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Evacuated tube solar collector with multifunctional absorber layers

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ABSTRACT

Solar water heaters (SWHs) are a well-established renewable energy technology that have been widely adopted around the world. In this study we have significantly improved the Evacuated Tube solar Collectors (ETCs) by utilizing the "dry-drawable" Carbon Nanotube (CNT) sheet coatings to increase the solar energy absorption and Phase Change Materials (PCMs) to increase the heat accumulation for application in solar water heaters. The proposed solar collector utilizes a phase change material namely Octadecane paraffin, with melting temperatures of 28 °C which is categorized as non-toxic with long-term chemical stability PCM. As PCMs particularly in powder form may not be effective by itself due to the poor heat transfer rate, low thermal diffusivity and thermal conductivity, by combining CNT layers with the high thermal diffusivity and thermal conductivity compare to phase change materials, we are able to overcome the shortcomings of PCMs and design an innovative and efficient solar water heater. With the current technology, we can provide a near ideal black body surface, absorbing a maximum of 98%, between 600 and 1100 nm, of solar light striking the surface, and providing additional spectral absorption which improves the performance of the solar heater. Applying CNT sheets in conjunction with PCM enables heat storage directly on the collector for a more constant output, even on a cloudy day and prolonged output of heat at night.

1. Introduction

A number of systems have been developed to collect solar energy and convert it into an alternative form of energy, electricity, or to use the solar energy to perform work, such as in the case of a solar water heater. An important component of all these systems is the solar collector, which absorbs the solar radiation from the sun and transfers it to some transfer medium such as water, which delivers the heat as hot water to a house or to a heat storage unit (Papadimitratos et al., 2016; Sobhansarbandi and Atikol, 2015). Among different types of solar collectors, one example of an advanced and highly effective type of solar collector is an Evacuated Tube solar Collectors (ETCs).

Evacuated tube solar collectors are designed in such a way that heat loss to the environment is reduced. Heat loss due to convection cannot cross a vacuum, as it forms an efficient isolation mechanism to keep the heat inside the collector tubes. Since two flat sheets of glass are normally not strong enough to withstand a vacuum, the vacuum is rather created between two concentric tubes. Fig. 1 shows a typical evacuated tube solar collector which has two concentric tubes of glass with a vacuum in between that admits heat from the sun and transfers it to the heat pipe. The concentric glass tubes in ETCs are half spherically closed on one side and fused together on the other side. In order to absorb the solar power, an environmentally friendly, highly selective absorber layer is provided on the external surface of the inner glass tube. The heat pipe is immersed inside of the inner tube and it transfers the absorbed heat to the manifold, which transfers the heat to a circulating water line. This design enables the evacuated tubes to have a maximum production, as they are optimized in geometry and performance.

Current selective absorbers are made of Aluminum-Nitride (Al-N) layers with solar absorption of 92%, thus 8% of solar energy is lost due to reflectivity of the absorber material (WesTech; Apricus). In addition, selective coating requires careful control over the sputtering process (up to 12 sputtered layers for some designs),

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Nomenclature

c_p	specific heat of PCM (kJ/kg K)	ρ	density of PCM (kg/m^3)
H	latent heat of fusion of PCM (kJ/kg)	G_t	global radiation (W/m^2)
T_m	melting temperature of PCM (°C)	T_W	water temperature in the tank (°C)

and thus the manufacturing costs are expensive. Such coating with high reflectivity is less efficient compared to a black body coating layer that has a high absorption amount of 98% (Zhang et al., 2005). Current solar absorbers require a gas or electric booster heater to provide functionality at night, on cloudy days, or in general when incident solar energy is insufficient, which this adds to installation and maintenance costs. Our target is to improve the ETCs by a qualitatively new technical approach for the selective absorptive layer. There is great potential to utilize carbon-based materials for the selective solar absorption coating in order to reduce the maintenance cost and removing the need for booster unit.

In this paper a new concept of multifunctional absorber layer (Carbon Nanotube (CNT) sheets) with inner layers of heat accumulator (Phase Change Material (PCM) microspheres) is introduced. The main obstacles in the incorporation of carbon-based materials into the medium and high temperature solar heaters, have been the poor heat conductivity and stability of such materials (Kutuzov et al., 2013). In this study applying a dry-drawable carbon nanotubes as "Absorbent Layer" is suggested, and is further improved by birolling into its porous network functional layers of heat accumulation microspheres of PCM. This unique strategy enables heat storage directly on the evacuated tube solar collectors when sunlight is insufficient (night times and cloudy days).

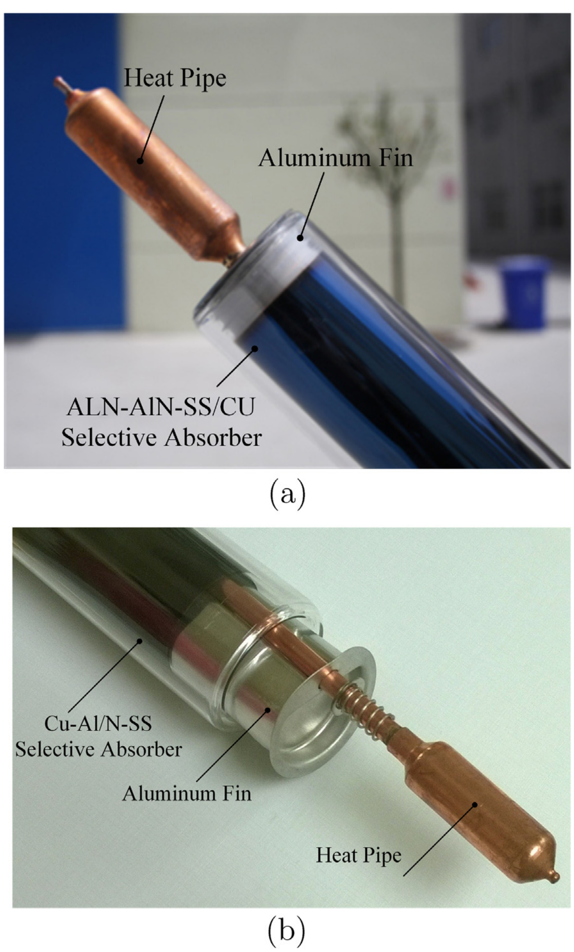

Fig. 1. Schematic of evacuated tube from: (a) WesTech Solar Energy Inc. (WesTech) (b) Apricus Solar Co. (Apricus; Papadimitratos et al., 2016).

Carbon nanotube thin films are widely used for converting solar radiation energy into other energy forms such as heat and electricity (solar cells) (Wei et al., 2007; Klinger et al., 2012). For the solar application in low temperatures, metal oxide sol-gels with carbon-nanotubes additives have been studied as a spectral selective solar absorber coating (with high absorptivity and low emissivity) (Katzen et al., 2005; Katumba et al., 2008; Mor et al., 2006).

Phase change materials (with melting temperature less than 50 °C) have been studied for solar storage systems either in a storage tank or directly on the flat plate collectors (Seeniraj and Narasimhan, 2008; Boy et al., 1987; Kürklü et al., 2002). Integration of phase change materials inside of the evacuated tube solar collectors have been studied in the previous work of the authors, which served as the motivation of current work, as it strongly supports the effective heat accumulation behavior of phase change materials (Papadimitratos et al., 2016). In non-solar applications, thermal and energy storage behavior of phase change materials by addition of expanded graphite and/or carbon nanotubes for their thermal conductivity enhancement has been widely investigated (Sarı and Karaipekli, 2007; Zhang and Fang, 2006; Wang et al., 2009; Shaikh et al., 2007).

To the best knowledge of the authors, there is no previous study on a nanocomposites based solar selective absorber layer containing carbon nanotubes sheets with filler of phase change materials. This novel absorber layer can be easily coated on the solar tubes and can provide scaffolding for additive materials. By applying the specific method of birolling (Lima et al., 2011), we were able to produce the composite with any degree of densification and guest additive concentration (up to 95%). Thus, the investigation of the properties of this multi-functional nanocomposite solar absorber will have fundamental scientific impact as well as potential technological applications.

2. Carbon nanotube sheets (heat absorption)

Carbon Nanotube sheets include an array of tube-shaped material, made of carbon, having a diameter measuring on the nanometer scale. CNT sheets have various structures, differing in length, thickness, type of helicity and number of layers. They are elastic and strong compared to other fiber materials which usually lack one or more of these properties. Due to the unique properties, carbon nanotube technology can be used for a wide range of applications, e.g., conductive and high-strength composites, energy storage and energy conversion devices, sensors, nanometer-sized semiconductor devices, probes and interconnects (Baughman et al., 2002).

Multi-Wall Nanotubes (MWNTs) comprise of an array of graphene sheet seamlessly wrapped into a cylinder, that are concentrically nested like rings of a tree trunk (Baughman et al., 2002). MWNTs have typically lower thermal conductivity compared to Single-Wall Nanotubes (SWNTs) due to overlap between individual nanotubes (Aliev et al., 2009; Kwon et al., 2004). Such deficiency