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Review

Evaluation of solar collector designs with integrated latent heat thermal energy storage: A review

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ABSTRACT

Solar collectors have been rigorously modified over the years to better serve the thermal needs of the era. Various design innovations have paved their way to invent new ways of gaining more solar energy in the form of useful heat. Few of these approaches have been commercialized and others have taught lessons. New technological advancements, like phase change materials (PCM), and their integration with solar collectors produced better results in recent years. Hence, various methods of integrating PCM inside the collector cavity were investigated. This review studies innovative concepts of integrating PCMs in flat plate (water/air), evacuated tube, and photovoltaic/thermal solar collectors. Flat plate collectors for water and air heating have been extensively studied. Uses of nano-composite PCM in solar collectors are also compiled. It was observed that maximizing the contact surface area between the PCM and the absorber plate significantly enhances the outlet temperatures. General trends, proportionalities and noteworthy observations are also discussed for each type.

1. Introduction

Solar thermal energy is considered the most promising among other renewable energy sources, due to its cleanliness and abundance in many parts of the world (Panwar et al., 2011). Solar thermal collector is the major component in any solar thermal application. It absorbs the incoming solar radiation, converts it to heat, and transfers the heat to a working fluid (usually air, water, or oil) flowing through (Kalogirou, 2004). Solar heating is not a new technology, but advanced techniques to increase the solar absorptivity and output temperature range are increasingly manifesting.

Heating by means of solar thermal energy is achieved through various types of solar collectors (flat plate, evacuated tube, and parabolic trough), of which flat plate collectors are the most common for low temperature applications (323–343 K). Hence, the present review focuses more on flat plate collectors. For higher working fluid outlet temperature requirement, evacuated tube or parabolic trough collectors are also employed; but they are expensive and have long payback time compared to flat plate collectors (Leckner and Zmeureanu, 2011). However, the output temperature requirement for a given application is what determines the type of collector to be employed.

Discontinuous nature of solar energy necessitate the use of thermal energy storage in order to increase the number of operating hours of solar driven systems. Sensible heat storage, latent heat storage and thermochemical/sorption heat storage are the usual forms of thermal energy storage, with sensible storage being the most matured (Zhang et al., 2016). Latent heat energy storage for solar applications is gaining more attention due to its compactness, high energy storage density and occurring at nearly constant temperature (Mohamed et al., 2016; Salunkhe and Jaya Krishna, 2017; Sharma et al., 2009). PCM has been used for latent heat energy storage considering the storage as a separate entity between the energy source (such as solar) and the receiving system or end user as reported in the literature (Jegadheeswaran and Pohekar, 2009; Riffat et al., 2013; Sharma and Sagara, 2005; Zalba et al., 2003) (Fig. 1). In addition, another concept of integrating PCM with solar collector as single component appeared recently. Many studies, both experimental and numerical, have been carried out integrating PCMs particularly in flat plate, evacuated tube and

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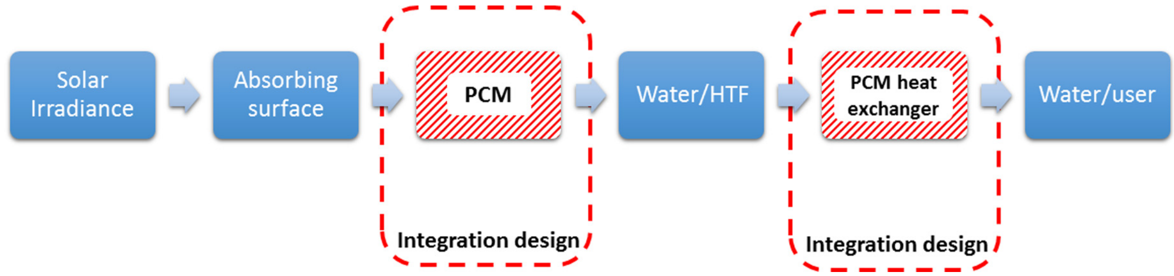

Fig. 1. Energy flow direction in solar collectors.

photovoltaic/thermal (PV/T) collectors. Pandey and Chaurasiya (2017) and Sharif et al. (2015) presented reviews on solar thermal collectors and devoted sections on the progress of collector-PCM configuration. However, to the best of the authors' knowledge, there is lack of review work focusing on integrated solar collector-PCM systems.

This paper reviews recent progress on integrated collector-PCM systems, considering various type of the solar thermal collectors. In addition, current research works on the use of nanoparticles in integrated solar collector-PCM are reviewed. The paper will serves as a source of useful information and strong point of reference for future research designs in this area.

2. Flat plate solar collectors

2.1. Flat plate water heating collectors

Numerous innovative investigations have been done to modify the basic design of flat plate solar collector to increase its thermal performance. PCMs have been a dedicated motivation to tap the promising outcomes in thermal stability and performance. PCM stabilizes the intermittent temperature fluctuations as well as extends the operating hours. Domestic flat plate solar water heating system can be incorporated with PCM in three ways: (a) under the collector absorber plate, (b) concentric to the flow line (Malvi et al., in press), or (c) a separate thermal energy storage unit (Eames and Adref, 2002; El Qarnia, 2009; Kaygusuz, 1995; Nallusamy et al., 2007). In this study, we compile and analyze innovative approaches in the literature to incorporate PCM inside solar collectors.

Integrating PCM with flat plate solar collector has been the oldest technique to enhance its thermal performance. Boy et al. (1987) first investigated integrating phase change material in a combined solar collector storage in 1987. Scarcely, other investigations were performed in later years, until Rabin et al. (1995) who studied another conceptual design with liquid and solid PCM layers. They used eutectic mixture of salt hydrates at PCM on a layer of stationary heat transfer liquid (SHTL) containing the heat exchanger. Their theoretical study suggested a PCM thickness of 30–65 mm for heating greenhouses. Their experimental study reported that two third of the solar radiation that falls on the collector can be stored. In 2006, Mettawee and Assassa (2006) experimentally investigated a completely new compact design of PCM solar collector with 1 m^2 effective area. They tested a 1.3 m length collector fixed at 318 K with a single water pipe at a specified central location to maximize heat intake from the surroundings filled with PCM (paraffin wax). They found that the heat gain increased with increase in mass flow rate of heat transfer fluid (HTF)-water; and that decreases over the time due to the low thermal conductivity of the PCM. They also concluded that the initial heat transfer is primarily through conduction and later through convection (within the PCM layers). Reddy (2007) numerically studied a PCM integrated solar collector of 1 m^2 size and paraffin wax as PCM with transparent insulation material instead of glass sheet as glazing. Interestingly, he placed fins below the absorber plate that penetrate inside the PCM. His model with 9 fins completely melted the wax maximizing the latent heat energy storage. Bouadila et al. (2014) used paraffin wax in two cavities (0.7 × 0.63 × 0.07 m) placed behind a collector made of size 2 m^2. Their temperature stratification analysis revealed a similar solid-liquid interface profile as Reddy (2007). They found a uniform useful heat output with the use of PCM for 5 h after sunset. A numerical modeling was conducted to study the PCM thermophysical behavior. Very similar design concept but with 4 rectangular cavities filled with PCM was used by Mauricio et al. (2017) in 1 × 1 m collector cavity. The melting point of the PCM was 333 K which turned out to be little high, as only in few cases the PCM changed its phase. The thermal efficiency calculated was 24%.

Kürklü et al. (2002) placed a 50 mm thick paraffin wax layer backed by a 100 mm thick water layer in a commercially available collector frame. Their collector was cheaper and lighter with a satisfactory thermal efficiency. They suggested more of similar studies and anticipated a domestic use of PCM-water panels. Similarly, Afolabi et al. (2017) introduced nano-additives in the PCM which enhanced the thermal efficiency to a maximum of 57.5% (with additives) from 52.2% (PCM without additives) extending the hot water production at night to approximately 7 h. Chen et al. (2010) in their numerical study, passed water pipes from within a 40 mm thick paraffin wax saturated in porous aluminum (Fig. 2). They observed a more uniform temperature distribution with the use of aluminum foam. However, it should be noted that they detached the HTF pipes with the absorber plate as opposed to conventional design and introduced aluminum porous material to transfer the heat into the flow. A similar numerical investigation was done by Hamed and Brahim (2015) where they found that the PCM charging is slower than discharging rate; and that they are independent of mass flow rate or PCM thickness.

In a more diverse method, Lee et al. (2006) experimentally investigated thermal behavior of water, paraffin wax and sodium acetate as PCMs with various ethyl alcohols as working fluids. The working fluid evaporates on heating, and then condenses to release heat that is used to charge the PCM in a two-phase heat exchanger. They found that tricosane (paraffin wax 116) performs the best with 40% alcohol level with charge and discharge efficiency 30% and 17% higher than water, respectively.

Reddy (2007) numerically investigated a 2D thermal model of solar collector fixed at 30° angle. His design included a transparent insulation material rather than a glass cover. Moreover, the absorber plate attached with variable number of fins underneath sits upon a bed of PCM. Water is flown freely under the PCM bed and the insulated steel cavity of the collector. He varied the number of fins (4, 9 and 19) of various pitch lengths (5, 10 and 20 cm). He found that 9 fins in 1 m^2 surface area give the best performance with complete PCM melting and higher latent energy storage. He suggested better absorption and insulation characteristics for better performance. Lin et al. (2012) experimentally investigated solar flat plate collector with PCM at various inclination angles (10°, 20° and 30°). They produced an extra 3 h hot water supply until the PCM and water temperatures reached an equilibrium. They found the optimum parameters for best performance (52%) to be at 10° collector inclination and 0.5 kg/min water flow rate.

Koca et al. (2008) performed energy and exergy analysis of a single unit comprising of a solar collector and a storage tank in a T-shaped