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Design, analysis and performance of a polymer–carbon nanotubes based economic solar collector

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Abstract

A low cost flat plate solar collector was developed by using polymeric components as opposed to metal and glass components of traditional flat plate solar collectors. In order to improve the thermal and optical properties of the polymer absorber of the solar collector, Carbon Nanotubes (CNT) were added as a filler. The solar collector was designed as a multi-layer construction with an emphasis on low manufacturing costs. Through the mathematical heat transfer analysis, the thermal performance of the collector and the characteristics of the design parameters were analyzed. Furthermore, the prototypes of the proposed collector were built and tested at a state-of-the-art solar simulator facility to evaluate its actual performance. The inclusion of CNT improved significantly the properties of the polymer absorber. The key design parameters and their effects on the thermal performance were identified via the heat transfer analysis. Based on the experimental and analytical results, the cost-effective polymer–CNT solar collector, which achieved a high thermal efficiency similar to that of a conventional glazed flat plate solar panel, was successfully developed.

Keywords: Renewable energy; Flat plate; Heat transfer analysis; Efficiency; Cost-effective; Prototype

1. Introduction

Renewable energy has been being firstly considered for a sustainable energy future. The exploration for a sustainable way to use energy has been increasingly required due to fossil fuel price increase, climate change and the associated adverse environmental impact. Solar energy can play a significant role to substitute non-renewable energy sources. Solar water heating systems (SWHS), which are one type of valuable and feasible solar energy devices, are very common systems and extensively used in many countries. Recently, the types of solar water heater collectors and their thermal energy performance have been extensively reviewed (Hossain et al., 2011). According to Renewables 2015 Global Status Report (REN21, 2015), cumulative capacity of solar hot water collectors increased by 9% in 2014 to reach 406 gigawatts-thermal (GWth) globally. SWHS offer an opportunity to reduce carbon dioxide (CO_2) emissions from homes and buildings and contribute to achieve the global target of doubling the share of renewable energy in the global energy mix from baseline share of 18% in 2010 to 36% by 2030 (IRENA, 2014).

Conventional flat plate solar collectors have been using a metal absorber plate and glass cover to transform solar energy into heat. In this collector, the incident solar energy is converted into heat and transmitted to a transfer medium, such as water. In the design of solar collector components, the transparent cover and the radiation absorber should have more attention. Glass is quite a common choice as a cover for solar thermal devices since it is transparent to the solar radiation and absorbs almost the infra-

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Nomenclature

A_s	area of collector
c_p	specific heat at constant pressure
g	gravitational acceleration
G_{solar}	solar intensity
H_1	air gap height
k	conductivity
$\dot{m}$	mass flow rate
q	heat flux
Q	heat transfer rate
T	temperature
α	absorptivity
β	coefficient of volume expansion
ε	emissivity
η	solar collector efficiency
v	kinematic viscosity
σ	Stefan–Boltzmann constant
τ	transmissivity
CNT	carbon nanotubes
PC	polycarbonate
Subscripts	
a	ambient
conv	convection
in	inlet
out	outlet
rad	radiation

red radiation (IR) re-emitted by the absorber plate. The use of a glass cover has two major disadvantages: its weight and fragility during transportation, installation and in service – increases shipping, installation and maintenance costs. Typically, the absorber of metals, which have large heat conductivities, is painted with black, solar selective paint to improve collector efficiency, but it causes an extra cost. The total weight and cost of the traditional solar collector is significant due to the high densities and values of metals and glass. Therefore, the use of plastic polymers has been recommended as an alternative material because of their low weight and good resistance against shocks (Dorfling et al., 2010; Tsilingiris, 1999; Wijeysundera and Iqbal, 1991).

According to the demand of cost-effective renewable energy sources, polymers have been investigated for the material of the absorbers and covers of solar collectors. The significant potential of polymer materials for the design and mass fabrication of low cost solar collectors has been shown (Abtahi, 1993; Dorfling et al., 2010; Kudish et al., 2002; Tsilingiris, 1999). Simple plastic film integral collector storage systems have been proposed as low cost solar water heaters (Tsilingiris, 1997). Design optimizations and the effects of the design parameters, such as the insulation thickness, the flow rate, the fluid layer thickness, the air gap thickness, the collector's length and the manifold configurations, on the performance of polymer solar collectors were investigated theoretically and numerically (Cristofari et al., 2002; Mintsa Do Ango et al., 2013; Missirlis et al., 2014). The optimum values of these parameters were proposed and the possibilities of the polymer application in the collector construction were shown. The efficiency and temperature distribution of a honeycomb polycarbonate collector was investigated by using experimental and numerical approaches (Martinopoulos et al., 2010). They observed the relation between the efficiency and the flow patterns inside the collector. Chen et al. (2015) compared full scale polymeric solar collectors with traditional metal solar collectors in the field experiments. The polymer solar collectors showed lower efficiency than the metal solar collectors, however, could decrease significantly the environmental impact. The extensive use of recyclable polymer solar collectors in assembly through on or a few extrusions allows not only a significant cost reduction of the solar water heating systems, but can also minimize the associated installation plumbing.

In this study, in order to improve economic competitiveness, a solar collector was developed by using polymeric components of the transparent cover and the solar radiation absorber. The solar collector was designed as a multi-layer construction with considering the economic manufacturing and selecting an effective material. The performance and characteristics of the solar collector have been analyzed using the mathematical heat transfer modeling. Furthermore, the prototypes of the proposed system were built and tested at a state-of-the-art solar simulator facility to evaluate the actual performance of the developed solar collector.

2. Solar collector design

2.1. Polymer materials for the solar collector

It is widely known that one of the disadvantages of polymer glazing in the solar collector is the degradation under long-lasting exposure to ultraviolet radiation (UVR). Only some of polymer materials are suitable for such a glazing application. The selected properties of the common polymer materials are shown in Table 1. Polycarbonate (PC) is one of the polymers which are stable against UVR. PC has been tested as a material of solar collectors by the researchers. The applicability of PC on the solar collector design has been shown (Chen et al., 2015; Cristofari et al., 2002; Martinopoulos et al., 2010). Additionally,