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Numerical model and simulation of a solar thermal collector with slurry Phase Change Material (PCM) as the heat transfer fluid

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Abstract

The performance of conventional, water based, solar thermal collectors is limited by some intrinsic limitations, such as the need for high irradiation levels and the heat loss due to the relatively high temperature of the heat transfer fluid. In order to overcome these limitations and to improve the performance of solar thermal collectors, a different kind of heat transfer fluid can be proposed. This fluid is based on the exploitation of the latent heat of fusion/solidification of suspended particles, which change their state of aggregation at a micron scale, but maintain the liquid state of the fluid at a macroscopic scale. The so-called slurry phase materials, or PCS, are examples of this kind of material.

In order to evaluate the effectiveness of such a concept, a numerical model of a PCS-based flat-plate solar thermal collector has been developed, presented and discussed. This model has been derived from the well-known Hottel–Whillier model, but several changes have been implemented so that a phase change of the heat transfer fluid can be handled, as well as the thermophysical properties of a non-Newtonian fluid, such as those of a PCS. The paper presents the main and auxiliary equations that have been introduced to modify the Hottel–Whillier model.

A numerical analysis conducted with the newly developed model is also presented in the paper. The aim of these simulations was to test the code and obtain a preliminary evaluation of the performance of the novel concept. Different (dynamic) boundary conditions (location, orientation, PCM concentration) were adopted to evaluate the performance of the PCS-based technology and compare it with that of a conventional solar thermal collector.

The outcomes of the simulations have proved model robustness and the possibility of using it for preliminary analysis. It was also shown that the adoption of the PCS as a heat transfer fluid can lead to an increase in solar energy exploitation of different magnitude according to the climate. The greatest benefit can be achieved for cold climates. The limitations of the analysis (e.g. fixed, non-optimal flow rate) are also discussed.
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Keywords: Slurry PCM (PCS); Solar thermal collector; Numerical model; Collector efficiency

1. Introduction

1.1. Background

Solar thermal collectors are the most commonly used devices for the exploitation of thermal energy from the Sun. These systems have been widely investigated since

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Nomenclature

List of abbreviations

HTF	heat transfer fluid
PCM	Phase Change Material
PCS	Phase Change Slurry
mPCM	microencapsulated Phase Change Material
mPCS	microencapsulated Phase Change Slurry
HDD	Heating Degree Days
HW	Hottel Willier model for flat-plate solar thermal collectors

List of symbols

c_p	specific heat [J kg^{-1} K^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
$\Delta h_{lat,mPCM}$	specific latent heat [J kg^{-1}]
$\Delta h'_{lat,mPCS}$	specific fictitious latent heat [J kg^{-1}]
β	ratio of mass of melted mPCM to total mass of mPCM [–]
$(\tau\alpha)_e$	optical losses of the collector [–]
$\dot{Q}_u$	useful heat flux [W]
T	temperature [°C]
A	area [m^2]
F_R	collector heat removal factor [–]
F'	fin effect factor [–]
G_T	global solar irradiance [W m^{-2}]
U_L	average thermal transmittance of the solar collector [W m^{-2} K^{-1}]
N	number of pipes in the solar collector [–]
l	width [m]
s	thickness [m]
L	length [m]
W	distance between the pipes in the solar collector [m]
y	distance covered by the fluid inside the solar collector along the riser pipes [m]
η	efficiency of the solar collector [–]
ρ	density [kg m^{-3}]
$b_{mPCM,co}$	ratio of the mPCM core mass to the mPCM shell mass [–]
a_{mPCM}	mPCM mass fraction in the mPCS mixture [–]
a_{gl}	water–glycol mass fraction in the carrier fluid [–]
λ	thermal conductivity [W m^{-1} K^{-1}]
d	diameter [m]
B	constant [–]
m	constant [–]
e	velocity gradient inside the mPCS [s^{-1}]
κ	thermal diffusivity [m^2 s^{-1}]
α	solar absorbance [–]
γ	azimuth angle [°]
ε	emissivity [–]
n_1	air refraction index [–]
n_2	cover refraction index [–]
K	extinction coefficient [m^{-1}]
θ	tilt angle [°]
ϕ	latitude [°]
φ	volumetric concentration of the mPCM [–]

Subscripts

in	solar collector inlet
int	internal
ex	external
pi	pipe
ca	air cavity inside the solar collector
pl	solar collector plate
co	solar collector cover
out	solar collector outlet
a	outdoor air
coll	collector
h	higher limit of the melting range
l	lower limit of the melting range
eff	effective
ins	insulation
bot	solar collector bottom
edg	solar collector edge
1, 2, 3	different parts of the collector, according to the mPCS state of aggregation
mPCM,co	core of the mPCM
mPCM,sh	shell of the mPCM
carrier	carrier fluid in which the mPCM particles are suspended
w	water
gl	glycol
opt	optimal

the '40 s (Hottel and Woertz, 1942) and nowadays constitute a mature technology that is applied at a large scale and is spreading significantly. At the end of 2011, the total thermal energy converted by solar thermal collectors was assessed to be about 235 GW h (Mauthner and Weiss, 2013), which corresponds to a total of approximately 335 × 106 m^2 of collector area. A recent report by the IEA on Solar Heating and Cooling has stated that, at the end of 2013, the installed capacity rose to 374.7 GW h, which corresponds to a total of 535 × 106 m^2 of collector area in operation worldwide (Mauthner et al., 2015).

Among other applications, the use of solar thermal panels in buildings has become more and more common (Tian and Zhao, 2013). In this context, the thermal energy produced by solar systems can be used to:

– satisfy the Domestic Hot Water (DHW) demand;
– space heating.

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