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Development of flat plate collector with plastic transparent insulation and low-cost overheating protection system

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HIGHLIGHTS

- Innovative flat plate solar collector with TIM is presented.
- The overheating protection system consisting of a ventilation channel with thermally actuated door is designed.
- The numerical model and the experimental tests are performed.
- The validation with experiments shows good agreement.
- A parametric study is performed to optimize the system design.

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ABSTRACT

In this work a flat plate collector (FPC) with plastic transparent insulation materials (TIM) and a low-cost overheating protection system destined for heat supply from 80 to 120 °C is presented. A ventilation channel with a thermally actuated door is inserted below the absorber allowing to protect the collector from stagnation conditions, while preserving good performance during normal operation. This collector is intended to have not only a comparable efficiency with the available commercial collectors but also low cost. For this objective, a prototype has been constructed and experimentally tested and in parallel, a numerical model has been implemented. The proposed numerical model is based on the resolution of the different components of the solar collector by means of a modular object-oriented platform. Indoor and outdoor tests have been performed in order to check the effectiveness of the designed overheating protection system and to validate the model. The comparison of the numerical results with experiments has shown a good agreement. Finally, an extended parametric study is performed in order to optimize the collector design: 3125 different configurations of FPC with TIM and ventilation channel were evaluated by means of virtual prototyping. The results allowed to propose the most promising design of a stagnation proof FPC with plastic TIM able to work at an operating temperature of 100 °C with good efficiency. The design presented in this paper can be considered promising for increasing the thermal performance of FPC and could be used in industrial applications that need heat at low-to-medium temperature level.

1. Introduction

A large industrial applications potential exists for solar heat at medium temperature levels in food and textile industry, or in solar drying of wood, crops and fruits, sterilizing, washing, cleaning, distillation and desalination fields [1]. Moreover, solar cooling and air conditioning systems are very interesting applications that need heat at temperature range of 70–120 °C [2].

Various types of solar collectors able to yield heat at medium temperatures are available in the current market including stationary/non-stationary and concentrating/non-concentrating collectors. Each type uses different technology, has different cost and provides different efficiency range and water temperature. Some of them have been reviewed in different previous studies such as stationary compound parabolic collectors (CPC), evacuated tubes collectors (ETC), Fresnel lens collectors (FLC), small parabolic trough collectors (PTC) and cylindrical trough collectors (CTC) [3–5]. Some others have been more recently introduced into the market such as hermetically sealed double glazed collectors with anti-reflective glass [6–8], solar thermal collectors with fixed mirror and moving absorber [9], concentrating flat plate collectors [10].

Moreover, a number of recent research works have been done with the aim to develop new designs of solar collectors able to

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Nomenclature

A_c	aperture area of the collector (m^2)
c	opening length of the channel (m)
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
$\bar{c}_p$	fluid specific heat at average fluid temperature ($J\,kg^{-1}\,K^{-1}$)
D	diameter of the absorber tubes (m)
D_h	hydraulic diameter of the channel (m)
e	inter-plate spacing (m)
f_w	wall fraction
f_r	friction factor
F	standard fin efficiency
F'	collector efficiency factor
g	gravity (ms^{-2})
G	solar radiation on the aperture of the collector ($W\,m^{-2}$)
h	convection heat transfer coefficient ($W\,m^{-2}\,K$)
h_{ch}	channel height (m)
hr	radiation heat transfer coefficient ($W\,m^{-2}\,K$)
$\tilde{h}$	enthalpy ($kJ\,kg^{-1}$)
$\dot{m}_f$	collector mass flow rate ($kg\,s^{-1}$)
$\dot{m}$	mass flow rate in the channel ($kg\,s^{-1}$)
n_t	number of parallel tubes in the absorber
Nu	Nusselt number ($Nu = hL/\lambda$)
p	pressure (Pa)
P_{ch}	channel perimeter (m)
Pr	Prandtl number
$\dot{Q}$	heat rate (W)
$\dot{q}$	heat flux per unit of length ($W\,m^{-1}$)
R	specific gas constant for dry air ($J\,kg^{-1}\,K^{-1}$)
Ra	Rayleigh number ($Ra = g\beta\Delta TL^3/\nu\tilde{\alpha}$)
Re	Reynolds number ($Re = uL/\nu$)
S	absorbed solar energy by the absorber plate per unit area ($W\,m^{-2}$)
S_{ch}	channel section (m^2)
S_{in}	inlet section of the channel (m^2)
S_{out}	outlet section of the channel (m^2)
t	time (s)
T	temperature (°C)
U	overall heat loss coefficient ($W\,m^{-2}\,K^{-1}$)
v	velocity ($m\,s^{-1}$)
W	tubes spacing (m)
$\dot{W}$	power (W)
x	position length in the flow direction (m)

Subscripts

ab	absorber
abs	absorbed energy
amb	ambient
airch	air in the ventilation channel
b	bottom
bo	bond
c	glass cover
ch	channel
conv	convection
cond	conduction
e	edge
eff	effective
f	fluid
fi	fluid inlet
fo	fluid outlet
fin	absorber fin
gr	ground
gap	air gap
gas	gas filling
h	hot wall
c	cold wall
i	inner
ins	insulation
insi	internal insulation surface (channel side)
inse	external insulation surface (ambient side)
L	loss
o	outer
sky	sky
s.rad	solar radiation
t	top
t.rad	thermal radiation
TIM	transparent insulation material
u	useful
w	TIM wall
wi	wind

Greek letters

α	absortivity
$\tilde{\alpha}$	thermal diffusivity ($m^2\,s^{-1}$)
β	thermal expansion coefficient (K^{-1})
σ	Stefan–Boltzmann constant $\sigma = 5.6710^{-8}\,W\,m^{-2}\,K^{-4}$)
ϵ	emissivity
ρ	reflectivity
$\tilde{\rho}$	density ($kg\,m^{-3}$)
$(\tau\alpha)$	transmittance–absorptance product
θ	collector slope (°)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
κ	IR-extinction coefficient of the TIM layer (cm^{-1})
κ_e	pressure loss coefficient due to the elbow
κ_b	pressure loss coefficient due to the butterfly door
δ	fin thickness (m)

yield good performance at medium temperature range. The proposed designs are mainly centered around the objective to reduce heat losses or to increment the received solar radiation by the absorber. Buttinger et al. [11] presented a new flat stationary evacuated CPC-collector that combined high efficiencies with the advantages of flat collectors. Hirasawa et al. [12] studied the reduction of natural convection heat losses from a solar thermal collector by placing a high-porosity porous medium above the collector plate showing an increase of 7% in the collector efficiency respecting to the conventional collector. Kim et al. [13] presented a numerical and experimental study of a stationary solar thermal collector using an evacuated glass and a counter-flow tube able to operate at a medium-temperature range. Fernandez and Dieste [14] developed a solar thermal collector based on solar concentrating systems and substitution of metallic materials by plastic ones for economical supply of heat between 40 and 90 °C. Nkwetta et al. [15] presented a novel design of a concentrator augmented solar collector array that is a combination of evacuated tube heat pipes and either an external or internal concentrator yielding good thermal performances for medium temperature applications.

Flat plate collectors (FPC) are generally designed for applications with typical working temperatures between 40 °C and 60 °C, which is mainly the case of domestic hot water systems. By using highly selective absorbers, FPC can currently work up to 80 °C with good efficiency [3]. FPC have important advantages over the other collector types because they are easier to manufacture,