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Original Research Article

Design, simulation and optimization of a compound parabolic collector

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ABSTRACT

In this study, the optical and the thermal performance of a compound parabolic collector (CPC) with evacuated tube are presented. In the first part, the optimization of the reflector geometry is given and in the next part the thermal analysis of the solar collector is presented. The design of the reflector has a great impact on the solar energy exploitation and for this reason is analyzed in detail. In the thermal analysis of the collector, the two most usual thermal fluids, the pressurized water and typical thermal oil, are compared. Pressurized water performs better and it is the most suitable working fluid for transferring the heat because of its properties; something that is analyzed in this study. Moreover, the optical efficiency of the collector for various solar angles (longitude and transverse) is investigated and the heat flux distribution over the absorber is given. In the last part, the temperature distribution over the absorber and inside the fluid are presented and a simple validation of the thermal model is also presented. The model is designed in commercial software Solidworks and simulated in its flow simulation studio.

Introduction

The increasing cost of fossil fuels and of the electricity conjugated with the environmental problems caused by the CO_2 emissions lead our society to turn its interest in renewable energy sources. Solar energy utilization is a promising way to cover a great part of worldwide energy demand by various ways. The conventional flat plate collectors (FPC) are widely used for domestic hot water production and for low temperature applications (30–90 °C). Concentrating collectors with high concentrating ratios operate in high temperature levels (300–400 °C) [1] by giving suitable heat for electricity production in power plants. Parabolic trough collectors (PTC), Fresnel collectors, central tower receivers and parabolic dish Stirling engines [2,3] are the main solar technologies for electricity production. For the intermediate temperature range from 100 °C to 300 °C lessens number of solar collector types are used while many industrial and residential applications operate in these temperature limits. Applications as desalination, oil extraction, low temperature electricity production, food production, methanol reforming and space cooling with absorption technology [4–13] demand energy sources in the above temperature range. The most suitable solar collector for these conditions is the compound parabolic collector (CPC) with evacuated tube which is able to produce efficiently the processing heat. The use of the evacuated tube is essential in order to overcome the limit of 100 °C and the conjugation with a concentrating trough leads to higher levels.

CPC belongs to non-imaging concentrators with low concentrating ratio (1–5) [14,15] which exploits mainly the beam radiation and a part of diffuse radiation [8]. The small concentration ratio recuses the tracking demand and many CPC systems are able to operate without tracking which lead to lower cost [16,17]. More specifically, a tracking system with the CPC axis in East–West orientation needs only a small seasonal adjustment in order to perform in a high way [15]. The geometry design of a CPC is related to the application and every manufacturer takes into consideration the operating condition in every case. Important point in the design is the relation between concentration ratio and the acceptance angle which is inversely [14,15]. CPC invented by Winston in 1960 in the U.S.A. and they presented in 1974 [18,19]. The first applications were about hot water supply and many studies have been made for improving their performance. Rabl in 1976 [20] developed a mathematical model for the average number of rays reflections in a CPC, something very important for the optical analysis. Studies for CPC with non-evacuated tubes for thermal performance have been made in order to predict the efficiency in various operating conditions [21,22]. The use of evacuated tubes was first analyzed in Argonne National Laboratory [23] in before 1980. Snail in 1984 [24] analyzed an integrated stationary CPC with evacuated tube. The final results proved an optical efficiency of 65% and a thermal of 50%. Kim et al. [25] compared a stationary and a tracing CPC and proved that the tracking mechanism improves the efficiency at about 15%. Because the tracking system is important

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Nomenclature

A	area, m^2
C	concentration ratio
c_p	specific heat capacity, J/kg K
D	diameter, mm
f	focal length, mm
G	solar radiation, W/m^2
H	parabola length, mm
h_m	mean convection coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	tube length, mm
m	mass flow rate, kg/s
Nu_m	mean Nusselt number
Pr	Prandtl number
p	absorber placement, mm
Q	heat flux, W
q	down part placement, mm
Re	Reynolds number
T	temperature, °C
U_L	losses coefficient, W/m^2 K
W	aperture length, mm

Greek symbols

β	peripheral absorber angle, °
γ	intercept factor
ε	emittance
η	efficiency
θ	solar incident angle, °
θ_c	half-acceptance angle, °
θ_L	longitude solar angle, °
θ_T	transverse solar angle, °
μ	dynamic viscosity, Pa s
ρ	reflectance
$(\tau\alpha)$	transmittance–absorptance product
φ	Parabola angle parameter, °

Subscripts and superscripts

a	aperture
abs	absorbed
am	ambient
b	beam
c	cover
ca	cover-air
ci	inner cover
co	outer cover
d	diffuse
e	exploited
fm	mean fluid
in	inlet
L	Local
loss	losses
m	mean
max	maximum
o	oil
opt	optical
out	outlet
r	receiver
ri	inner receiver
ro	outer receiver
s	solar
th	thermal
tube	receiver tube
u	useful
w	water

parameter, many other researches have been worked in this area. Sallabery [26] analyzed how the tracking error influences on the long-term performance of the system and reported that the yearly energy loss is about 1%. A comparison of N–S and E–W orientated CPCs presented by Kim [5]. Mathematical equations for solar transversal projection angle, longitudinal projection angle are developed by Wang [27] so as the tracking systems to be analyzed more.

A lot of research has been conducted worldwide for the CPC performance improvement. The use of asymmetric CPC, which means two different parabolic shapes, has been studied from many researchers. The main idea is the development of a non tracking collector which performs well during the day due to the different shape of the reflector's parabolas that allows the collector to operate efficiently for a great range of incident angles. Abu-Bakar [28] studied a rotationally asymmetrical compound parabolic concentrator with a PV module, while Souliotis et al. [29] and Kessentini [30,31] analyzed asymmetrical CPC for integrated solar systems with one and two tanks inside the collector respectively. Moreover, Singh et al. [32] made a very interesting review about integrated collector solar water heaters stating the novelties that are able to increase their efficiency. These systems include compound parabolic reflectors, phase change materials and special materials (absorber and cover) in order to achieve high daily performance. The idea of solar cooker examined by Harmin [33] where a booster reflector was located in order to increase the optical efficiency in the stationary mode operation. The use of lens in the trough in order to increase the acceptance angle is an innovative idea which is being examined in recent years. Su et al. [34] made a comparison between lens-walled CPC, a common CPC and a dielectric solid CPC. The results showed that lens-walled CPC has greater acceptance angle, but it has lower optical efficiency in low incidence angles. Guiqiang et al. [14] analyzed also a lens-walled CPC with a PV module and resulted that the lens creates a uniform flux distribution in the PV-module which increases their efficiency.

In this study, a CPC with an evacuated tube is designed and simulated, while both an optical and thermal analysis has been conducted. Firstly, an optimization of its geometry is made in order to maximize the optical efficiency. Also, a parametric analysis for different solar angles (transversal and longitudinal) is given to calculate the optical losses for different cases. Moreover, a thermal efficiency comparison between pressurized water and thermal oil as working fluids is presented for different operating conditions. Finally, a deeper analysis for the best working fluid, the pressurized water, is presented. The simulation of the collector has been done with commercial software Solidworks flow simulation. The innovative point of this study is the reflector design. The methodology that is followed lead to an intercept factor close to 1, which is the ideal modeling. Moreover, a comparison between pressurized water and thermal oil is presented in order to determine the most suitable fluid energetically.

Examined model

A compound parabolic collector with an evacuated tube is examined in this study. The model was designed in Solidworks by a parametrical way in order to optimize its geometry. This optimization gives the opportunity to improve the collector optical