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Adoption of nanofluids in low-enthalpy parabolic trough solar collectors: Numerical simulation of the yearly yield

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ABSTRACT

Energy demand in the world is continuously increasing and fossil fuels resources must be replaced by renewable resources with lower environmental risk factors, in particular CO_2 emissions. Concentrating solar collectors appear to be very promising for that purpose. Thus, this work presents a numerical analysis for the evaluation of the yearly yield of a low-enthalpy parabolic trough solar collector (PTC). To increase the thermal efficiency of such systems, six water-based nanofluids at different weight concentrations are investigated: Fe_2O_3 (5, 10, 20 wt%), SiO_2 (1, 5, 25 wt%), TiO_2 (1, 10, 20, 35 wt%), ZnO (1, 5, 10 wt%), Al_2O_3 (0.1, 1, 2 wt%), and Au (0.01 wt%). The simulation environment was validated by experimental tests using water as heat transfer fluid, in two prototypes of PTC located in the city of Ancona (central Italy), while the convective heat transfer coefficient of nanofluids was measured through a dedicated apparatus. A typical meteorological year was built to perform the simulation, which presents a time-resolution of one hour. A specific arrangement for the PTC was defined, while different inlet fluid temperatures were considered at a mass flow rate of 0.50 kg/s: 40, 50, 60, 70, and 80 °C. For this last temperature, the variation in flow rate was also studied (at 1 kg/s and 1.5 kg/s). Results show that only Au, TiO_2, ZnO, and Al_2O_3 nanofluids at the lower concentrations, present very small improvements compared to the use of water, while increasing the concentration of nanoparticles no advantage with respect to water appears.

1. Introduction

The growth in energy consumption over the past 20 years has been significant and demand for energy will continue to grow due to global population increase. The global commercial low-temperature heat consumption is estimated to be about 10EJ per year only for hot water production [1]. The industrial energy consumption in the industrialized countries accounts for 30% of the total required energy; in Europe, two-thirds of this energy consists of heat [2]. The only way to meet this global heat demand without contributing to climate change and environmental problems implies the utilization of renewable sources.

Solar energy is the most abundant permanent energy resource on earth. One of the most popular low-temperature application of solar system is for domestic water heating. Beyond the domestic applications, solar energy has several potential fields of application for low-temperature industrial processes. A wide range of collectors can be used for these low-temperature applications: flat plate, evacuated tube, compound parabolic, and more advanced types such as parabolic trough collectors (PTCs), which appear to be one of the most promising technologies to use the energy of solar radiation [3].

The PTC technology was largely subsidized and developed during the last decade [4]. Today, the most urgent demand consists of increasing the thermal efficiency of these systems: this is particularly true for low-enthalpy (or low-temperature) PTCs. This group of PTCs should provide thermal energy to domestic applications (domestic water heating, swimming pool heating, space heating and cooling) and to industrial processes (pressurization, concentrates, boiler feed-water, preheating water, pasteurization, cooking, bleaching, dyeing, pressing, washing, sterilization) at temperatures up to about 100 °C [3]. One possible solution to improve the thermal efficiency of such systems could lie in the use of nanofluids as heat transfer fluids. In fact, it is reasonable to expect an increase in the thermal efficiency of low-enthalpy PTCs when the heat transfer base fluid is substituted with a nanofluid of appropriate concentration of nanoparticles.

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Nomenclature

Latin symbols

A_a	aperture area (m^2)
A_f	ratio of ineffective area to the whole aperture area
C	concentration ratio
c_p	specific heat at constant pressure (J/(kg K))
D	diameter (m)
DNI	direct normal irradiance (W/m^2)
E	energy for unit of aperture area (MJ/m^2)
f	focal distance (m)
H	radiation of the monthly average day (kW h/m^2)
h	convective heat transfer coefficient (W/(m^2 K))
K	extinction coefficient of the cover (1/m)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
Pr	Prandtl number
p	pressure (bar)
Q	heat flux (W)
r	specular reflectance of the mirror
Re	Reynolds number
RH	relative humidity
S	beam radiation (W)
T	temperature (°C)
W	aperture (m)
v	velocity (m/s)
x	axial distance (m)

Subscripts

a	absorber
bf	base fluid
b	beam
calc	calculated
c	convective, cover
e	environment
exp	experimental
f	fluid
i	inlet, inner, subsection
k	conductive
m	mean, mirror
nf	nanofluid
np	nanoparticle
n	normal
o	outer, outlet
r	radiative, receiver
u	useful
w	wall

Greek symbols

α	absorptance of the absorber
γ	intercept factor
δ	declination (°)
ϵ	emissivity
ζ	friction factor
η	thermal efficiency
η_o	optical efficiency
θ	angle of incidence (°)
θ_z	zenith angle (°)
λ	thermal conductivity (W/(m K))
λ_{eff}	effective conductive coefficient (W/(m K))
μ	dynamic viscosity (Pa s)
ξ	roughness of the absorber (m)
π	pi
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (W/(m^2 K^4))
τ	transmittance of the cover
$(\tau\alpha)$	transmittance-absorptance product
Φ	volume fraction of nanoparticles
ϕ	mass fraction of nanoparticles
ω	hour angle (°)

Acronyms

AAD	absolute average deviation
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
DIISM	Dipartimento di Ingegneria Industriale e Scienze Matematiche
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
GMT	Greenwich Mean Time
HTF	heat transfer fluid
IAPWS	International Association for the Properties of Water and Steam
MAD	maximum average deviation
OECD	Organization for Economic Co-operation and Development
PTC	parabolic trough collector
RMSE	root mean square error
TMY	Typical Meteorological Year
UNIVPM	Università Politecnica delle Marche

Some literature papers discuss how nanofluids affect solar PTCs, e.g., in Kasaeian et al. [5] carbon nanotube/oil based nanofluids were tested as working fluids founding an enhancement of 11% in the global efficiency of vacuumed tube. A literature review [6] on the applications of nanofluids in solar energy systems concluded indicating the necessity of further studies on the characterization of nanofluids, due to controversial results obtained until now. Another review [7] considered the efficiency in cooling photovoltaic and thermal solar collector systems.

SiO_2–water nanofluid is a promising heat transfer media: in literature it was studied in horizontal tubes finding an enhancement of heat transfer coefficient compared to pure water from 10% to 60% [8], in tubes under both steady and vibration states observing the larger increase of about 182% [9], and in Azmi et al. [10] obtaining a maximum heat transfer coefficient of 94.1% in a tube with twisted tape inserts. However, nanofluids are very complex fluids and experimental data acquired by using different experimental techniques could be different. Therefore, within an International Nanofluid Property Benchmark Exercise (INPBE), thermal conductivity of identical samples of stable colloidal dispersions of nanoparticles was studied at ambient temperature by over 30 organizations worldwide, using a variety of experimental approaches [11]. In this work, we consider one of those nanofluids, SiO_2, 50 wt%, Grace & Co., Ludox TM-50. Thermal conductivity measurements [12] found a good agreement (the deviation is 0.1%) with measurements at the same conditions by Buongiorno et al. [11]. Water-based SiO_2 nanofluid was studied for possible technical applications, e.g., it was tested in a loop thermosyphon [13] and in a car radiator [14]. Whereas, there are not studies involving SiO_2 nanofluids in a PTC.