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Parabolic trough solar collector for low enthalpy processes: An analysis of the efficiency enhancement by using twisted tape inserts

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A B S T R A C T

Concentrated solar energy is a promising source of energy which is currently attracting many efforts to enhance its exploitation. In particular, parabolic trough collectors for low enthalpy processes is an emerging technology. Lately, many work is done focused on the improvement of these devices. One technique to achieve this is by augmenting the heat transfer in the receiver tube by inserting a twisted tape in the tube. In this work, we develop a thermodynamic model framework to analyse the performance of a parabolic trough collector with a twisted tape insert. We find the set of conditions under which a twisted tape insert is useful to boost the performance of a parabolic trough collector. This set of conditions corresponds to devices with low twisted ratios operating at low Reynolds numbers. The proposed model is supported with experimental data.

1. Introduction

A parabolic trough concentrator (PTC) is a promising solar concentration technology to integrate solar energy into the primary energy sources. This technology converts the solar beam radiation into thermal energy in its linear focus receiver. PTC applications can be divided into two main groups: a) for electricity generation and b) for thermal applications in solar heating for industrial processes.

Concentrated Solar Power (CSP) Plants is one of the main renewable energy technologies for the production of electricity by means of the Rankine cycle. This is a common technology employed for commercial projects in the capacity range from 10 MWe to 90 MWe, and the operating temperature is in the range from 300 to 400 °C. CSP projects have recently become more economically appealing due to the improvements in concentrated solar power technology and cost [1]. It is important to point out that in recent years, a way to harness the solar energy is to co-generate through Concentrated Solar Power (CSP) technology coupled to an Organic Rankine Cycle (ORC) with potential applications to industrial processes [2].

On the other hand, the generation of thermal energy for some industrial processes requires temperatures between 85 and 250 °C [1]. These applications are cleaning, drying, evaporation, distillation, pasteurization, sterilization and cooking, among others, as well as applications with low-temperature heat demand and high consumption rates (domestic hot water, space heating and swimming pool heating), and heat-driven refrigeration and cooling [3] [4], and [5]. It is common that these kind of concentrators are modular devices with solar collector areas in the range of 2.5–5.0 m^2 and they are used to generate hot water and low enthalpy steam. Table 1 shows some efficiency curves that have been reported in the literature for this type of PTCs.

The efficiency equations shown in Table 1 are established on the basis of the First Law of Thermodynamics.

Recently, one of the aims of solar-thermal engineering is to enhance parabolic trough concentrators for industrial processes. Some research reported in literature is addressed to the development of new devices, new applications, control methodologies, thermodynamic and technical-economic analysis, as well as the development of components, support structures, reflective

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Nomenclature

Symbols

A_a	Aperture area [m^2]
A_r	Receiver area [m^2]
$C_o = A_a/A_r$	Concentration ratio [−]
C_p	Specific heat at constant pressure [kJ/kgK]
D_i	Internal diameter [m]
D_o	External diameter [m]
$\dot{E}_D$	Exergy destruction [W]
$\dot{E}_U$	Exergy useful [W]
$\dot{E}_S$	Exergy supplied via solar energy [W]
F'	Efficiency factor [−]
F_R	Heat removal factor [−]
f	Focal length [m], Friction factor [−]
G_B	Direct solar radiation [W/m^2]
h	Heat transfer coefficient [W/m^{2}K]
I	Irreversibility
l	Length [m]
$\dot{m}$	Mass flow rate [kg/s], ($\dot{m} = \rho\dot{V}$)
$N_{S,a}$	Augmentation entropy generation number [−]
Nu, $\overline{Nu}$	Nusselt number (internal and external flow) [−]
P	Pressure [kgm/s^2]
Pr, $\overline{Pr}$	Prandtl number (internal and external flow)[−]
$\dot{Q}_{loss}$	Heat loss [W]
$\dot{Q}_u$	Heat useful [W]
$\dot{Q}_*$	Solar beam radiation collected by the PTC [W]
Re, $\overline{Re}$	Reynolds number (internal and external flow) [−]
$\dot{S}_{gen}$	Entropy generation rate [W/K]
T_a	Ambient temperature [K]
T_{in}	Temperature at the input of the receiver tube [K]
T_{out}	Temperature at the output of the receiver tube [K]
T_r	Temperature of the receptor [K]
$TR = y/w$	Twist ratio [−]
$T_s = 4500$ K	Apparent temperature of the Sun [K]
U_L	Global loss coefficient [W/m^{2}K]
V	Velocity [m/s]
$\dot{V}$	Volumetric flow rate [l/min]
W_a	Aperture width [m]
w	Tape width [m]
y	Tape pitch length [m]

Greek letters

α	Absorptivity [−]
$\alpha = k/\rho C_p$	Thermal diffusivity [m^2/s]
ΔF_R	Enhancement factor for the heat removal factor [−]
Δf	Change in the friction factor [−]
ΔP	Pressure drop [kgm/s^2]
ΔNu	Enhancement factor for the Nusselt number [−]
$\Delta\eta_I$	Enhancement factor by First Law [−]
$\Delta\eta_{II}$	Enhancement factor by Second Law
ε	Emissivity [−]
γ	Intercept factor [−]
η_o	Optical efficiency [−]
κ	Thermal conductivity [W/mK]
μ	Dynamic viscosity [kg/ms]
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3], Reflectivity [−]
η_I	Thermal efficiency [−]
η_{II}	Exergy efficiency [−]
σ	Stefan–Boltzmann constant [5.67051×10^{-8}Wm^{-2}K^{-4}]
ϕ	Rim angle []∘

Subscripts

air	air
D	Circular tube
E	Empty tube
TT	Twisted tape inserts
r	Receptor
v	wind
w	water

materials, materials for the receiver, and absorber surfaces. One way to enhance the efficiency of a solar collector is to produce a high convection heat transfer coefficient in order to increase the heat exchange between the solar energy arriving into the surface of the absorber and the thermal fluid. Heat transfer enhancement techniques can be classified into active and passive techniques, the former needs an external power source and the later dispenses it. Both techniques have been applied to improve heat transfer in several areas such as nuclear reactors, chemical reactors and for general purpose in heat exchangers. In the literature the applications of twisted-tape inserts in tubular heat exchangers, as a passive technique for heat transfer enhancement, have been widely studied. Various designs of twisted tapes have been tested in many devices for heat transfer augmentation [15–34].

In particular, the use of twisted tapes could play a significant role to improve the performance of solar water heating systems [35], since twisted tapes can be inserted inside the flow tubes in solar water heating systems to enhance the heat transfer rate, however the pumping power may increase significantly and its cost becomes significant during the operation. A brief review of the literature in this topic is presented below.

In 2000, Kumar and Prasad [36] studied the heat transfer and the pressure drop in a solar water heater with twisted tapes inserts. Their experimental investigations showed that the heat transfer increased by 18–70%, whereas the pressure drop increased by 87–132%, as compared to plane collectors. They observed that heat losses were reduced (due to the lower value of the plate temperature) consequently increasing the thermal performance by about 30% over the plane solar water heaters under the same operating conditions. The effect of twisted-tape geometry, flow Reynolds number, and intensity of solar radiation on the thermal

Table 1
Thermal efficiency for different low-medium-temperature parabolic trough concentrators.

Equation	Reference
$\eta_I = 0.66 - 0.233(\Delta T/G_B)$	[6]
$\eta_I = 0.65 - 0.382(\Delta T/G_B)$	[7]
$\eta_I = 0.642 - 0.44(\Delta T/G_B)$	[8]
$\eta_I = 0.638 - 0.387(\Delta T/G_B)$	[9]
$\eta_I = 0.69 - 0.39(\Delta T/G_B)$	[11] and [10]
$\eta_I = 0.0543 - 0.1889(\Delta T/G_B)$	[12]
$\eta_I = 0.5608 - 2.468(\Delta T/G_B)$	[13]
$\eta_I = 0.5523 - 2.0099(\Delta T/G_B)$	[14]