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Performance model and annual yield comparison of parabolic-trough solar thermal power plants with either nitrogen or synthetic oil as heat transfer fluid

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ABSTRACT

The majority of commercial parabolic-trough plants in the world operate with synthetic oil as heat transfer fluid in the solar field. However, the synthetic oils that are available at affordable cost present some challenges such as their flammability, environmental toxicity and a temperature limitation of around 400 °C. As alternative, this work proposes the use of pressurized nitrogen as heat transfer fluid. In order to analyze the feasibility of this technology, a comparison between a plant with nitrogen and a conventional plant with synthetic oil has been carried out. In both cases, 50 MW_e parabolic-trough plants with 6 h of thermal storage are used as reference. A performance model including the solar field, the thermal storage system and the power block has been developed for each plant in the TRNSYS simulation software. This paper also describes the specifications, design and sizing of the solar field and explains the basic operation strategy applied in each model. Both annual simulations have been performed considering the same location, Almería (Spain), and meteorological data. In summary, the results show that similar net annual electricity productions can be attained for parabolic-trough plants with the same collection area using either nitrogen or synthetic oil as heat transfer fluid.

1. Introduction

In solar thermal power (STP) plants, solar radiation is concentrated with the help of mirrors and converted to heat, which drives a power cycle connected to an electrical power generator. In addition, STP plants can be coupled to thermal energy storage (TES) systems in order to provide energy dispatching to meet the electricity demand. Most of the STP plants currently in operation use a field of parabolic-trough collectors to redirect and concentrate sunlight onto a receiver tube located at the focal line of the mirrors. Each collector tracks the sun by rotation around a horizontal axis. Up to date, STP plants with parabolic-trough technology are widely developed, with about 3000 MW_e installed and in operation around the world [1].

The heat transfer fluid (HTF) circulating inside receiver tubes of parabolic-trough collectors of commercial plants is typically synthetic oil [2]. However, synthetic oils used as HTF are toxic, flammable and expensive fluids that have a maximum working temperature around 400 °C. In order to overcome these issues, alternative fluids such as water [3], molten salts [4] or pressurized gases [5] are nowadays being studied. These fluids do not pose the safety and environmental issues of synthetic oil and are able to work at higher temperatures in the solar field. Since the efficiency of thermodynamic cycles increases with the temperature of the heat source, higher solar field temperatures would provide higher efficiencies for the power block [6]. Additionally, higher temperature differences between solar field inlet and outlet would make TES more efficient, increasing the storage capacity per volume and thus reducing the amount of storage medium.

Pressurized gases are safe and clean fluids from an environmental viewpoint. Additionally, they have no temperature limitations when they are used as HTF in parabolic-trough collectors and allow a suitable integration with a thermal storage system based on molten salts. Nevertheless, since the required pumping power of gases to compensate circuit pressure drop is inversely proportional to the square of the pressure [5], a high working pressure is needed to avoid excessive pumping consumptions.

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Nomenclature

A_c	net collection area, m^2
c_p	specific heat capacity, J/(kg K)
D	diameter, m
E_b	direct normal solar irradiance, W/m^2
F	proportionality factor
g	standard gravity, m/s^2
H	tank level, m
HTF	heat transfer fluid
HX	heat exchanger
k	thermal conductivity, W/(m K)
K	pressure drop/quadratic mass flow rate coefficient, $kg^{-1}\ m^{-1}$
$K(\theta)$	incidence angle modifier
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
N_{loops}	number of collector loops in the solar field
P	electric power, W
p	pressure, Pa
Q	thermal energy, J
$\dot{Q}$	thermal power, W
STP	solar thermal power
t	time, s
T	temperature, K
TES	thermal energy storage
U	internal energy, J
v	fluid velocity, m/s

Greek symbols

Δ	difference or variation
η	efficiency
θ	incidence angle, °
ρ	density, kg/m^3

Subscripts

clean	cleanliness
col	solar collector
dist	distribution pipes
eq	equivalent
gross	gross power or energy
in	inlet
loop	collector loop
loss	thermal or electric losses
net	net power or energy
night	during the night
nom	nominal
oil	synthetic oil
old	value in the previous time step
opt,0°	peak optical
out	outlet
PB	power block
pipe	steel pipes
pump	pumping
salt	molten salts
SF	solar field
SG	steam generator
sh	shadowing
start	startup
tanks	storage tanks
use	useful

The evaluation of the technical and economic feasibility of pressurized gases as HTF was addressed by CIEMAT in the 'Gas-cooled solar collectors' project [7]. The program included the analysis of several working gases (helium, CO_2, N_2 and air) and the design, construction and testing of an experimental facility with 100 m of parabolic-trough collectors at Plataforma Solar de Almería. Firstly, helium was discarded due to its high cost and the possible leaks through piping and components because of the small size of helium atoms [8]. Both N_2 and air are very similar in terms of thermohydraulic properties, but CO_2 shows a higher density and similar specific heat at the expected working conditions, which leads to lower pumping consumptions. As a consequence, CO_2 was chosen as working fluid for the test facility. However, in case of water presence, CO_2 could react to form carbonic acid (H_2CO_3), which is corrosive to carbon steel [9]. Since carbon steel is widely used in STP plants, the use of CO_2 would imply that the water content should be carefully controlled. Although air does not have the strong drying requirements of CO_2, it still would require preventive measures in order to limit the water content in the circuit. On the contrary, N_2 presents less corrosion issues than either CO_2 or air and can be obtained in a simple way from compressed air by means of a nitrogen generator [10]. Therefore, nitrogen could be the most feasible HTF among the proposed gases for a commercial STP plant.

The overall costs of a large solar field with nitrogen as HTF will be higher than that of a synthetic-oil field due to the incremental cost of distributed blowers and heat exchangers. On the other hand, higher temperature differences in TES imply a lower molten salts inventory and therefore the cost of storage will be lower for the N_2 plant. Moreover, the cost of synthetic oil and the corresponding equipment (pumps, expansion vessels, conditioning system, etc.) will be replaced by a lower cost of nitrogen.

Although the behavior of N_2 as HTF in an optimized loop of parabolic-trough collectors has been modeled in a previous work [11], a performance model of a whole plant is required to assess its commercial feasibility. This model should address several uncertainties posed by this technology, such as the required pumping power, the effect of thermal inertia of the piping or the specific plant operation. In order to compare the new technology with conventional STP plants, another performance model for synthetic-oil that applies the same assumptions as the N_2 model should be also developed. The use of the same meteorological data input for both models will allow us to compare electricity production for a certain period of time, but the difference between both plants may strongly depend on the time of year. In order to consider the influence of seasonal variability, annual yield results are presented in this analysis.

The objectives of this work are the definition, modeling and annual yield analysis of two parabolic-trough STP plants using either nitrogen or synthetic oil as HTF, taking as reference a 50 MW_e plant with 6 h of TES located in Almeria. This paper also describes the solar field layout and explains the two performance models developed. Finally, the annual results of both plants are compared and discussed.

2. Description of the STP plants

Two 50 MW_e parabolic-trough STP plants have been considered for the analysis, one with nitrogen as HTF and one with synthetic oil. Fig. 1 shows the basic diagrams of the plants to be modeled, which are composed of the solar field, the storage system and the power block. In parabolic-trough STP plants, the cold HTF is pumped through the solar field where it is heated up. Then, the