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Optimization of non-evacuated receiver of solar collector having non-uniform temperature distribution for minimum heat loss

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ABSTRACT

The present paper contains a numerical study of heat loss from a non-evacuated receiver typically used in parabolic trough collectors. To calculate temperature distributions on the receiver pipe (T_P), an energy balance has been established over the entire cross-section of the receiver pipe at different fluid temperatures. In the energy balance, the flux distribution has been estimated by assuming normal incidence of solar insolation considering the sun as a point source. The temperature distributions of the receiver pipe are found, as per expectation, to be non-uniform. These temperature distributions have been fitted by sinusoidal and step functions and are used as temperature boundary conditions in a CFD study to optimize the size of the receiver. The mechanisms of heat loss that have been considered in this study are heat loss from (1) pipe to glass tube by conduction, convection and radiation and (2) glass tube to surrounding by convection (natural and forced) and radiation. The values of diameters of receiver pipe taken in this study are 33 mm, 48 mm, 60 mm, 70 mm, 89 mm and 102 mm. The radius ratio (RR) varied from 1.2 to 3 by changing diameter of glass tube. It is observed that, the critical value of RR for minimum heat loss is dependent upon receiver pipe diameter (D_{Po}). The critical values of RR for pipe diameter (D_{Po}) 33 mm, 48 mm, 60 mm, 70 mm, 89 mm and 102 mm are 1.5, 1.4, 1.375, 1.35, 1.3 and 1.25 respectively. The value of critical RR is lower for higher values of pipe diameter. The value of critical RR for a particular diameter of receiver is independent of receiver temperature and external wind velocity. Comparison of heat losses in non-uniform and uniform temperature cases shows that the values of heat losses in the two cases differ only by 1.5%.

1. Introduction

Among all solar thermal technologies, parabolic trough collector (PTC) is technically and commercially the most mature. In 2010, it claimed the largest share of electricity generation by solar thermal technologies [1]; being capable of generating temperatures up to 400 °C, suitable for electricity generation. In the chemical and allied process industry however, more than 40% of the energy is used as industrial process heat (IPH) for direct thermal applications. Steam temperatures required for IPH are normally below 250 °C. The largest share of the total IPH demand is currently met by saturated steam at the requisite temperature [2]. [3] and Riffelman et al. [4] have compared thermal and economic performance of flat plate collectors, evacuated receiver with compound parabolic concentrators and parabolic troughs at different temperatures. The results of these studies showed that small-sized parabolic-trough collectors achieve the highest economic performance to supply heat between 120 °C and 200 °C.

Parabolic reflector with receiver pipe is schematically shown in Fig. 1. PTC receiver assembly (Fig. 1B) normally consists of an inner metallic absorber pipe (2), enclosed within a glass tube enclosure (3) with an annular gap between the two. The radiation from the sun is reflected by the curved mirror to the outer surface of the absorber tube and is absorbed by the tube wall. The working fluid flowing through the receiver carries away the energy conducted to the inner surface of the inner tube. The receiver pipe is covered by a glass tube to reduce radiative as well as convective heat losses to the surrounding. For large scale parabolic collectors, the absorber pipe is generally of the order of 40–100 mm outer diameter and glass tube is generally installed with 55–150 mm outer diameter.

To further reduce heat losses from absorber, air is evacuated from the space between absorber and glass cover (evacuated receiver). Also the radiative heat transfer is minimized by using solar selective coating on the outer surface of the inner metallic receiver pipe. Solar selective coatings have high absorptivity for

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Nomenclature

2D	two dimensional
a	non-uniformity in temperature (K)
C_p	specific heat (J/kg k)
D_G	diameter of glass tube (m)
D_p	diameter of receiver pipe (m)
F	focal length (m)
f	friction factor
g	acceleration due to gravity (m/s^2)
Gr	Grashoff number
h	heat transfer coefficient (W/m^2 K)
I_b	solar beam radiation (W/m^2)
j	collector end modifier
k	thermal conductivity (W/m k)
K	incident angle modifier
k_e	equivalent thermal conductivity (W/m k)
k_e/k	effective thermal conductivity
Nu	Nusselt number
Pr	Prandlt number
q	rate of heat transfer (W/m)
q_f	energy gain by the thermic fluid (W/m)
q_L	energy loss from receiver pipe (W/m)
q_s	solar energy absorbed by the receiver pipe (W/m)
Ra	Rayleigh number
Re	Reynolds number
R_G	radius of glass tube (m)
R_P	radius of receiver pipe (m)
RR	radius ratio
T	temperature (K)
T_∞	temperature outside the boundary layer (K)
T_P	average temperature of receiver pipe (K)
T_U	uniform temperature (K)
U	overall transfer coefficient (W/m^2 K)
u	velocity in x direction (m/s)
U_o	reference velocity (m/s)
v	velocity in y direction (m/s)

Greek letters

α	absorptivity of selective coating
β	thermal expansion coefficient (K^{-1})
γ	reflectivity of mirror surface
η	optical efficiency
θ	angle (°)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
τ	transmissivity of glass tube
ψ	rim angle (°)
ς	intercept factor

Subscript

f	fluid
i	inner
m	maximum
o	outer
v	vacuum
w	surface of pipe

wavelengths dominating the solar spectrum and low emissivity at wavelengths corresponding to temperatures less than 1000 °C. Heat transfer from glass tube to ambient air is partly by radiation, but mostly by convection: both natural and forced by the wind.

In most of solar receiver studies reported in literature [5–7], the temperature distribution on receiver pipe is assumed to be uniform. Heat is transferred between receiver pipe and glass tube by natural convection and radiation. This is similar to heat transfer between air filled annular gap between two concentric pipes. Extensive literature is available on this topic [8–10]. However, even here, the work is mostly carried out under the conditions of uniform temperatures of the inner and outer pipes or when a constant heat flux is incident on the inner pipe. In some investigations [8,9], the researchers have studied the effect of gap width and eccentricity on heat transfer and suggested correlations for effective thermal conductivity (k_e/k) as a function of Rayleigh number (Ra_L) where Ra_L is dependent upon the gap width. On the other hand, some researchers have studied the effect of the radius ratio ($RR = R_{Gi}/R_{Po}$) on heat transfer. In this connection Kumar, El-sherbiny and Moussa [10,11] proposed correlations between Nusselt Number (Nu) and Ra_i for different values of RR where Ra_i depends upon diameter of inner pipe. Alshahrani and Zeitoun [12] proposed an equation for k_e/k as a function of modified Rayleigh number Ra_m, which indicates dominance of convective heat transfer in the total heat transfer.

In recent years, work has been reported on PTC to study the heat transfer between receiver pipe and glass tube. Assuming uniform temperature distribution on receiver pipe, Al-Ansary and Zeitoun [6] proposed receiver design for low temperature and studied its performance numerically. They fitted fiberglass insulation into the portion of the receiver annulus that does not receive concentrated sunlight; and found that the presence of fiberglass insulation reduces heat loss significantly. Daniel et al. [5] proposed a new design of receiver with double glass envelopes, having two annular gaps. The inner gap is filled with air at atmospheric pressure and the outer one is evacuated. In their study, they also assumed uniform temperatures across the receiver pipe and glass tube; and they found that the receiver they designed performed better than a conventional evacuated single gap receiver. Kassem [7] has numerically investigated natural convective heat transfer for solar receivers in non-evacuated annular gap between the receiver pipe and outer glass envelope. In his simulation, he considered a fixed value of RR, and the glass envelope was considered to be isothermal. However he did consider a sinusoidal distribution of heat flux on receiver pipe.

Dudley et al. [13] performed tests at Sandia National Laboratories to determine thermal losses and thermal efficiency of the PTC used in LS2 Solar Thermal Electric Generation Systems (SEGS). Foristall [14] implemented both a one-dimensional (1D) and a two-dimensional (2D) model by dividing the absorber into several segments. A direct steam generation (DSG) collector model was proposed by Odeh et al. [15] based on the absorber wall temperature rather than the working fluid temperature. Padilla et al. [16] presented a 1D heat transfer model of a PTC taking into account the thermal interaction between adjacent surfaces and neglecting the non-uniformity of the solar flux. Lei et al. [17] have investigated all the modes of heat losses, end losses and thermal emissivity of the coating of a newly designed receiver in order to evaluate its thermal performance. They have presented new testing method to accurately test the coating emissivity. Ouagued et al. [18] have developed a heat transfer model in order to evaluate the performance of a tracking solar parabolic trough collector. The receiver, heat collector element (HCE), is divided into several segments and heat balance is applied in each segment over a section of the solar receiver.

Bhowmik and co-worker [19,20] have developed correlations for heat loss factor for different configurations of solar receiver. They proposed a semi-empirical equation for the heat loss factor