Energy Conversion and Management 79 (2014) 666–673

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermodynamic model to study a solar collector for its application to Stirling engines

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ARTICLE INFO

Article history:
Received 22 August 2013
Accepted 16 December 2013
Available online 31 January 2014

Keywords:
Solar collector
Optical analysis
Overall loss coefficient
Fluid temperature
Absorber tube
Heat loss
Thermal analysis

ABSTRACT

Energy production through clean and green sources has been paid attention over the last decades owing to high energy consumption and environmental emission. Solar energy is one of the most useful energy sources. Due to high investment cost of centralized generation of electricity and considerable loss in the network, it is necessary to look forward to decentralized electricity generation technologies. Stirling engines have high efficiency and are able to be coupled with solar energy which cannot be applied in internal combustion engines. Solar Stirling engines can be commercialized and used to generate decentralized electricity in small to medium levels. One of the most important steps to set up an efficient solar Stirling engine is choosing and designing the collector. In this study, a solar parabolic collector with 3500 W of power for its application to Stirling engines was designed and analyzed (It is the thermal inlet power for a Stirling engine). We studied the parabolic collector based on optical and thermal analysis. In this case, solar energy is focused by a concentrating mirror and transferred to a pipe containing fluid. MATLAB software was used for obtaining the parameters of the collector, with respect to the geographic, temporal, and environmental conditions, fluid inlet temperature and some other considerations. After obtaining the results of the design, we studied the effects of changing some conditions and parameters such as annular space pressure, type of the gas, wind velocity, environment temperature and absorber pipe coating.

1. Introduction

As a non-emission and lasting energy, solar energy and its related applications has been widely studied such as solar buildings [1], solar water heating systems and solar energy conversion systems [2–19]. In solar energy systems, thermal energy storage (TES) unit is an important component to ensure the system stability and steady operation with high efficiency performance; due to dependence of its performance on weather conditions and time. Latent heat thermal energy storage (LHTES) has more density and grater temperature of constant phase change, in comparison with TES. Recently, parabolic trough power plant has become as a unique and progressed mean for solar electricity production. A parabolic trough solar collector (PTC) utilizes the energy of sun radiation and employs its useful thermal energy for the heat transfer fluid (HTF) which circulates in the system.

By determining the geometry and thermal properties of a solar system, the thermal performance and energy obtained by the HTF can be estimated under different conditions. PTCs usually operate at 400 °C. Synthetic oil is utilized as HTF generally. Primary design of the solar power plant, prediction of thermal losses, study of collector degradation effects and HTF flow rate control require heat transfer analysis [20]. Researchers have been working on numerous heat transfer models of PTCs, since 1970s.

Edenburn [21,22] evaluated the efficiency of a PTC by using an analytical heat transfer method and the results were satisfying. Ratzel et al. [23] performed both analytical and numerical study of the heat losses in an annular receiver. Clark [24] has studied the thermal and economical performance of parabolic trough receivers. Dudley et al. [25] presented a one dimensional steady state thermal model of SEGS LS-2 parabolic collector. This model was verified with experimental data of Sandia National Laboratories (SNL) for various receiver annulus settings.

Thomas [26] has investigated a set of numerical equations based on heat transfer and heat loss analysis in a PTC receiver. A

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http://dx.doi.org/10.1016/j.enconman.2013.12.039

Nomenclature

A_f	the ratio of loss area to total area of concentrator
C_p	specific heat capacity (J kg^{-1} °C^{-1})
D	diameter (m)
F_R	the ratio of heat transfer to maximum heat transfer
F'	collector efficiency factor
h	convection heat transfer coefficient (W m^{-2} °C^{-1})
h_f	HTF convection heat transfer coefficient at T_f (W m^{-2} °–C^{-1})
I_b	beam radiation incident on the receiver surface
k	thermal conductivity (W m^{-1} °C^{-1})
g	gravitational constant (9.81 m s^{-2})
$\dot{m}$	mass flow rate (kg s^{-1})
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
T	temperature (°C)
T_p	is the mean temperature of absorber tube
N	number of day from 1st January
h_s	the hour angle
La	latitude
U_L	achieved through heat transfer modeling between external surface of absorber tube and environment
W_a	the collector aperture (m)

Greek letters

ν	kinematic viscosity (m^2 s^{-1})
β	volumetric thermal expansion coefficient (ideal gas) (K^{-1})
σ	Stefan–Boltzmann constant
φ_r	rim angle
φ	the angle between collector axis and reflector beam
ρ	surface reflectance
ε	emissivity
α	absorbance
$\boldsymbol{\delta_s}$	inclination angle

Acronym

SNL	Sandia National Laboratories
TES	thermal energy storage
LHTES	latent heat thermal energy storage
PTC	parabolic trough solar collector
HTF	heat transfer fluid

one dimensional energy balanced model was designed by Forristall to evaluate heat transfer of solar receiver [27]. Stuetzle [28] presented an unsteady state analysis of solar collector by partial differential equations to determine the outlet temperature. Valladares and Velasquez [29] investigated a numerical model for a single pass solar receiver. They showed that the proposed configuration increases the thermal efficiency of the solar collector. Recently, three dimensional heat transfer analysis of PTCs was carried out by simultaneously use of the Monte Carlo Ray Trace Method (MCRT) and CFD analysis [11,30,31].

In the present work, initially, we review the solar radiation energy and the effective parameters on absorbed solar flux. These parameters depend on season, time of day, location and incident beam. Then, we analyze based on optical. Absorbed reflective flux by absorber pipe is one of the results of the optical analysis. In the next step, thermal analysis with respect to the energy equilibrium model is carried out. This model includes all the necessary equations to determine the components in the energy balance such as type of the collector, terms of absorber pipe, the optical properties and the environmental conditions. The absorbed heat is results of this analysis that are gained using MATLAB software. According to the analysis and the considered power of collector, we wrote a code in MATLAB software and we studied and designed the collector. This design is considered the geographic, temporal, and environmental conditions such as the atmospheric pressure, the environmental temperature, and wind velocity. Also, other factors like type of the fluid, the annular space pressure (between the absorber pipe and the glass coating) and some design considerations for the components of the collector including concentrator, absorber tube and glass coating on the absorber are studied and designed.

2. Optical analysis

Kalogirou studied parabolic collectors through optical analysis. The angle between incident beam on the edge of concentrating surface (where mirror radius r_r, is maximum) and center line of the collector is φ_r which is called rim angle [32].

Diameter is found from following equation.

$$D = 2r_r \sin(\theta_m) \quad (1)$$

θ_m which is shown in Fig. 1, is a function of the tracking mechanism precision and reflective surface disorders [32].

$$r = \frac{2f}{1+\cos(\varphi)} \quad (2)$$

where φ is the angle between the collector axis and the reflector beam.

When φ changes from 0 to φ_r consequently, r changes from f to r_r and D increases from $2f\sin(\theta_m)$ to $\frac{2r_r \sin(\theta_m)}{\cos(\varphi_r+\theta_m)}$. Eq. (2) in φ_r angle;

$$r_r = \frac{2f}{1+\cos(\varphi_r)} \quad (3)$$

W_a is found from Eq. (4)

$$W_a = 2r_r \sin(\varphi_r) \quad (4)$$

where W_a is the collector aperture (m).

Through Eqs. (3) and (4)

$$W_a = \frac{4f\sin(\varphi_r)}{1+\cos(\varphi_r)} \quad (5)$$

$$W_a = 4f\tan\left(\frac{\varphi_r}{2}\right) \quad (6)$$

In parabolic collectors, a number of reflective beams to the concentrating do not have incident to receiver, which is known as end effect and the area is illustrated in Fig. 2.

$$A_e = fW_a tan(\theta)\left[1+\frac{W_a^2}{48f^2}\right] \quad (7)$$

These kinds of collectors are often restricted by opaque plates which causes shadow on a part of reflector [32,38,39].

$$A_b = \frac{2}{3}W_a h_p tan(\theta) \quad (8)$$