Theoretical analysis to determine the efficiency of a CuO-water nanofluid based-flat plate solar collector for domestic solar water heating system in Myanmar

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A B S T R A C T

The efficiency of a flat plate solar collector using water based CuO nanofluid as a working fluid is analyzed theoretically. A mathematical model and a program, written in MATLAB code were used for calculating the efficiency of a flat plate solar collector for a domestic solar water heating system considering weather conditions of a city in Myanmar. This calculation includes three aspects. Firstly, the maximum solar energy availability for the flat plate solar collector tilted at the optimum angle was estimated. Secondly, the convective heat transfer coefficient of nanofluid was calculated as a function of volume concentration and size of the nanoparticle. Thirdly, the overall heat loss coefficient of the flat plate solar collector was calculated using a method of iteration. Through these calculations, the collector efficiency was obtained as a function of volume concentration and size of the nanoparticle. The results showed increasing in collector efficiency by increasing the volume concentration up to 2% while the effect of nanoparticle size on the efficiency was marginal. The use of the CuO-water nanofluid as a working fluid could improve the efficiency of flat plate solar collector up to 5% compared with water as a working fluid under the same ambient, radiant and operating conditions.

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1. Introduction

Energy consumption in building sector has been rising due to the increase in global population. Parts of the major energy consumption in building sector are space heating, air-conditioning, and water heating systems. Hot water demand in various applications contributes an important proportion of energy consumption in building sector. Most of the water heating systems rely on the electric power which is generated by the burning of fossil fuels (e.g., natural gas and coal). Due to increasing demand for energy, many types of research have been carried out to exploit renewable energy sources alternative to fossil fuels. Solar energy stands out from other available alternatives energy sources for desirable environmental and safety aspects. One of the most simple and direct applications of solar energy is the conversion solar radiation into heat energy. So, water heating systems have become popular in utilizations of solar energy. Solar water heating system without any fuel costs is not only the key solution for reducing building energy consumption but also for the well-intentioned environmental benefit. However, current solar water heating systems (SWHSs) are not yet commercial because of its cost and installation as the overall size is bigger compared to electric water heaters (EWHs). Moreover, the efficiency is also low. But probably saving the operating cost in the long run and reducing the environmental impact raised by the conventional water heaters leads to the use of SWHSs for heating water in both residential and industrial sectors.

SWH systems are generally very simple in operation as only solar radiation is used to heat domestic water. The major component of an SWH system is the solar collector that captures the incoming solar radiation and converts it into heat and then transfers that heat to a working fluid flowing through the collector tube. Then the heated working fluid transfers the heat into the domestic water in a storage tank for any application as desired (Kalogirou, 2004). Because of this working principle, the performance of solar collector strongly influences the performance of the SWHSs. The higher performance of the solar collector can give a better performance of a solar water heating system. In order to operate at high efficiency, firstly the collector has to maximize the absorption of incident solar radiation and secondly it has to keep the useful thermal gain much higher than the thermal losses from it (Eisenmann et al., 2004).
Among various types of solar collectors, flat plate solar collector is the most intensively used type of collectors for domestic solar water heating and solar space heating applications where low and medium temperature are required (Kalogirou, 2003). Flat plate solar collector is simple in design, low in cost, easy to construct and requires little maintenance. However, it has relatively low efficiency compared to other types of collectors because some major drawbacks limit the efficiency of this collector. One of them is high thermal losses (from the absorber plate to the surrounding) because of the absence of optical concentration and the presence of larger area from where heat is lost (Bhatt et al., 2011). Other is the use of conventional working fluids such as water, ethylene glycol and oil which are inherently poor heat transfer fluids. The poor heat transfer properties (absorption properties) of these fluids obstruct the effectiveness of heat transfer to the fluid. These drawbacks cause the reduction in efficiency of the collector. Therefore, there are still continuous efforts to improve the efficiency of the flat plate solar collectors.

Enhancement of energy collection by the collector can compensate the heat losses from the collector. In the case of flat plate solar collector, the collected energy can be maximized by setting its angle of tilt with the horizontal (with respect to the ground) in an optimum position for a particular day or a specific period. As flat plate solar collector is always installed in a fixed position, the solar radiation received by the collector and the heat losses from the collector vary with its tilt angle with the horizontal (Morcos, 1994; Elminir et al., 2006). Thus, the accurate determination of the optimum tilt angle and to adjust this tilt angle from time to time is essential for maximizing energy collection. The optimum tilt angle can be adjusted for various specified period and this adjustment depends on the location and the operational limitations. For example, some studies have been made on the tilt angle of the flat plate solar collectors and reported that the optimum tilt angle is almost equal to the value of latitude angle of the relevant location when the optimum tilt angle is adjusted once in a year. However, some other studies recommended two times adjustment in a year, one is for summer and another one is for a winter season. Whereas some studies reported that the daily adjustment of optimum tilt angle gives the maximum receiving energy rather than the monthly, seasonal and annual adjustments (Moghadam et al., 2011).

In addition, enhancement of heat transfer in solar collectors can improve the thermal performance. Augmenting heat transfer (from the absorber to the fluid flowing inside the collector tube) can enhance heat transfer in the solar collector. The higher the heat transfer to the fluid, the higher is the heat transfer coefficient of fluids \( h_0 \) and the lesser is the overall heat loss coefficient \( U_0 \). Overall, the collector efficiency factor \( F' \) would be increased. This leads to more useful heat gain and consequently the better efficiency would be obtained (Duffie and Beckman, 2013). In this regard, one of the simple methods for augmenting the heat transfer to the fluid is to use working fluids with advanced heat transfer properties. As nanofluids are the suspension of metallic or non-metallic nanoparticles with a diameter smaller than 100 nm in a base fluid, they have higher thermal conductivities when compared to the thermal conductivities of base fluids such as water, oil, and ethylene glycol (Choi, 1995; Wang et al., 1999; Eastman et al., 2001). The high thermal conductivity fluids could gain more heat from the collector absorber and reduce the heat losses from the absorber to the surrounding.

Over the last few years, some research works have been made on the solar thermal collector augmented with nanofluids to improve the efficiency, to obtain the smaller size and to compact the design (Faizal et al., 2013). Tyagi et al. (2009) carried out a theoretical investigation using \( \text{Al}_2\text{O}_3 \)/water nanofluid on the direct absorption solar collector (DASC) and observed that the collector’s efficiency increased significantly not only by varying the particle volume fraction but also the glass cover transmittance and collector height. Taylor et al. (2011) investigated experimentally graphite/thermoplastic VP-1 nanofluids on 10–110 MW solar power tower collector and observed 5–10% improvement in efficiency while using the nanofluids in the receiver section. Otanicar et al. (2010) carried out experimental and numerical studies by using nanofluids (Carbon Nanotube, Graphite & Silver) on direct absorption solar collectors (DASC). Their results showed that nanofluids improved the efficiency up to 5%. Khullar et al. (2012) investigated thermoplastic VP-1 based aluminum nanofluid with 0.05% volume concentration both theoretically and experimentally on concentrating parabolic solar collector (CPSC). Their results showed 5–10% increase in thermal efficiency when compared with the conventional CPSC. He et al. (2011) studied experimentally two different nanofluids (\( \text{TiO}_2 \)/water & CNT/water) on vacuum tube solar collector in different weather patterns. The results showed the temperature of CNT/water nanofluid to be higher and the CNT/ water nanofluid was more suitable for vacuum tube solar collector application. Lu et al. (2011) observed 30% increase in thermal performance of evacuated tubular solar collector using \( \text{CuO} \) nanofluid instead of water only. There is a very limited number of research works in the area of a flat plate solar collector (FPSC) using nanofluids as a working fluid for augmenting the collector performance. Yousefi et al. (2012a, 2012b) investigated experimentally the effect of Multi-Wall Carbon Nanotube (MWCNT)-water and \( \text{Al}_2\text{O}_3 \)-water nanofluid with Triton X-100 as a surfactant on the efficiency of flat plate solar collector. Their results have shown a substantial increase in the efficiency of flat plate solar collector by increasing the weight fraction of MWCNTs from 0.2% to 0.4% while there is the increase in 28.3% efficiency with 0.2% weight fraction of \( \text{Al}_2\text{O}_3 \)-water nanofluid.

The review of the literature shows that the tilt angle change of solar radiation falling on the collector surface is related to the local climatic condition, geographic latitude and the period of its use. Hence, different locations will have different optimum tilt angle for a yearly used solar collector. Likewise, the thermo-physical properties change of nanofluid mainly depends on the volume concentration and size of the nanoparticle as well as on operating temperature of nanofluids. Therefore, it is necessary to predict the optimum operating parameters, like optimum tilt angle for maximizing solar incident and optimum volume concentration and size of nanoparticle for the preparation of nanofluid in order to maximize the efficiency of the nanofluid-based solar thermal collector. The prime focus of this study is the use of the \( \text{CuO} \)-water nanofluid as a working fluid in a flat plate solar collector installed at the optimum tilt angle for a domestic solar water heating system. The attention is focused on analyzing theoretically the maximum enhancement in efficiency of a \( \text{CuO} \) nanofluid based flat plate solar collector. The analysis has been based on total solar radiation reaching the collector absorber plate, heat transfer of working fluid (with respect to the thermo-physical properties of \( \text{CuO} \)/water nanofluid), and overall heat losses from the collector (with respect to the tilt angle of the collector).

2. Parameter estimation methodology

This study considers that the efficiency of FPSC depends mainly on three main parameters which are (i) incident solar radiation on tilted surface, (ii) convective heat transfer coefficient of working fluid (nanofluid) flowing through the tubes in the collector and (iii) overall heat loss from the collector. A mathematical model and a MATLAB based simulation program were used for evaluating these parameters to ascertain the collector efficiency. The first
attention is focused to find the optimum tilt angle for a flat plate solar collector facing south in Taunggyi, a city of Myanmar, on the basis of maximizing the total solar radiation ($I_T$) falling on the collector surface over a specific period of time. The second attention is focused on the evaluation of convective heat transfer coefficient ($h_{fi}$) of a water based CuO nanofluid flowing inside the tube of the flat plate solar collector as the working fluid. The convective heat transfer coefficient is computed through the Nusselt number of nanofluids as a function of nanoparticle volume concentration and size. Then, the thermal losses (described by collector overall heat loss coefficient, ($U_L$) from the collector tilted at the optimum position was calculated considering the operating and ambient temperature for the coldest winter month of the year. Once the values were obtained, they were used to compute the theoretical efficiency of the flat plate solar collector using MATLAB program is shown in Fig. 1.

2.1. Estimation of total solar radiation on tilted surface, $I_T$

Liu and Jordan (1963) considered the total solar radiation on the tilted surface, $I_T$, as the sum of beam radiation, isotropic diffuse radiation, and solar radiation diffusely reflected from the ground and obtained the equation for an hour as follows:

$$I_T = I_bR_b + I_d\left(\frac{1 + \cos \beta}{2}\right) + I_{qg}\left(\frac{1 - \cos \beta}{2}\right)$$

(1)

where $\beta$ is the tilt angle of collector, $\rho_g$ is the diffuse ground reflectance factor (which is equal to 0.2 for bare ground) and the beam radiation on horizontal surface is given by $I_b = I - I_d$. The geometric factor, $R_b$, for the collector surfaces in the northern hemisphere tilted toward the equator (surface azimuth angle $\gamma = 0$) and the diffuse radiation on horizontal surface, $I_d$, dependent of the clearness index, $k_T$, are determined according to the relations given in reference (Duffie and Beckman, 2013; Erbs et al., 1982). The total solar radiation on the horizontal surface, $I$, can be expressed as follows:

$$I = H \times \frac{\pi}{24} (a + b \cos \omega) \times \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \frac{\pi}{180} \cos \omega_s}$$

(2)

where constants are given by $a = 0.409 + 0.5016 \sin(\omega_s - 60)$; $b = 0.6609 - 0.4767 \sin(\omega_s - 60)$; hour angle $\omega = \pm (360/24) t$ and sunset hour angle $\omega_s = \cos^{-1}(\tan \phi \tan \delta)$ where $\phi$ and $\delta$ are site latitude angle and solar declination angle. The monthly mean daily solar radiation intensity on a horizontal surface, $H$, is estimated according to the Rietveld model (Rietveld, 1978) which is believed to be applicable anywhere in the world.

![Fig. 1. Calculation process flow chart.](image-url)
For optimum tilt angle, $\beta_{opt}$, which gives the maximum solar radiation on the flat plate solar collector in a specific period, the derivative of $I_t$ with respect to $\beta$ must be zero, i.e. $dI_t/d\beta = 0$. In this study, the $\beta_{opt}$ calculation was based on maximizing the solar radiation reaching on a tilted collector surface using the Morcos model (Morcos, 1994) and is given by:

$$
\beta_{opt} = \tan^{-1}\left(\cos\gamma\cos\delta \sin\phi \cos\omega - \sin\delta \cos\phi / [\cos\delta(1 - \rho_p)] \times \cos\theta_i/2\tau_t - \rho_p \cos\theta_i/2 + \sin\delta\sin\phi + \cos\delta \cos\phi \cos\omega\right)
$$

(3)

where the transmission coefficient for beam and diffusion radiation are given by $T_t = a_0 + a_1 \exp(-k/cos\theta_i)$; $\tau_t = 0.2710 - 0.2939\tau_t$ where constants $a_0$, $a_1$, and $k$ are determined according to the relations given in reference (Morcos, 1994) and the angle of incident of the beam radiation on the horizontal surface, $\theta_i$ is given by $\cos\theta_i = \cos\delta \cos\phi \cos\omega + \sin\delta \sin\phi$ (Duffie and Beckman, 2013).

Using the above relations, maximum total solar radiation on an optimum tilted surface is calculated for the specific days of the year. The collector location considered in this study is at Taunggyi city, Myanmar (Latitude = 21°47'N, Longitude = 97°1’E, Altitude = 1436 m above sea level.

### 2.2. Estimation of convective heat transfer coefficient, $h_f$

Once the solar radiation is incident on the collector absorber plate, it raises the temperature of the absorber plate above the ambient temperature and the process of heat loss from the absorber to the surrounding starts. If the working fluid flowing inside the collector tubes removes too much heat, the temperature of the absorber decreases, and reduces heat loss. Therefore, it is useful to know the characteristic of heat transfer to the fluid for the simulation of the collector performance. Convective heat transfer takes place whenever a fluid contacts with a solid surface due to the temperature difference between the surface and the fluid. The convective heat transfer coefficient of fluid flowing inside a circular tube can be calculated from the equation of dimensionless Nusselt number as follows:

$$
h_f = \frac{Nu_k}{D_i}
$$

(4)

In the above equation, $h_f$ is the heat transfer coefficient, $Nu$ is the Nusselt number, $k$ is the thermal conductivity of the fluid flowing in the tube and $D_i$ is the inside diameter of the tube. In general, Nusselt number is related to the dimensionless Reynolds number and Prandtl number. For the pure fluid flowing in a tube in the laminar and turbulent region, the correlations for the estimation of Nusselt numbers are as follows (Yunus, 1998):

$$
Nu = 3.66 \quad \text{(Fully developed laminar flow)}
$$

(5)

$$
Nu = 0.023Re^{0.8}Pr^{0.4} \quad \text{(Turbulent flow)}
$$

(6)

Li and Xuan (2002) proposed the general form of Nusselt number relating to nanofluids for a laminar ($Re < 2300$) and turbulent flow ($Re > 2300$) by the following relations:

$$
Nu_{nf} = 0.4328(1 + 11.285\phi_p^{0.754}Re_d^{0.218}Pr_{nf}^{0.333}k_{nf}^{0.4}) \quad \text{(For laminar flow)}
$$

(7)

$$
Nu = 0.0059(1 + 7.62866\phi_p^{0.6886}Re_d^{0.001}Pr_{nf}^{0.9228}k_{nf}^{0.4}) \quad \text{(For turbulent flow)}
$$

(8)

In the above equations, the dimensionless numbers are given by Reynolds number $Re = \nu \rho_d D_i / \mu_d$; Prandtl number $Pr = \nu \rho_d C_p / k_d$; Peclet number $Re_d = \nu D_i / \lambda_d$ where $V$ is the mean flow velocity, $d_p$ is the diameter of nanoparticle, $\mu_d$ and $C_p$ are the dynamic viscosity and specific heat capacity of nanofluid respectively.

The regression equation for nanofluid thermal conductivity, considering the particle size, concentration and temperature applicable for $3 < d_p < 170\, \mu m$, $0 < \phi_p < 0.03$, $15 < T_{nf} < 72\, ^\circ C$ is given by:

$$
\kappa_{nf} = \kappa_w \left(0.93042 + 0.1245\phi_p - 0.08445 \frac{T_{nf}}{70} + 0.6436 \frac{d_p}{170}\right)
$$

(9)

The regression equation for nanofluid specific heat, considering the particle volume concentration and temperature applicable for $0 < \phi_p < 6\%$, $20 < T_{nf} < 70\, ^\circ C$ is given by:

$$
C_{pnf} = C_{pw}(1.036 - 0.0298\phi_p - 0.07261 \frac{T_{nf}}{70})
$$

(11)

where the subscript w and n refer to water and nanofluid respectively and the physical properties of water ($\rho_w, \mu_w, k_w, C_{pw}$) are determined using the regression equations in Table 1 (Azmi et al., 2010). Using the above relations, the thermo-physical properties of nanofluid defining the dimensionless numbers ($Re, Pe, Pr, k_d, \kappa_{nf}$) were calculated as a function of particle volume concentration for different nanoparticle sizes in a nanofluid. These dimensionless numbers are used to obtain the convective heat transfer coefficient, $h_f$, of nanofluid.

### 2.3. Estimation of overall heat loss coefficient, $U_t$

The distributions of absorbed solar energy on the collector absorber plate are the useful energy gain by the working fluid and the thermal losses from the absorber plate. These losses cause the reduction of the collector efficiency. If all losses occur to a common sink temperature, $T_s$, the overall heat losses coefficient, $U_t$, is the sum of top, bottom and edges coefficients and can be obtained by the following correlation (Duffie and Beckman, 2013) :

$$
U_t = U_t + U_b + U_e
$$

(12)

where $U_b = \kappa_{ins} / \delta_{ins}$, the back heat loss coefficient considering heat loss due to conduction through the back insulation of the solar collector; $U_e = (\kappa_{glass} / \delta_{glass})$, the edge heat loss coefficient based on the collector area, $A_c$, assuming the heat loss is due to one-dimensional sideways heat flow around the perimeter of the collector. The major heat loss of the collector is from the top through the glass cover when compared to bottom and edges losses. The top heat loss coefficient, $U_t$, is considered as the heat losses due to convection and radiation from the absorber plate (Klein, 1975):
The collector efficiency is defined as the ratio of the actual useful energy gain over a specific period of time to the incident solar energy over the same period. This actual useful energy gain is equal to the collector heat removal factor, \( F_K \), times the maximum possible useful energy gain. The factor \( F_K \) is a quality relating the actual energy gain of a collector to the useful heat gain if the whole collector surface were at the fluid inlet temperature and it can be determined according to the relation given in reference (Duffie and Beckman, 2013). Knowing the overall heat loss coefficient and the collector heat removal factor, the mean plate temperature, \( T_{pm} \), can be calculated by the relation given in reference (Duffie and Beckman, 2013). The obtained value is compared with the initialized mean plate temperature. The iterative calculation process is necessary until \( T_{pm} \) is closed to the initial value to obtain the final value of \( U_I \) and \( F_K \) for estimating the thermal efficiency of the flat plate solar collector. Finally, the thermal efficiency of the flat plate solar collector can be computed by the following equation:

\[
\eta = \frac{Q_w}{I_T (T_2 - T_1)} = F_K (T_2 - T_1) U_I \frac{(T_1 - T_2)}{I_T}
\]  

(15)

For a given solar collector and operating conditions, the collector efficiency varies only with heat removal factor, \( F_K \) and overall heat loss coefficient, \( U_I \). So that the efficiency is obtained as a function of particle volume concentration and particle size of nanofluid.
daytime for the average day for the months of June and July are observed to be negative. When the tilt angle is negative, the collector is facing the north and when it is positive, the collector is facing the south. The hourly optimum tilts angle for the month of September remains almost constant throughout daytime which is approximately equal to the latitude angle.

3.1.2. Hourly total solar radiation on optimum tilted surface

The total solar radiation on the south-facing flat plate solar collector for an hour, tilted with the optimum tilt angle \((\beta = \beta_{opt})\) at solar noon, was computed for the average day for each month in the year using the standard solar data of Taunggyi city. The set of Eqs. (1)–(3) was used in the MATLAB program for this computation. Fig. 3 shows that the variation of hourly total solar radiation, \(I_{T,T}\), on optimum tilted surface for the average day of each month. The value of total solar radiation increases with daytime and reaches its peak value at solar noon. The highest total solar radiation (3.8 MJ/m² h) occurs in March at noon, and the lowest one is 1.8 MJ/m² h in July at noon.

3.1.3. Monthly total solar radiation on tilted surface

The optimum tilt angle, \(\beta_{opt}\), for each month was calculated by finding the average value of the hourly optimum tilt angles for the average day for each month in the year. The solid line in Fig. 4 shows the variation of \(\beta_{opt}\) for each month in the year. The optimum tilt angle for a flat plate solar collector facing south is 56° in December. The optimum tilt angles for the month of May to August are observed to be negative values. According to the results, the collector must be set north facing during those months. In this study, all the negative values of the optimum tilt angle were considered zero (horizontally). This is due to the fact that the practical orientation for the collector installed in the northern hemisphere is south facing with the positive tilt angle. The monthly optimum tilt angles were used for estimating the monthly total solar radiation, \(I_{T}\), for an hour on the tilted collector surface and results show the bar graph in Fig. 4. The maximum monthly total solar radiation occurs in March (summer month) with the tilt angle of 26° and the value of 2.44 MJ/m² h. The minimum one occurs in July and August (rainy months) with the tilt angle of 0° and the value of 1.3 MJ/m² h.

3.2. Convective heat transfer coefficient, \(h_{fi}\)

The heat transfer coefficient is calculated, using Eq. (4), and plotted in relation to the particle volume concentration in nanofluid. In this calculation, the nanoparticle volume concentration of \((0 < \phi_p < 4\%)\) and nanoparticle size of \((20 < d_p < 150 \text{ nm})\) are considered variables. The properties of CuO material for the
water-based CuO nanofluid are considered according to Table 3 given in the reference (Abouali and Ahmadi, 2012). These properties are assumed to be constant at the operating temperature of the collector considered in this study. With the increase in particle volume concentration from 0.1 to 3.5%, the nanofluid density increases from 990 to 1177 kg/m³ whereas for the specific heat of nanofluid the value decreases from 4070 to 3646 J/kg m³ as shown in Figs. 5 and 6. The figures also suggest that both value of density and specific heat does not change with varying particle size. Fig. 7 illustrates the thermal conductivity of nanofluid variation with the particle volume concentration in the range of 0.1–3.5% for different particle diameters (20, 30, 60, 90, 120, 140 nm). The thermal conductivity of nanofluid increases as the particle volume concentration increases in the base water but decreases as the size of nanoparticle increases. The maximum value of 0.8082 W/m K occurs at 3.5% particle volume concentration with the particle diameter of 25 nm. From Eq. (9), the viscosity of nanofluid is computed for various particle sizes and plotted as shown in Fig. 8. The figure depicts that as the volume concentration increases, the viscosity of the nanofluid increases; it also increases with respect to increasing diameter of nanoparticle in the base water. The viscosity value for 3.5% CuO nanofluid with the particle diameter of 140 nm is 0.8540 x 10⁻³ kg/m s. Fig. 9 shows the value of convective heat transfer coefficient range of 201–1540 W/m² K with varying volume concentration (0.1–3.5%) and particle diameter (i.e. 25 nm, 30 nm, 60 nm, 90 nm, 120 nm and 140 nm). The heat transfer coefficient was found to be a strong function of the volume concentration compared to the particle diameter. The increase in heat transfer coefficient with varying particle diameter is more obviously at higher particle concentration than lower one.

### 3.3. Overall heat losses coefficient, \( U_t \)

The specifications of the selected design condition for the flat plate solar collector listed in Table 2 were used in Eqs. (12) and (13) for computing overall heat loss coefficient of the flat plate solar collector in this study. The mean plate temperature, \( T_{pm} \), is the only variable for the overall heat loss coefficient, \( U_t \), especially for the top loss coefficient, \( U_t \), when the other factors are constants for the given flat plate solar collector. The overall heat loss coefficient was calculated for the month of December, the coldest winter month with lowest average ambient air temperature (8°C) and average wind speed (1 km/h). The mass flow rate of the nanofluid flowing through the absorber tubes was 0.02 kg/s, the recommended test flow rate for liquid flat plate collector and an initial guess for the mean plate temperature \( T_{pm} \) was \( T_f + 10°C \) (Duffie and Beckman, 2013). Fig. 10 presents the overall heat loss coefficient of the collector versus the particle volume concentration as a function of particle size in the nanofluid. It was found that the overall heat loss coefficient of the collector decreases with increase in volume concentration of nanoparticle in nanofluid up to 2% of volume concentration. Further increase in volume concentration elevates the overall heat loss coefficient of the collector. The minimum value of overall heat loss coefficient occurs at 2% volume concentration of nanoparticle for all particle sizes. However, the nanofluid loading with a smaller particle size has higher heat loss of the collector than with a larger particle size.

### 3.4. Collector efficiency, \( \eta \)

The heat transfer coefficient, \( h_p \), and the overall heat losses coefficient, \( U_t \), were used to obtain the collector efficiency factor, \( F' \), and the heat removal factor, \( F_k \). The variation of the collector efficiency factor, \( F' \), with the particle volume concentrations for different particle sizes is presented in Fig. 11. The factor \( F' \) increases more rapidly at lower volume concentration loading in the nanofluid (i.e. 0.1–0.5%) than the higher one. It was also observed that the larger the particle diameter, the higher the collector efficiency factor. However, it is clear from the plot that the increase in collector efficiency factor due to increase in nanoparticle size is marginal compared to increasing in particle concentration. The heat removal factor, \( F_k \), is plotted in relation to particle volume concentrations.
Fig. 5. Variation of the density of CuO nanofluid with the particle volume concentration for different particle diameters.

Fig. 6. Variation of the specific heat of CuO nanofluid with the particle volume concentration for different particle diameters.

Fig. 7. Variation of the thermal conductivity of CuO nanofluid with the particle volume concentration for different particle diameters.
Fig. 8. Variation of the viscosity of CuO-nanofluid with the particle volume concentration for different particle diameters.

Fig. 9. Variation of the heat transfer coefficient of CuO-nanofluid with the particle volume concentration for different nanoparticle diameters.

Fig. 10. Variation of overall heat loss coefficient with volume concentrations for different particle sizes.
for various particle sizes as shown in Fig. 12. It is noticeable that the increases in the factor $F_R$ with increasing particle concentration loading peaks at 2% of volume concentration and gradually drops after 2% volume concentration. As the particle diameter increases (for the same volume concentration), the factor $F_R$ increases slightly. The maximum value of heat removal factor is found to be around 0.946 at a volume concentration of 2% with 140 nm particle diameter in Fig. 12.

The temperature difference $(T_i - T_a)$ and total solar radiation, $I_T$, were assumed constants in estimating the collector efficiency for the selected month (December). Therefore, the collector efficiency in Eq. (15) is a function of the two parameters, the absorbed energy parameter $F_a(\tau \xi)$ and the removed energy parameter $F_R U_L$ in this study.

Fig. 13 displays the variation of collector efficiency $\eta$ with volume concentration of nanoparticles for different particle sizes in the nanofluid. The collector efficiency increases with increase in particle concentration in nanofluid up to 2% of volume concentration (for the same particle size) and gradually diminishes after 2% volume concentration. This phenomenon is due to the increase in the overall thermal loss coefficient of the collector $U_L$ at higher volume concentration as depicted in Fig. 10. Also, the collector efficiency curves of all particle loadings have shown that, a larger particle diameter provides higher collector efficiency than that of a smaller diameter in nanofluid. Fig. 13 suggests that for maximum collector efficiency, a 2% volume concentration of nanoparticle is optimal loading in the nanofluid. The minor collector efficiency changes with respect to particle sizes. It is observed that the efficiency of the water based CuO-nanofluid collector is higher than that of water as a working fluid. The comparative result of $F_R U_L$ and $F_a(\tau \xi)$ for the CuO nanofluid and the water in Table 3 revealed that the collector efficiency is increased by 5%: by using of 2% CuO nanofluid with 25 nm particle diameter as a working fluid.

Based on the results, it has been found that the enhanced heat transfer of flat plate solar collector by the use of nanofluid is the one of the driving factors for improved collector efficiency in solar water heating application. Heat transfer enhancement in collector, in turn, increases collector efficiency leading to a smaller and compact design of solar collector. It will then reduce the cost and energy needed to manufacture the solar collector due to reduction of the material usage, cost and energy required in manufacturing (Faizal et al., 2013). This trend could cause the initial cost of a DSWH system to decrease, further decreasing payback period can be achieved compared to that of the conventional DSWH system.
water storage tank or building water supply system. Fluid as one of the heat exchanger fluids can transfer heat to the storage tank or integrated with the building, a separate circulation loop of nanofluid is essential. This may be achieved by having heat exchanger where nanofluid cannot be directly connected to either the water storage tank or integrated with the building, a separate circulation loop of nanofluid is essential. This may be achieved by having heat exchanger where nanofluid as one of the heat exchanger fluids can transfer heat to the water storage tank or building water supply system.

4. Conclusion

The efficiency of the CuO-water nanofluid based flat plate solar collector for domestic water heating application was analyzed theoretically. This analysis has been performed for the given flat plate solar collector with the operating conditions for the coldest winter months of the location of interest. Based on the study, the following conclusion can be drawn:

- Hourly optimum tilt angles, \( \beta_{opt,h} \), for the average day of each month in the year were determined for Taunggyi city (Latitude = 20°47'N), Myanmar. The monthly optimum tilt angle for the collector changes throughout the year, it is to notice that the monthly optimum tilt angle is the average of the hourly optimum tilt angles for the average day of each month in the year. The monthly optimum tilt angles are found to be negative for the months of May to August and they are considered zero for the south facing solar collector. The monthly optimum tilt angle for December, the coldest winter month of Taunggyi city, is found to be 56° where the total solar radiation incident on the collector surface obtained for an hour is 1.74 MJ/m².
- The monthly total solar radiation, incident on the collector surface south facing, changes throughout the year with its maximum value of 2.44 MJ/m² h in March (summer month) and minimum value of 1.3 MJ/m² h in July and August (rainy month).
- With the mass flow rate of 0.02 kg/m² s, the Reynolds number of laminar value of less than 2300 is observed. The convective heat transfer coefficient increases with increasing volume concentration and size of nanoparticle in nanofluid.
- The overall heat loss coefficient decreases with increase in volume concentration of nanoparticle in nanofluid up to 2% of volume concentration. Further increase in volume concentration causes the heat loss to increase. This may be due to the relative heat absorption rate of the nanofluid, flowing inside the tube at the mass flow rate of 0.02 kg/m² s, peaks at around 2% particle volume concentration loading in the nanofluid. It is observed that the larger the nanoparticle sizes in the nanofluid, the lower the heat loss in the collector.
- With the increase in volume concentration of nanoparticle in the nanofluid, the collector efficiency factor \( \text{REC} \) is observed to increase in the range of 0.9752–0.9935. Meanwhile, the increases in the factor \( \text{FR} \) with increasing particle concentration loading peaks at 2% of volume concentration and gradually drops after 2% volume concentration due to higher heat losses.
- The collector efficiency near its maximum value is found when the value of overall heat loss coefficient and heat removal factor is at its minimum and maximum. It is observed that a 2% volume concentration appears optimal loading for the collector nanofluid. A minor increase in the collector efficiency occurs with the increase in nanoparticle sizes in the nanofluid. It can be concluded according to the results that the collector efficiency is a strong function of particle volume concentration loading compared to particle size in nanofluid. A 5% increase in the collector efficiency can be achieved in CuO-H₂O nanofluid at an optimal particle concentration of 2% (vol), with 25 nm particle size. Therefore, the use of nanofluid is the one of the driving factors for improved collector efficiency in solar water heating application.
- Finally, at the moment, the nanofluid production cost is certainly high as it requires advanced and sophisticated equipment. However with time, it is expected that nanofluid will be produced in commercial scale and the cost will be reduced. So improvement in efficiency is justified from cost perspective. As nanofluid cannot be directly connected to either the water storage tank or integrated with the building, a separate circulation loop of nanofluid is essential. This may be achieved by having heat exchanger where nanofluid as one of the heat exchanger fluids can transfer heat to the water storage tank or building water supply system.
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References