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Experimental investigation of transparent parabolic trough collector based on gas-phase nanofluid

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HIGHLIGHTS

- A new PTC, with transparent receiver tube, has been experimentally studied.
- Two axes solar tracking PTC, with 4 m^2 reflecting surface has been realized.
- A mixture of CuO nano-powder and air has been used as working fluid.
- The experimental tests showed nanopowder deposition within the receiver pipe.
- In a day of measurement, the mean efficiency of about 65% has been reached.

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ABSTRACT

An experimental study on new high temperature parabolic trough collector (PTC), with transparent receiver tube, based on gas-phase nanofluid, has been carried out for the first time in this work. Two-axes solar tracking PTC, with 4 m^2 reflecting surface has been realized. Besides, two coaxial quartz tubes, with vacuum in the inner space were used as receiver pipe, with air-dispersed CuO nano-powders as working fluid. The aim of this work was to investigate the technological issues related to the use of gas-based nanofluid coupled with transparent quartz receiver and to evaluate the performance of the first prototype, comparing numerical and experimental results. The experimental campaign highlighted a critical issue related to nanopowder deposition within the receiver pipe, due to humidity. Moreover, in a day of measurement, the fluid temperature higher than 145 °C has been maintained for about 10 h, reaching a maximum value of 180 °C, with a mean efficiency of about 65%.

1. Introduction

In recent years, several types of parabolic trough collector (PTC) have been largely investigated and tested, renewing worldwide interest in this technology, that is suitable for electric power generation [1–4].

As known, PTC is the most common type of concentrating solar power technology. These systems typically use synthetic oil or molten salts as heat transfer fluid. Notwithstanding its characteristics of flammability and toxicity and its relatively low maximum working temperature (<400 °C), synthetic oil represents the most common heat transfer fluid in PTC power plants [5].

On the other hand, molten salts, while can work up to 600 °C [5–8], require expensive anti-freezing systems because of their solidification temperature of about 220 °C [9,10].

To overwhelm the limitations of synthetic oil and molten salts, according to de Risi *et al.* [11], in this work the authors proposed to use gas-phase nanofluid as heat transfer fluid in parabolic trough collector, with transparent receiver tube (named transparent parabolic trough collector, TPTC). The main difference between traditional opaque and innovative transparent receiver is related to the heat transfer mechanism between solar radiation and working fluid: in the first case the fluid is heated by thermal convection through the opaque receiver tube, while in the second case, the nanofluid is directly irradiated and heated by solar radiation. Several studies conducted on direct absorption liquid based nanofluids demonstrated advantages of direct absorption with respect to indirect one [12–15].

In recent years, numerous works have been carried out on thermal conductivity and heat transfer in nanofluids [16–26]. Furthermore, the high absorption coefficient of solar radiation, which characterizes different nanofluids [27–32] has been the inspiration for several studies. About that, Miller and Koenigsdorff [33]

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Nomenclature

a	aperture of mirror [m];
C_p	specific heat capacity [J/kg K]
d	diameter of receiver tube [m]
f	focal length of mirror [m]
I_b	solar radiation [W/m^2]
I_t	solar radiation passing through the receiver [W/m^2]
k	wave number
$K_{\alpha\gamma}$	angular factor
$\dot{H}_{abs}$	heat rate incident absorbed by heat transfer fluid [W]
$\dot{H}_{inc}$	heat rate incident on the receiver [W]
$\dot{H}_{loss}$	heat rate loss with the surroundings [W]
$\dot{H}_{inc}$	heat rate incident on receiver [W]
L	length of receiver tube [m]
$\dot{m}_{NF}$	mass flow rate of *NF* [kg/s]
m	nanoparticles complex refractive index;
N	number of nanoparticles per unit volume;
r	mean radius of nanoparticles;
R	thermal resistivity of receiver tube [K/W m]
S	area of the mirror [m^2]
S_I	effective area of the mirror [m^2]
t	global receiver transmittance
T_{env}	environmental temperature [K]
T_{in}	inlet temperature [K]
T_{NF}	temperature of *NF* [K]
T_{out}	outlet temperature [K]
W	minimum diameter of the receiver tube [m]

Greek letters

α	global receiver absorptance
γ	shape factor
ε	mean optical efficiency
η	solar to thermal efficiency
θ	incident radiation angle [°]
θ_r	rim angle [°]
ρ_s	mirror reflectivity
τ	*NF* trasmissivity

presented a thermal model of solar central receiver that volumetrically absorbs concentrated sunlight directly in flowing gas stream seeded with submicron carbon particles, while Bertocchi *et al.* [34] proposed a solar particle receiver, in which the particle/gas energy transfer is concluded within a short path length, which allows compact design and minimal conduction heat losses.

The above-mentioned studies encourage the use of gas-based nanofluid to directly absorb solar radiation, therefore in this paper, for the first time, a lab-scale prototype of TPTC operating with gas-based nanofluid as heat transfer fluid is experimentally investigated. The basic idea was to disperse nanoparticles, characterized by high optical absorbance and heat capacity, within an air steam flow running in a transparent receiver, in order to obtain direct absorption of solar radiation and a subsequent temperature increasing of the nanofluid. Therefore, aim of this work was to evaluate the performance of the prototype and to investigate technological problems related to use of gas-based nanofluid coupled with transparent quartz receiver. Finally, by comparing numerical and experimental results, the mathematical model of TPTC, developed in [11], has been validated.

2. Description of the system

A lab-scale prototype of TPTC has been realized in Lecce (Italy), according to the results of a previous numerical study on direct absorption solar power systems [11]. The prototype consists essentially of 4 m^2 TPTC, with blower for air-based nanofluid movement, heat dissipator, nanoparticles injection system and pressure regulation system to ensure constant pressure into the nanofluid circuit. In Figs. 1 and 2 a schematic layout and a picture of the prototype are shown, respectively.

In the main circuit (red line in Fig. 2), the air-based nanofluid is forced to pass through the transparent receiver by means of a blower. To compensate the increment of volume, related to the increase in temperature, ensuring constant pressure into the circuit, two water tanks, Tank$_1$ and Tank$_2$ connected with a bidirectional pump have been used (pressure regulation system in Fig. 2). The control system modifies the water level within the Tank$_1$ and subsequently the air volume, according to the measured pressure. A particles separator ensures no contamination between nanofluid circuit and water tank. The particles are loaded into the prototype by means of an injection system positioned on the blower intake.

2.1. The transparent receiver

The transparent receiver tube has been developed and realized through two coaxial quartz pipes, with vacuum of about 1 mbar absolute pressure within the annular space. Vacuum has been employed in order to reduce convective heat transfer from the receiver tube to the environment. The inner and outer quartz pipes have been connected together by means of a quartz annulus welded to both, so as to obtain a closed volume (Fig. 3a). Therefore, vacuum between the two pipes has been done by means of a mechanical pump connected to the quartz probe, shown in Fig. 3b. Finally, after the vacuum condition has been reached, the quartz probe has been locally heated up to its melting temperature and closed by clamping. In this first prototype, no coating (to reduce radiation heat losses) has been deposited on the quartz tube surface. Table 1 summarizes the main characteristics of the transparent receiver, while in Fig. 4 an optical scheme is reported.

In order to characterize the energy loss due to receiver positioning errors and to evaluate the relationship between imperfections of construction and optical performance of the system, a raytracing analysis has been carried out, by means of Opticad software, taking into account, as Sun-like light, a source with a dispersion angle of 0.534°. Fig. 5 shows the ray-tracing results for different positionings of the receiver with respect to the base of the mirror.

From the analysis of Fig. 5, it can be noticed that a deviation of 10 mm in the collector positioning, with respect to the geometric focus, leads to marked differences in the optical results. This value of deviation represents the precision level needed in construction of TPTC.

2.2. The parabolic mirror

The parabolic mirror is composed by two reflective panels of dimensions 1600 × 1250 mm, properly curved, to obtain a parabolic profile, whose focus is placed at distance of 1000 mm from the base of the mirror. Thereby, a linear extension of the parabolic mirror equal to 2500 mm has been obtained. The prototype of TPTC has been designed to withstand a headwind of 140 km/h and a temperature of 550 °C on the receiver and 100 °C on the mirror. Particularly, several FEM calculations have been carried out, according to the reference normative *NTC 2008 – 3.3*, which imposes a wind withstand of 140 km/h coupled with a safety factor of 1.4, for outdoor installations located in Lecce (Italy).