Energy Conversion and Management 76 (2013) 162–168

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energy, economic and environmental analysis of metal oxides nanofluid for flat-plate solar collector

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ARTICLE INFO

Article history:
Received 19 April 2013
Accepted 20 July 2013

Keywords:
Nanofluid
Flat-plate solar collector
Energy saving
Economic
Environment

ABSTRACT

For a solar thermal system, increasing the heat transfer area can increase the output temperature of the system. However, this approach leads to a bigger and bulkier collector. It will then increase the cost and energy needed to manufacture the solar collector. This study is carried out to estimate the potential to design a smaller solar collector that can produce the same desired output temperature. This is possible by using nanofluid as working fluid. By using numerical methods and data from literatures, efficiency, size reduction, cost and embodied energy savings are calculated for various nanofluids. From the study, it was estimated that 10,239 kg, 8625 kg, 8857 kg and 8618 kg total weight for 1000 units of solar collectors can be saved for CuO, SiO_2, TiO_2 and Al_2O_3 nanofluid respectively. The average value of 220 MJ embodied energy can be saved for each collector, 2.4 years payback period can be achieved and around 170 kg less CO_2 emissions in average can be offset for the nanofluid based solar collector compared to a conventional solar collector. Finally, the environmental damage cost can also be reduced with the nanofluid based solar collector.

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1. Introduction

The population and world energy demand is increasing and accelerating while fossil fuel sources are declining fast. The environment is polluted by fuel burning and climate change has becoming huge global problem. Therefore, a lot of studies related to energy efficiency and renewable energy have been conducted to address this issue [1–42]. Commonly, most houses in Malaysia are using Electric Water Heater for shower. This is mainly because the price of Electric Heater is cheap and relatively easy to install. However, the world is facing a huge problem now because of declining source of energy and using the precious electrical energy for heating does not really a good idea since heat can be harnessed directly from the sun. Potentially, Malaysia is located on the equatorial, with hot and humid climate throughout the year and monthly solar radiation approximately around 400–600 MJ/m^2 [26]. Solar energy source is sustainable, free, clean and infinite. However, current solar heater is still expensive, low in efficiency and big in size. One of the effective methods to increase the efficiency is to replace the working fluid with nanofluids. Researches on thermal efficiency by applying nanofluids on flat-plate solar collector have been made in the past few years by numerous researchers [43–52]. Experimental investigation conducted by Yousefi et al. [45] on the effect of Al_2O_3 based nanofluid shown the increase of 28.3% efficiency of flat-plate solar collectors. Lenert and Wang [53] presented a model and experimental study of concentrated solar power application using carbon-coated cobalt (C–Co) nanoparticles and Therminol VP-1 base fluid and concluded that the efficiency is more than 35% with nanofluid and the efficiency will increase with increasing nanofluid height. Lu et al. [54] shown that the application of Copper Oxide (CuO) nanoparticles in evacuated tubular solar collector will significantly enhance the thermal performance of evaporator and evaporating heat transfer coefficient increased by 30% compared to water as working fluid. Five percentage improvement in efficiency was found out by Otanicar et al. [55] by using diversity of nanoparticles with water as base fluid for micro-solar-thermal collector. Shin and Banerjee [56] applied novel nanomaterials in molten salts base fluid for concentrated solar power coupled with thermal storage and experienced an enhancement in operational efficiencies. They also concluded that the cost of electricity will be reduced. Taylor et al. [51] used graphite based nanofluid in high flux solar collectors that resulting in 10% increase in efficiency.

Because of higher thermal conductivity and efficiency of nanofluids, smaller and compact design of solar thermal collector has become possible without affecting the output desired. Smaller size collector can reduced the material usage, cost and energy required

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0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.07.038

in manufacturing [30]. Some studies were made on the potential of size reduction of various engineering applications by using nanofluids. Work had been done by Saidur and Lai [1] in vehicle's weight reduction, Kulkarni et al. [57] in building heat exchanger's heat transfer area, Leong et al. [33] on the reduction of air frontal area of a car radiator and Leong et al. [30] on the size reduction of shell and tube recovery exchanger. Some studies had been made to evaluate the economic and environmental impact of solar hot water system [58–61], one particular study focus on the environmental and economic analysis of direct absorption microsolar thermal collector utilizing graphite nanofluid [48], and also studies have been made on the potential of size reduction of flat-plate solar collectors when applying Al_2O_3 nanofluid [62] and MWCNT nanofluid [63]. However, none of the studies focus on the size reduction of flat-plate solar thermal collector and its associated energy and cost saving when applying various oxide nanofluids. Therefore, this study will focus on the potential of size reduction and its associated energy saving of flat-plate solar collectors when applying Al_2O_3, SiO_2, TiO_2 and CuO nanofluid.

2. Properties of nanofluids

Various researchers have published the properties of nanoparticles and thermal properties of nanofluids as the basis of research on nanofluids applications. Table 1 shows the published specific heat, thermal conductivity and density of different nanoparticles.

Improvement in thermal properties of nanofluids such as thermal conductivity and convective heat transfer that have been described in Section 1 above had a few mechanism contributing to it as listed by Keblinski et al. [66] such as Brownian motion, particle and liquid interface nanolayer and heat transfer in nanoparticles. However, all this special characteristics cannot be achieved unless the nanoparticles are properly dispersed and stable. Surfactants can play a major role in achieving better dispersion and stability of nanofluids [67,68].

3. Collector size calculation

The important intention for this analysis is to investigate the potential of size reduction of flat-plate solar collector. The specification of flat-plate solar collector is taken from Yousefi et al. [43–45]. The most important element in solar thermal collector is the working fluid. The fluid will pass through pipes attached to the absorber plate that absorbed heat from sunlight. The fluid will absorb heat from the plate and as it flows through the pipes the temperature will increase. The useful heat gain and collectors efficiency can be calculated and compared between the conventional working fluid and proposed nanofluids. The important useful heat gain by the working fluid can be expressed as:

$$Q_u = \dot{m}C_p(T_{out} - T_{in}) \quad (\text{kJ}) \tag{1}$$

where T_{out} is the fluid outlet temperature (Kelvin), C_p is the heat capacity at constant pressure (kJ/kg K), $\dot{m}$ is the mass flow rate of the working fluid (kg/s).

The heat capacity and density of nanofluid can be calculated by [69]:

$$C_{p,nf} = C_{p,np}(\varphi) + C_{p,bf}(1-\varphi) \quad (\text{kJ/kg K}) \tag{2}$$

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_{np} \quad (\text{kg/m}^3) \tag{3}$$

where $C_{p,nf}$ is the heat capacity of nanofluid (kJ/kg K), $C_{p,np}$ the heat capacity of nanoparticles (kJ/kg K), $C_{p,bf}$ the heat capacity of base fluid (kJ/kg K), φ is the volume fraction of nanoparticles in nanofluid (%).

Thermal efficiency of a flat-plate solar collector can be calculated from:

$$\eta = Q_u/(I_T A_c) = \dot{m}C_p(T_{out} - T_{in})/I_T \quad (\%) \tag{4}$$

where I_T is the the solar radiation incident on the tilted collector.

After the thermal efficiency of solar collector been determined, the potential of reduction of the size of collector's area can be estimated by:

$$A_c = \dot{m}C_p(T_{out} - T_{in})/(I_T\eta) \quad (\text{m}^2) \tag{5}$$

And mass flow rate of the working fluid can be calculated by:

$$\dot{m} = \rho\dot{V} \quad (\text{kg/s}) \tag{6}$$

Size reduction calculation is carried out based from variations of efficiency of collectors using different nanofluids. Efficiency is the function of density, specific heat and mass flow rate of different nanofluids calculated with regard to volume fraction of nanoparticles.

4. Nanofluid solar collector embodied energy analysis

In this section, the study is on the embodied energy of a solar collector. Only energy used to manufacture the solar collector is considered where else the distribution, maintenance and disposal phase of the collectors are neglected because according to Ardante et al. [70], more than 70% of the embodied energy of the system comes from the manufacturing of the collector. The analysis was done with the reduction of collector area as the functional unit that influences the overall weight and embodied energy of the collector. Two major materials that are being used in solar collector are glass and copper with the weight ratio of 30 kg glass and 10 kg copper for a 40 kg collector. The embodied energy index is 15.9 MJ/kg and 70.6 MJ/kg for glass and copper respectively [55]. By using the result of size reduction, the weight and the embodied energy for solar collector can be calculated accordingly.

5. Economic analysis

The results of the thermal performance of nanofluid solar collector and size reduction can also be used to estimate the cost saving. By using nanofluid as working fluid in solar collector, large portion of copper and glass used in the system can be eliminated based on the scaling of the overall percentage weight of the collector. The capital cost of the collector will then be offset by the cost of the nanoparticles. The energy usage per day in conjunction with

Table 1
Properties of different nanomaterial and base fluid [64,65].

Material	Specific heat, C_p (J/kg K)	Thermal conductivity, k (W/m K)	Density, ρ (kg/cu m)
Alumina (Al_2O_3)	773	40	3960
Copper Oxide (CuO)	551	33	6000
Titanium Oxide (TiO_2)	692	8.4	4230
Silicon di Oxide (SiO_2)	765	36	3970
Water (H_2O), base fluid	4182	0.60	1000

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