency of these systems is not favorable due to the poor thermo-physical properties of working fluid. Using nano-fluid is proposed as an efficient method in order to improve the heat transfer properties of the working fluid. Adding nanoparticles to base fluid, leads to enhancement in thermal properties of working fluid. Thermo-physical properties of base fluid depend on several parameters including particle concentration and size. In this study, the effect of these parameters is theoretically investigated on the thermal performance of a flat-plate solar collector. In addition, the collector efficiency is evaluated for different shapes of the cross-section of the riser pipe. It is observed that increase in nanoparticle volume fraction, enhances the efficiency of a flat-plate collector and the maximum obtained value was approximately 80%. Reversely, particle size increase from 20 nm to 80 nm, causes more than 3% reduction in efficiency. In addition, for different shapes of the pipe cross section, including circle, square, and triangle; circular cross sections leads to the highest efficiency in a flat-plate solar collector.

keywords: *Thermophysical properties, flat - plate solar collector, nano-fluid, solar collector efficiency*

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NOMENCLATURE

A_c	Surface area of solar collector m^2
d	Particle diameter, nm
D	Tube diameter, m
C_p	Heat capacity (J/kg K)
F_R	Heat removal factor
I_T	Incoming solar radiation (Mj/m^2)
$\dot{m}$	Mass flow rate of fluid flow (kg/s)
Q_u	Rate of useful energy gained (W)
T	Temperature (K)
U_L	Overall loss coefficient of solar collector (W/m^2k)
h	Convective heat transfer coefficient (W/m^2k)
k	Thermal conductivity (W/m K)
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
f	Friction factor

Greek symbols

$\tau\alpha$	Absorptance–transmittance product
φ	volume fraction of nanoparticles in nano-fluid
ρ	Density
μ	Dynamic viscosity(kg/m s)
η	Collector efficiency

Subscripts

b Bulk

f Base fluid

nf Nano-fluid

p Nanoparticle

w Tube wall

a Ambient

i Inlet

o Outlet

1. INTRODUCTION

Today, the majority of energy demand is provided by fossil fuels. Due to environmental pollution and the decay of these energy sources, human beings are seeking new sources of energy, especially renewable ones. Solar thermal energy is garnering significant interest nowadays due to its affordable cost and its environmental advantages. Flat-plate solar collectors are devices which convert solar radiation into heat and transfer to a working fluid which can be used in cooling, heating, and water desalination [1–3]. These devices are conventional; however, flat-plate collectors have low efficiencies due to poor thermo-physical properties of the working fluid. Hence, there is a large effort to enhance their efficiency and decrease the cost of produced power. Replacing the conventional fluids with more appropriate fluids such as nano-fluid, the fluids with nano sized solid particles suspended in them, has been proposed as an effective method to improve heat transfer properties in thermal systems. The suspended metallic or nonmetallic nanoparticles change the heat transfer characteristics of the base fluid [4,5]. Different theoretical and experimental methods are introduced to increase the efficiency of the solar water heater [6–9]. R. Nasrin et al. [10] numerically investigated the forced convective flow and heat transfer by water- Cu, water-Al2O3, water-CuO and water- Ag nano-fluid through a flat plate solar collector. In this research, the results showed that the thermal performance of solar collector enhanced by applying nano-fluid. Tiwari et al. [11] theoretically demonstrated the enhancement of collector efficiency for a nano-fluid-based flat-plate collector and the potential of 31% reduction in emission in comparison with conventional models. Noghrehabadi et al [12] experimentally investigated thermal efficiency of a symmetric conical solar collector by using SiO2/water nano-fluid with 1% mass fraction as the coolant. Their results showed that the maximum efficiency and outlet-inlet temperature difference of conical collector using SiO2/ water nano-fluid were approximately 62% and 6.8 0C, respectively and the solar collector is more efficient in the higher values of the flow rate and solar radiation. Otanicar [13] observed an improvement in the efficiency of a micro-solar-thermal-collector under exploiting on nanotube, graphite and silver nano-fluids. In another research, Delfani et al [14] synthesized a prototype of a direct absorption solar collector and experimentally investigated its thermal performance by using different volume fractions of multi wall carbon nanotubes in water and ethylene glycol mixture as working fluid. Obtained results showed that the efficiency of direct absorption solar collector using 100 ppm carbon nanotube nano-fluid is 23% higher than that of a flat plate collector; whereas, the efficiency of a flat plate collector using the base fluid is 4.4% higher than that of a direct absorption solar collector [14].

Choi [15] showed that the conventional liquid thermal performance could remarkably be improved by utilizing nanoparticles. Among the physical properties, those which usually are evaluated in view of practical applications are thermal conductivity and dynamic viscosity of nano-fluid [16–20]. Natarajan [21] has investigated the thermal conductivity enhancement of the base fluids using carbon nanotubes and proposed these fluids as a unique heat transport medium in order to enhance the efficiency of the conventional solar water heater. Tyagi [22] compared the performance of nano-fluid-based non concentrating direct absorption solar collector (DAC) with a conventional flat-plate collector, theoretically. In this research, a mixture of water and aluminum nanoparticles, was used as the absorbing medium. It was revealed that the efficiency of a DAC using nano-fluid as the working fluid is up to 10% higher than that of a flat-plate collector. Yousefi et al. [23] observed 28.3% enhancement in efficiency for 0.2wt.% nanoparticles concentration compared with pure water in a flat-plate collector. Y. Devarajan et al. [24] experimentally demonstrated that adding 0.4% of Al2O3, CuO and ZrO2 nanoparticle to water as heat transfer fluid, enhanced the heat transfer and efficiency of the solar flat plate collector.

As mentioned, several studies have been conducted on the effects of nano-fluid in heat transfer and in some of these articles, the effect of these properties on the efficiency of the solar system were investigated and the structural factors of the collector have not been taken into account. In this paper, we first studied the thermophysical properties of the nanofluid and their effects on the efficiency of the flat–plate solar collector, and then we investigated the effect of a structural factor in the collector, such as the impact of changing the pipe cross section on the efficiency of the solar collector, until obtained the effects of both factors (structural and thermophysical) on efficiency of collector. Choosing the best pipe cross section in addition to improving the collector's thermal efficiency is also economically important. In order to achieve these goals, we firstly investigated the Azmi and sharma validation with experimental results, and then calculated the collector efficiency which we had no experimental data for that. The collector efficiency is evaluated with different particle concentration and diameter of nano-fluid. Afterwards, this mode is extended to evaluate the collector efficiency for different shapes of pipe cross section. The energy balance equation is solved in MATLAB. It was observed that efficiency increases with enhancement of particle concentration. While enhancement of the diameter of spherical nanoparticles, decreases the efficiency. In addition, between different shapes of the pipe cross section, including circle, square, and triangle, circle cross sections leads to the highest efficiency in a flat-plate solar collector.

2. THERMAL PERFORMANCE OF A FLAT-PLATE COLLECTOR

The efficiency of a solar thermal receiver is the ratio of collected thermal energy ( ) to the total incident energy, which is shown in Eq. (1). The useful energy can also be expressed in terms of the energy absorbed by the absorber and the energy loss from the absorber as given by Eq (2) which is obtained by Duffie and Beckman [25]. Therefore, the instantaneous collector efficiency is obtained via Eq (3):

$$\eta = \frac{\text{usefulenergy}(Q_u)}{\text{totalincidentenergy}} = \frac{\dot{m} c_p (\bar{T}_o - \bar{T}_i)}{A_{ac} C_T} \tag{1}$$

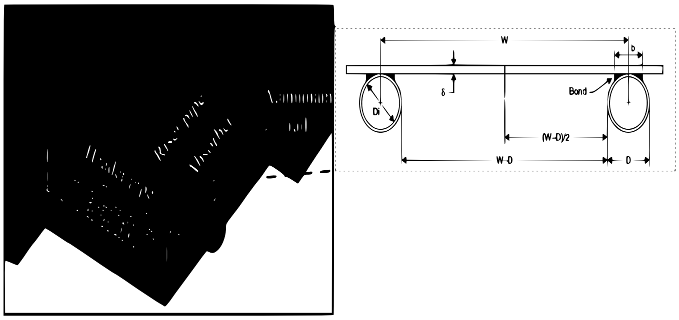

Fig. 1. Schematic of a flat-plate sheet and tube

$$Q_u = A_{Sc} F_R((G_T \iota\alpha) - U_L(T_i - T_a)) \tag{2}$$

$$\eta = \frac{\text{usefulenergy}(\text{Q}_u)}{\text{totalincidentenergy}} = F_R(\tau\alpha) - F_R U_L \frac{T_i - T_a}{G_T} \tag{3}$$

where $\dot{m}$ is the fluid mass flow rate, C_P is nano-fluid specific heat capacity, $A_S C$ is the area of the collector, F_R is the heat removal factor, G_T is the incoming solar radiation, $\iota\alpha$ is the absorptance-transmittance product, U_L is the overall loss coefficient, T_i is the inlet fluid temperature, T_o is the outlet fluid temperature of solar collector, and T_a is the ambient temperature. The absorbed solar energy is transferred to the working fluid. Heat removal factor is obtained by the product of collector efficiency factor (F') and collector flow factor (F''), which is shown in Eq. (4),Eq. (5), and Eq. (6), respectively.

$$F_R = F' \times F'' \tag{4}$$

$$F' = \frac{{}^{1}\!/_{U_L}}{W\left[\frac{1}{U_L[D+(W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{nf}}\right]} \tag{5}$$

$$F'' = \frac{\dot{m} C_P}{A_c U_L F'}[1 - \exp(\frac{-A_C U_L F'}{\dot{m} C_P})] \tag{6}$$

Fig .1 shows the schematic of a flat-plate solar collector sheet and tube. According to Fig.1, in Eq.(5, W is the distance between two parallel tubes, D is the tube outer diameter, C_b is the bond conductance which can be calculated from knowledge of bond thermal conductivity γ , the average bond thickness, and the bond width b which are presented in Eq. (7).

$$C_b = \frac{K_b b}{\gamma} \tag{7}$$

$$F = \frac{\tanh[m(W - D)/2J]}{m(W - D)/2} \tag{8}$$

$$m = \sqrt{\frac{U_L}{k\delta}} \tag{9}$$

In addition, F refers to the fin efficiency which is shown in Eq. (8). The parameter in Eq. (9) is substituted for convenience in Eq. (8) in order to obtain fin efficiency. δ and k are the sheet thickness and thermal conductivity.

Since nano-fluid is applied in this study as heat transfer agent, it influences the dimensionless parameters of collector including collector efficiency factor and collector flow factor through h_{if} and C_p. Therefore, it is necessary to evaluate thermo-physical properties of the nano-fluid. Afterwards, effects of different parameters of nano-fluid on dimensionless values of collector are obtained in order to assess thermal performance of the flat-plate solar collector.

A. Evaluation of the effect of nanoparticle on thermo-physical properties of the base fluid

Thermal conductivity of nano-fluid is one of the most effective parameters in its thermal performance. In order to calculate thermal conductivity of nano-fluid, numerous theoretical studies have been conducted dating back to the classic work of Maxwell [26]. A model was developed to determine the effective thermal conductivity for spherical particles embedded in a base medium which is shown in Eq. (10).

$$K_{nf} = K_f \left[\frac{1 + 2\varphi(\frac{1-(\frac{n_f}{K_p})}{2(\frac{K_f}{K_p})+1})}{1 - \varphi(\frac{1-(\frac{n_f}{K_p})}{2(\frac{K_f}{K_p})+1})} \right] \tag{10}$$

In the above equation, K_p and K_f are the conductivities of the particle material and the base fluid, respectively, and φ is volume fraction of nanoparticles. In order to investigate the impact of particle concentration (φ), particle size (d_p), and fluid temperature (T_{nf}) on thermal conductivity, Azmi and Sharma [27] has proposed the following equation:

$$\frac{K_{nf}}{K_W} = 0.9808 + 0.0142\varphi + 0.2718(\frac{T_{nf}}{70}) - 0.102(\frac{d_p}{150}) \tag{11}$$

Another influential parameter in heat transfer of nano-fluid is its dynamic viscosity. A comprehensive review on theoretical models and correlations related to nano-fluid viscosity was conducted by Mahbubul et al. [28]. Einstein relation [29] is labeled the pioneer for evaluating viscosity and most of other derivations have been basically established from this relation. Most of relations determine the viscosity of nano-fluid as a function of particle concentration. Azmi and Sharma model expresses nano-fluid viscosity as a function of particle concentration (φ), particle size (d_p), and fluid temperature (T_{nf}) in Eq. (12).

$$\frac{\mu_{nf}}{\mu_W} = 0.9042 + 0.1245\varphi - 0.08445(\frac{T_{nf}}{72}) + 0.6436(\frac{d_p}{170}) \tag{12}$$

In the present study, percentage of volume concentration (φ) is utilized to calculate the mixture properties of nano-fluids. Density (ρ_{nf}) and specific heat ($C_{p,nf}$) of nano-fluid are evaluated using solid–liquid mixture equation which is estimated through Eq. (13) and Eq. (14).

$$\rho_{nf} = \varphi \times \rho_p + (1 - \varphi) \times \rho_t \tag{13}$$

$$C_{p,nf} = \frac{\varphi(\rho c)_P + (1 - \varphi)(\rho C_p)_f}{\varphi\rho_p + (1 - \varphi)\rho_f} \tag{14}$$

In order to determine convective heat transfer, the following equation is applied in the study:

$$h_{nf} = \frac{NuK}{D_h} \tag{15}$$

where Nu is the Nusselt number, k is the thermal conductivity and D_h is the hydraulic diameter of the pipe.Various models are proposed for predicting Nusselt number in a tube. A complete list for evaluating nano-fluid Nusselt number is brought in Sundar study [30]. These models usually depend on particle type, particle concentration, flow regime and several other variables such as temperature. In addition, the restrictions must be considered in utilizing these models; since they are valid in specific ranges of Reynolds and Prandtl numbers. Maigaet al. [31] correlation is applied in the current study for evaluating Nusselt number in turbulent regime which is represented in Eq. (16). Reynolds and Prandtl numbers are checked while using this equation.

$$Nu = 0.085R_e^{0.71}\overset{0.35}{\text{Pr}} \tag{16}$$

Checking parameters:

$$10^4 < \text{Re} < 10^5$$

$$6.6 < \text{Pr} < 13.9$$

$$0.0 < \varphi < 10$$

Reynolds and Prandtl numbers are calculated by the following correlations:

$$\text{Re} = \frac{\rho V D_h}{\pi \mu} \tag{17}$$

$$pr = \frac{\mu C_p}{k} \tag{18}$$

where ρ is the density of the fluid, D_h is the pipe hydraulic diameter, μ is the viscosity, C_p is the specific heat capacity, and is the thermal conductivity.

B. Non-circular cross-sections

To handle non-circular cross-sections such as triangular, rectangular, the concept of hydraulic diameter D_h is applied. This parameter is defined as:

$$D_h = \frac{4A}{P} \tag{19}$$

where A is the cross-sectional area and P is the wetted perimeter. For a circular tube of diameter D and, $A = \pi D^2/4$, and $P = \pi D$ the above definition yields $D_h = D$. For turbulent flow in non-circular cross -sections, the correlations for circular tubes are utilized. Hence, while using non-circular cross-sections, the hydraulic diameter is used instead of the diameter in these correlations and the thermal performance in non-circular cross-sections can be evaluated.

3. RESULTS AND DISCUSSION

Azmi and Sharma model is applied in this study in order to evaluate thermal conductivity and viscosity of nano-fluid. To survey the precision of the Azmi and Sharma model, the results are compared with experimental data for Al_2O_2 nanoparticles solved in water. The constant parameters are shown in table. 1.

Fig. 2 demonstrates the results for thermal conductivity via temperature enhancement. The volume fraction is considered 1%. Experimental data are brought from Ref. [32,33].

Fig. 3, compares the viscosity of nano-fluid according Azmi and Sharma model with experimental data in Refs. [34,35].The temperature is considered 20 °C. The results show that Azmi and Sharma correlations are reliable models for evaluating both thermal conductivity and viscosity of nano-fluids.

Table 1. Constant parameters for evaluating thermo-physical properties of nanofluid

Material	Viscosity (Pa.S)	Thermal conductivity $W.m^{-1}k^{-1}$	Specific heat $J.Kg^{-1}k^{-1}$	Density kg/m^2
Water	89×10^{-4}	0.610	4181	997.3
Al_2O_2		36	890	3950

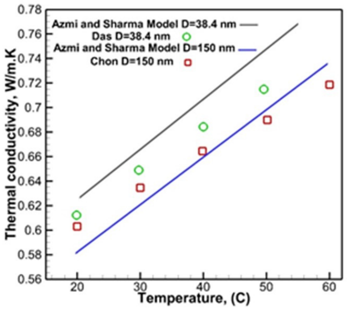

Fig. 2. Comparing the thermal conductivity of nano-fluid through Azmi model with experimental data.

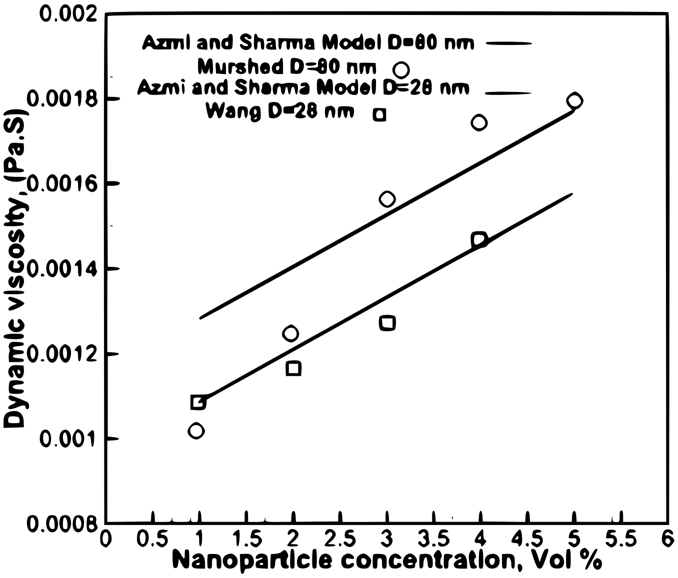

Fig. 3. Comparing the viscosity of nano-fluid through Azmi model with experimental data.

A. Evaluating collector efficiency

In this part, calculations are conducted for 15 nm spherical nanoparticles. In order to explore the effect of particle volume concentration on collector efficiency, the properties are assumed for alumina nanoparticles and water as base fluid. Azmi and Sharma models are applied to determine viscosity and thermal conductivity. The specifications of parameter which are used in this research are presented in table 2.

Fig. 4 shows the variation in collector efficiency as a function of the particle volume fraction. The particle volume fraction varies in the range 0.0% to 1% in these calculations. It can be observed from this figure; the collector efficiency increases rapidly

Table 2. Specification parameters for evaluating collector efficiency using nanofluid

Specification	Dimension/ Value	Unit
Diameter of Al2O3 nanoparticle	15	Nm
particle volume fraction (φ)	0.0 to 1	%
The particle sizes	20-80	nm
mass flow rate	0.07	kg/s
area of the collector	2	m^2
Solar irradiation	800	W/m^2
distance between two parallel tubes (w)	100	mm
the tube outer diameter (D)	10	mm
absorber thickness (δ)	1	mm
bond conductance (C_p)	100	W/m.K

with volume fraction and tends to reach a maximum value of around 80% near the upper limit.

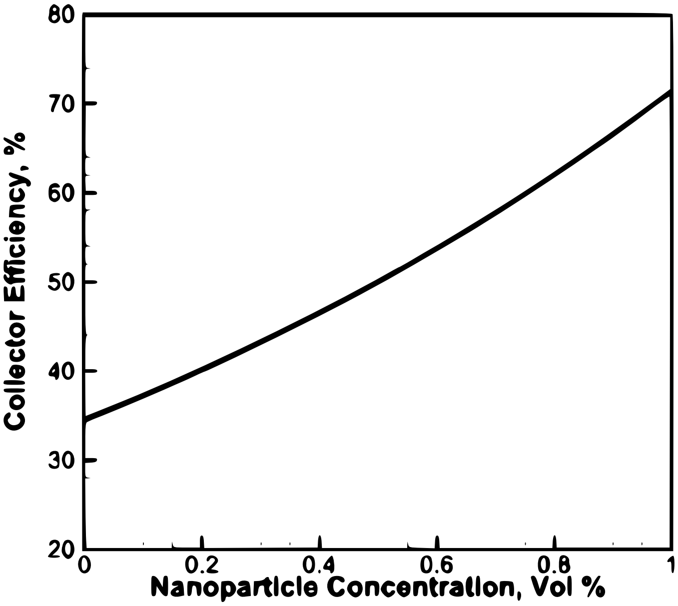

Fig. 4. Collector efficiency as a function of particle concentration.

The variation in the collector efficiency as a function of the particle size is presented in Fig. 5. In this part, the collector efficiency is evaluated in a constant particle volume fraction. The particle volume fraction is considered 0.7 %. The particle sizes in these calculations varied from 20 nm to 80 nm. This figure shows that reducing the particle size leads to an even enhancement in efficiency. In this model, with decreasing the particle size, the thermal conductivity of the suspension enhances. Due to this fact, collector efficiency enhances by decreasing the particle size.

B. Evaluating collector efficiency for non-circular cross-sections

In order to investigate the effect of non-secular cross-sections, the thermal performance of circular pipes are compared with triangle and square cross sections. In this case, a constant mass flow rate for three cross-sections is considered. Hence, the cross-sections for the three shapes have the same area. The diameter for the circle cross-section is considered 10mm. All other parameters are the same data as represented in table 2. The parameters related to the geometry of the equilateral triangle and square cross-sections are shown in table. 3.

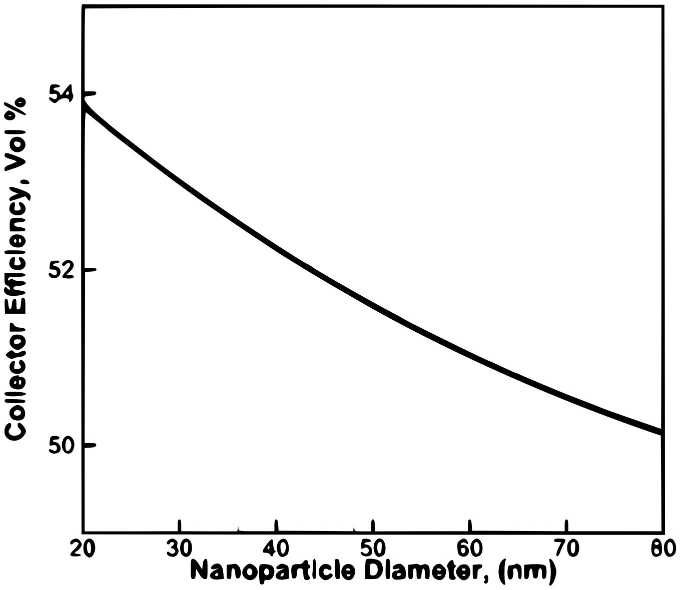

Fig. 5. Collector efficiency as a function of particle diameter.

Table 3. Parameter related to the geometry of the cross-section

Cross-section shape	Area (m^2)	Perimeter (m)	Hydraulic diameter(m)
Circle	7.85×10^{-5}	0.0314	0.01
Square	7.85×10^{-5}	0.0354	0.0089
Equilateral triangle	7.85×10^{-5}	0.0404	0.0078

Fig. 6 demonstrates the collector efficiency for three different pipe cross-sections as a function of particle concentration. Based on obtained results, circular cross-section leads to the highest efficiency in the solar collector and the equilateral triangle cross section has the minimum efficiency in the solar collector. In the corner of square and triangle cross-sections, the velocity of fluid flow is very low. Hence, the value of Nusselt number decreases drastically in the corners and reduction in the rate of heat transfer is expected. This effect leads to reduction in collector efficiency for the cross-sections with corners.

4. CONCLUSION

Using nano-fluids as working fluid in a solar collector has been demonstrated here to offer unique advantages over conventional fluids. The influences of various parameters, such as nanoparticle size, volume fraction, and shape of the pipe cross-section on the flat-plate collector efficiency are studied. For spherical alumina nanoparticles, the collector efficiency enhances by increasing particle volume fraction. Moreover, according to the obtained results, in constant volume fractions of nanoparticles, the increase in particle size causes reduction in the collector efficiency. Results show that for different shapes of the pipe cross-section including circle, square, and equilateral triangle, the circular cross-sections has the highest efficiency in a flat-plate solar collector. In addition, as the Nusselt number decreases

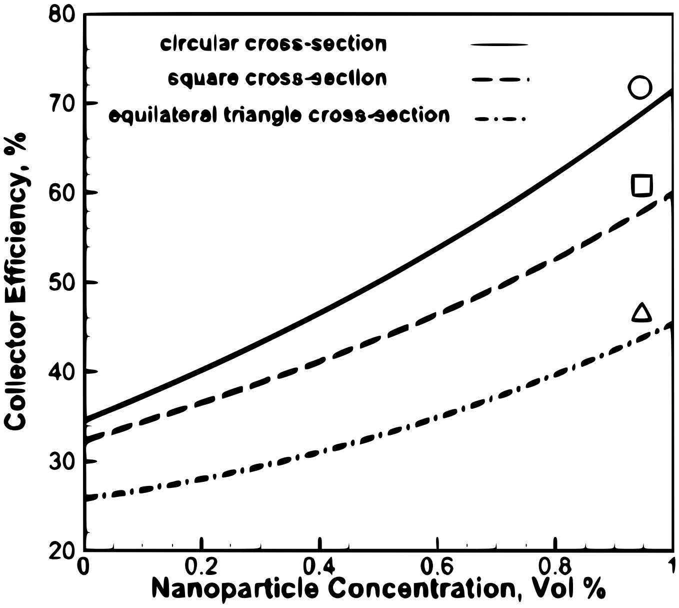

Fig. 6. Collector efficiency for different pipe cross-sections as a function of particle concentration.

drastically in the corners of square and triangle shape cross-sections, heat transfer reduces in these cross-section shapes.

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