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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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ABSTRACT

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.

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).

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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_{fi}) and the lesser is the overall heat loss coefficient (U_L). 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 nonmetallic 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 Al_2O_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/therminol 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). The results showed that nanofluids improved the efficiency up to 5%. Khullar et al. (2012) investigated therminol VP-1 based aluminum nanofluid with 0.05% volume concentration both theoretically and experimentally on concentrating parabolic solar collector (CPSC). The results showed 5–10% increase in thermal efficiency when compared with the conventional CPSC. He et al. (2011) studied experimentally two different nanofluids (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 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 Al_2O_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 Al_2O_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 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 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 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