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Integration of transparent insulation materials into solar collector devices

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ABSTRACT

The integration of Transparent Insulation Materials (TIMs) into Flat Plate Collectors (FPCs), Parabolic Trough Collectors (PTCs), and Central Receiver (CR) collectors is studied in this paper. A general model including optical and thermal analyses is developed. The effects of TIM's properties, such as the emittance, thermal conductivity, extinction coefficient, and thickness, on the collectors' performance, are analyzed. At low absorber temperatures, performances of traditional-type collectors are relatively high. The efficiency of these collectors reduces dramatically at high temperatures due to the increment in heat losses. The incorporation of a TIM decreases thermal losses, leading to higher collectors' efficiencies at high absorber temperatures. The main goal of this study is to determine the critical operation temperature from which thermal losses reduction overcome the optical efficiency losses due to a TIM integration. In general, for high performance collectors, TIMs are characterized by low emittances and thermal conductivities, high transmittances, and low extinction coefficients.

1. Introduction

Renewable-based technologies are becoming fundamental alternatives for energy conversion and power generation. The use of these technologies can mitigate the negative environmental impact caused by the extensive use of fossil fuels. Among renewable resources, solar energy is probably the most promising alternative to satisfy the rising energy demand. The solar radiation can be directly collected and converted into thermal energy for water and space heating using Flat Plate Collectors (FPC). Traditionally, this type of collectors consists of a multilayer system composed of absorber elements, such as tubes, plates or channels, where the solar energy is converted into heat and then transferred to a working fluid. In FPCs, the absorber is located between a transparent cover (glass envelope) and a backing insulation layer to reduce heat losses. Operating temperatures of between 80 °C and 120 °C can be achieved with this type of collector using water as the working fluid (Kessentini et al., 2014). Higher temperatures can be achieved by concentrating the solar energy. Concentrated solar power (CSP) technologies use a solar receiver located in a focal point or focal line, where the energy is concentrated after reflection processes. Two of the main CSP technologies are the Parabolic Trough Collector (PTC) and the Central Receiver (CR) collector (also known as solar tower). The temperatures reached with these collectors allow the system to operate in conjunction with modified Brayton or Rankine power generation cycles driven by solar energy.

PTC systems consist of an absorber, usually a metallic tube, where the energy is transferred to a working fluid, a concentric glass envelope, an annular air gap or vacuum to reduce heat losses, and a solar tracking mechanism. Working fluids, such as water, oil and organic compounds, are typically used for operating temperatures of between 100 °C and 400 °C (Fernández-García et al., 2010). PTCs can generate vapor to be used directly in a power cycle and also, they can heat thermal oil or organic fluids to indirectly generate vapor in a heat exchanger (Fernández-García et al., 2010). Higher operating temperatures and power generation capacities can be obtained using CR collectors. Two types of receivers for solar tower systems are commonly used: external and cavity receivers.

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Nomenclature

T	temperature (K)
q_{ab}	energy absorbed (W)
q_{loss}	energy losses (W)
I_r	peak direct-normal radiation (W/m^2)
h	convection heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
R	thermal resistance (K/W)
H	height (m)
D	diameter (m)
L	length (m)
t	radius or thickness (mm)
σ	Stefan–Boltzmann constant (W/m^2 K^4)
α	absorber's solar absorptance
R_{ra}	reflected radiation (%)
μ	TIM's Extinction coefficient (m^{-1})
τ_s	glass envelope's transmittance
ε	thermal emittance
C	concentration ratio
N	number of absorber tubes in CR
η	efficiency (%)

subscripts

FPC	flat plate collector
PTC	parabolic trough collector
CR	central receiver
HTF	heat transfer fluid
GE	glass envelope
TIM	transparent insulation material
ab	absorber
cf	collector field
env	environment
Sky	sky
loss	losses
cd	conduction
cv	convection
r	radiation
re	receiver
tot	total
lim	limit
0	reference condition
c	collection

The first type consists of a series of panels of tubes arranged in a cylindrical layout. Usually, darkened metal tubes have been used with steam and molten salt for operating temperatures of between 500 °C and 600 °C; higher temperatures, of up to 900 °C, are possible for tubular receivers operating with gas (Eduardo and Manuel, 2007). Cavity receivers, on the other hand, have the absorbing surface or volume inside of an insulated compartment to provide some level of insulation with the surroundings. Both types of receivers can be designed to collect solar energy in a surface or volume by using porous materials resistant to high temperatures. Usually, external receivers operate at higher temperatures and the heliostat field can be accommodated around the tower. On the other hand, the insulation in cavity receivers can lead to higher efficiencies due to lower heat losses; however, its geometry restricts the accommodation of the heliostats in a portion of azimuthal angles (Wagner, 2008).

In general, higher operating temperatures in solar collectors lead to larger cycle efficiencies, but also increase thermal losses that reduce the collection efficiency. Such a situation represents a great potential for improvement of solar collectors via design optimization. To accomplish such a goal, numerous experimental and theoretical studies have been done in FPCs (Chen et al., 2015; Capeillere et al., 2014), PTCs (Vasquez-Padilla et al., 2011; Kalogirou, 2012; Mwesigye et al., 2016), and CR collectors (Osorio et al., 2016a; Osorio et al., 2016b; Iverson et al., 2013; Rodríguez-Sánchez et al., 2014)∗∗. In particular, multi-layer glass covers and transparent insulating materials have been analyzed to reduce thermal losses in FPCs (Bahrehmand and Ameri, 2015; Cadafalch and Consul, 2014; Girurugwiro, 2012; Londoño-Hurtado and Rivera-Alvarez, 2003). Roughened absorber plates (Gupta et al., 1997), as well as external or internal fins with rectangular and triangular shapes inside the channels or tubes (Bahrehmand and Ameri, 2015; Ho and Chen, 2008; Karwa et al., 2015) have been proposed in order to increase the heat transfer coefficient by increasing the effective heat transfer area, and by inducing turbulence in the working fluid, leading to significant improvements in the collector's efficiency. In order to improve the efficiency of PTCs, novel design changes have been proposed. Some of these changes include the addition of helical fins (Muñoz and Abánades, 2011) and porous discs (Kumar and Reddy, 2009) inside the absorber, and the incorporation of external fins (Ho and Chen, 2008). Significant progress in the performance of PTC plants has been accomplished using selective coatings on the absorber due to an increment in the solar absorptance, and a reduction in the thermal emittance (Farooq and Raja, 2008). Similarly, in CR collectors, remarkable improvements in the efficiency have been accomplished by implementing different designs, including tubes with dimpling and induced roughness (Soo Too and Benito, 2013; Sharma and Kalamkar, 2015), spiral tubes (Yang et al., 2010), hexagonal pyramidal elements (Garbrecht et al., 2013), and multi-diameter tubes (Boerema et al., 2013). Different materials for tubes, such as stainless steels and nickel alloys, coatings and glasses, have also been tested to reduce heat losses (Lata et al., 2008; Pye et al., 2014; Atkinson et al., 2015; Deubener et al., 2009). In addition, the performance of a wide variety of heat transfer and working fluids have been assessed (Pye et al., 2014), as well as porous materials inside the tube (Lim et al., 2014), and suspended particles in the working fluid to enhance the heat transfer coefficient (Ordonez-Malla, 2015).

Thermal insulation is an essential alternative to reduce heat losses and enhance the performance of any thermal component or system. In this work, the effect of the integration of Transparent Insulation Materials (TIMs) on the performance of solar collectors' receivers is investigated. A general thermal and optical model for FPCs, PTCs and CR collectors is presented. The effects of integrating a TIM, and different TIM's properties, on the performance of these collectors are studied. The efficiency of the proposed designs is assessed and compared with that of traditional solar collector configurations. TIMs have been successfully used in FPCs to allow higher operating temperatures and reduce energy losses (Kessentini et al., 2014; Cadafalch and Consul, 2014; Girurugwiro, 2012; Londoño-Hurtado and Rivera-Alvarez, 2003)∗∗. These materials are transparent to solar radiation wavelengths while providing good thermal insulation and restricting infrared energy losses via re-radiation (Saxena et al., 2015). Several models to evaluate different arrangements of square-cell honeycomb TIMs in FPCs have been developed (Ghoneim, 2005). In general, increments in the efficiency of between 7% and 12% in TIM-integrated FPCs have been reported (Hirasawa et al., 2013; Hellstrom et al., 2003). Besides FPC, and some isolated works on