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Combined heat loss analysis of solar parabolic dish – modified cavity receiver for superheated steam generation

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Abstract

In this article, a 3-D numerical modeling is carried out to determine combined convection and surface radiation heat losses from a modified cavity receiver of parabolic dish collector used as mono-tube boiler for sub-cooled, saturated and superheated steam generation conditions. The forced convection heat loss from the modified cavity receiver is estimated using Nusselt number correlation developed for the modified cavity receiver. The effect of receiver inclination (β), operating temperature (T_w), emissivity of the cavity cover (ϵ), thickness of insulation (t_{ins}) on the combined heat losses from the modified cavity receiver is investigated. The boundary conditions for wall temperature and insulation thicknesses are chosen to match the three steam generation conditions. It is found that the natural convection heat losses are higher at $\beta = 0^\circ$ (receiver facing sideward) and lower at $\beta = 90^\circ$ (receiver facing down) whereas the forced convection heat loss is higher at $\beta = 90^\circ$ and lower at $\beta = 0^\circ$. The variation of radiation heat losses is marginal for all values of β and vary with T_w. The effect of various parameters such as receiver inclination, wind direction (φ), wind speed and diameter ratios on forced convection heat loss from the receiver has also been studied. The forced convection heat loss at lower wind speeds (<2.5 m/s) is lower than the natural convection heat losses. The maximum heat losses occur at side-on wind direction ($\varphi = 0$) followed by head-on wind directions ($\varphi = 30$–90°) and back-on wind directions ($\varphi = -90^\circ$ to -30°). The heat losses vary with diameter ratios for different configurations of the receiver. The forced convection heat loss is 1.2–9 times higher than natural convection heat loss for diameter ratio (ratio of cavity diameter to aperture diameter, d/D) = 0.4 at 5 m/s and receiver inclinations varying from 0° to 90°. Nusselt number correlations have been proposed based on the numerical analysis to estimate the combined convective and radiative heat loss. The present study attempts to estimate natural convection, forced convection and surface radiation heat losses from the modified cavity receiver under various conditions.

Keywords: Solar parabolic dish; Modified cavity receiver; Combined convection and radiation heat losses; Numerical modeling

1. Introduction

The solar energy utilization significantly minimizes the dependency on fossil fuels. The solar thermal technologies have a large amount of potential for process heat in 2050 (Taibi et al., 2011). Concentrating solar collectors can be utilized for production of high temperature heat. Different solar collectors are used for industrial process heat applications based on the temperature ranges and operating pressure which require hot water/steam for their operations. About 28% of overall energy demand is found in industrial sector of European Union countries (EU27) which can utilize the solar energy. In several industries such as food, textiles, pulp and paper industries the share of heat demand below 250 °C is about 60%. Solar Heat and Cooling programme (Task 49) of International Energy Agency concentrates at three areas: process heat collectors,

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Nomenclature

A	heat transfer area (m^2)
C_p	specific heat capacity (J/kg K)
D	aperture diameter of the receiver (m)
d	cavity diameter of the receiver (m)
d/D	diameter ratio
E_b	energy leaving a surface (W)
F_{ji}	view factor between surfaces j and i
f	body force per unit volume (N/m^3)
Gr	Grashof number
g	acceleration due to gravity (m/s^2)
H	irradiation (W/m^2)
H_o	external contribution to radiation (W/m^2)
h	heat transfer coefficient (W/m^2 K)
J	radiosity
k	thermal conductivity (W/m K)
Nu	Nusselt number
p	pressure (N/m^2)
Q	heat loss from the receiver (W)
Re	Reynolds number
S2S	surface to surface
T	temperature (K)
t	thickness of insulation (mm)
V	wind speed (m/s)
V_r	velocity vector in r direction
V_θ	velocity vector in θ direction
V_z	velocity vector in z direction

Greek symbols

γ	conductivity parameter
ϵ	emissivity of the cavity cover
φ	wind direction (°)
β	angle of inclination of the receiver (°)
ν	kinematic viscosity of the fluid (m^2/s)
ρ	density of the fluid (kg/m^3)
ρ_r	reflectivity of the surface
ξ	angle (°)

Subscripts

cu	copper tubes
f	fluid
fc	forced convection
h	hot
i, j	surfaces
ins	insulation
m	area weighted average
ms	mild steel cover
nc	natural convection
rad	radiative
w	receiver inner wall surface
∞	ambient

process integration and intensification and design guidelines for tapping this potential at higher levels (Brunner, 2015). Kalogirou (2003) provides details of hot water/steam temperatures for different industrial process heat applications. In this context, present study aims at investigating heat losses from the cavity receiver of solar parabolic dish system for process heat and power generation applications. The solar parabolic dish collector is one of the most efficient energy conversion technologies of the four concentrated solar power (CSP) technologies namely; linear Fresnel collector, parabolic trough collector, parabolic dish collector and solar power tower. Solar parabolic dish collectors is the most efficient among CSP technologies for steam generation; the receiver thermal efficiency of parabolic dish, trough, tower are 0.85–0.9, 0.729, 0.783 respectively (Lovegrove et al., 2007). The receiver/absorber plays an important role in CSP technologies to convert concentrated solar energy into high temperature heat. The main purpose of the receiver is to absorb maximum amount of concentrated solar energy and its conversion to heat with minimum losses (Kumar and Reddy, 2007).

Various cavity studies related to electronic cooling and buildings have also been presented by Wu et al. (2010) apart from those related to solar receiver design. Kumar and Reddy (2008) performed combined laminar convection and radiation heat loss analysis from a modified cavity receiver. The receiver wall temperature is considered isothermal and the outer cavity surface is considered to be adiabatic. Based on the analysis, it is found that the cavity receiver with area ratio of 8 has better performance. Prakash et al. (2012) numerically investigated the natural convective heat loss from open cavities viz., cubical, spherical and hemispherical cavities for equal heat transfer area with constant wall temperatures of 100, 200, 300 °C and proposed a Nusselt number correlation with the involving effect of cavity shape, Rayleigh number, inclination angle and opening ratio. Various researchers considered isothermal receiver cavity surface and adiabatic cavity walls with or without wind conditions. But in practical, the cavity wall surface temperature depends on the type of application it is used for and the cavity walls are not adiabatic. The varying temperature boundary condition along the walls of the cavity receiver is considered for three different steam generation conditions say, superheated (500 °C, 45 bar) (Lovegrove et al., 2007), saturated (250 °C, 40 bar) and sub-cooled (180 °C, 10 bar) conditions (Tamme, 2007). The estimation of combined convection and surface radiation heat losses from modified cavity receiver considering varying temperature boundary conditions based on the three different steam generation conditions are carried out by Vikram and Reddy (2014, 2015).