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A coupled numerical model for tube-on-sheet flat-plate solar liquid collectors. Analysis and validation of the heat transfer mechanisms

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HIGHLIGHTS

- A novel 3D coupled model for flat-plate solar liquid collectors has been developed.
- The predicted thermal efficiency is in agreement with the experimentally obtained.
- The implemented solar load model accounts for high and low wavelength radiation.
- Enhanced asymptotic Nusselt number for mixed convection inside risers is reported.
- Irregular free convection in air gap is due to non-uniform absorber temperature.

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ABSTRACT

A 3D numerical model for flat-plate liquid solar collectors has been developed. This model is envisioned for predicting the efficiency curve of the collector, for which the different heat transfer mechanisms involved are simultaneously taken into account: solar radiation absorption, transmission and reflection; natural convection in the air cavity; heat conduction across the tube-absorber welded junction; mixed convection flow in the risers; and heat losses by convection and radiation to the ambient. To ensure the reliability of the model, the heat transfer results inside the risers and in the air cavity were contrasted with well-known experimental correlations available in the open literature.

The thermal efficiency obtained with this numerical model is successfully validated against own experimental data. This heat transfer model is intended for evaluating the impact of different operating conditions and design features on the overall performance of solar collectors, reducing costs in prototype construction and experimentation.

Contents

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Nomenclature

A_A	absorber area (m^2)
AR	aspect ratio ($AR = H/L$) (–)
$C_\mu, C_{\epsilon 1}, C_{\epsilon 2}$	turbulence model constant (–)
G	solar irradiance (direct and diffuse) ($W\,m^{-2}$)
H	air cavity height (m)
L	air cavity depth (m)
MCV	Mixed Convection Validation model (–)
NCV	Natural Convection Validation model (–)
$\dot{Q}$	useful power (W)
$\dot{Q}_t$	useful power supplied by each tube (W)
T	temperature (K)
T_{avg}	averaged temperature $(T_{in} + T_{out})/2$ (K)
T_h, T_c	air cavity hot and cold wall, respectively (K)
T^*	reduced temperature $(T_{avg} - T_{amb})/G$ ($W^{-1}\,m^2\,K$)
W	air cavity width (m)
c	width of contact zone (absorber-tube) (m)
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
d	internal tube diameter (m)
d_0	external tube diameter (m)
f_μ, f_1, f_2	damping functions (–)
g	gravity acceleration ($m\,s^{-2}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
l_n	wall normal distance (m)
$\dot{m}$	mass flow rate per tube ($kg\,s^{-1}$)
p	pressure (Pa)
q''_w	heat flux on the pipe wall ($W\,m^{-2}$)
q''_{conv}	top heat losses by convection ($W\,m^{-2}$)
q''_{rad}	top heat losses by radiation ($W\,m^{-2}$)
r, ϕ, z	cylindrical coordinates (m)
u	wind velocity ($m\,s^{-1}$)
u_i	mean velocity components in the x_i direction ($m\,s^{-1}$)
x, y, z	Cartesian coordinates (m)
x_i	Cartesian space coordinates $(i = 1, 2, 3)$ (m)

Dimensionless numbers

Gr_d	Grashof number for mixed convection in tubes $\left(g\beta q''_w d^4\right)/(k\nu^2)$
Nu_l	local Nusselt number on the absorber plate
Nu_{lcorr}	local Nusselt number on the absorber plate from experimental correlation
Nu_z	local Nusselt number on inner wall pipes hd/k
Pr	Prandtl number $\mu c_p/k$
Ra_d	Rayleigh number for mixed convection in tubes $\left(g\beta q''_w d^4\right)/(\alpha\nu)$
Ra_H	Rayleigh number for natural convection in cavities $(g\beta(T_h - T_c)H^3)/(\alpha\nu)$
Re_d	Reynolds number $\rho U d/\mu$
Re_t	turbulent Reynolds number $k^2/\nu\epsilon$
Ri	Richardson number Gr_d/Re_d^2
z^*	dimensionless distance in z direction $z/(LRePr)$

Greek symbols

α	thermal diffusivity ($m^2\,s^{-1}$)
β	thermal expansion coefficient (K^{-1})
δ_{abs}	absorber plate thickness (m)
δ_{gc}	glass cover thickness (m)
δ_{ins}	insulation thickness (m)
δ_w	weld thickness (m)
η	thermal efficiency (–)
θ	collector tilt angle (°)
μ	dynamic molecular viscosity ($kg\,m^{-1}\,s^{-1}$)
μ_t	turbulent molecular viscosity ($kg\,m^{-1}\,s^{-1}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
ν_t	turbulent kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	Stefan–Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
$\sigma_k, \sigma_\epsilon$	model constants (–)

Optical parameters

α	absorptivity (–)
ϵ	emissivity (–)
ρ	reflectivity (–)
τ	transmissivity (–)

Subscripts

abs	absorber plate
amb	ambient
$crit$	critical
ext	external
gc	glass cover
f	fluid
in	water inlet
out	water outlet
w	wall

1. Introduction

In 2011 the energy dependence in Europe reached a 53.8% over the total amount of energy consumption [1], and the trend shows an increasing value. The residential sector is responsible for the 24.7% of the final energy consumption. The use of flat-plate solar collectors to produce hot water is an effective means to reduce the energy dependence in this sector, hence contributing to the energy security through the use of renewable energies. In this regard, the EU Member States have committed themselves to achieving a 20% of renewable consumption in Europe's final energy by 2020. According with [2], the contribution of solar water heaters to this target, in the less ambitious scenario, would be 2.4%. The increasing importance of thermal solar collectors has led to significant progresses in their design features, all leading to an increase of the thermal efficiency. Main breakthroughs during the last years include new absorber plate characteristics [3–5]; improvements in the hydraulic or geometric design [6,7]; use of alternative materials [8]; and reduction of the thermal losses [9–11]. The accurate prediction of the thermal efficiency of an improved design is however an open question,