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Heat loss characteristics of trapezoidal cavity receiver for solar linear concentrating system

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ABSTRACT

In this paper, a numerical study of combined natural convection and surface radiation heat transfer in a solar trapezoidal cavity absorber for Compact Linear Fresnel Reflector (CLFR) is presented. The CFD package, FLUENT 6.3 is used to develop the 2-D, non-Boussinesq, steady state, laminar, combined natural convection and surface radiation heat transfer model for a trapezoidal cavity absorber. The validation of the present non-Boussinesq numerical procedure is compared with other closed cavity model. Based on the validated non-Boussinesq model, the combined heat loss coefficients are predicted for various parameters such as Grashof number, absorber angles, surface emissivity, aspect ratio, temperature ratio and radiation–conduction number. The numerical simulation results are presented in terms of Nusselt number correlation to show the effect of these parameters on combined natural convection and surface radiation heat loss.

1. Introduction

Combined convective and radiative heat transfer in enclosures has been receiving a good deal of research interest of many researchers due to its relevance to many engineering applications such as solar energy collection devices, energy efficient buildings, and double pane window. Among solar energy collection devices, Compact Linear Fresnel Reflector (CLFR) design concept has been proposed for high temperature steam generation applications. In this design concept, a series of long narrow flat mirrors are aligned and tilted at an angle such that the direct beam solar radiations falling on the mirror elements are reflected onto the focal line. Usually, the trapezoidal cavity absorber is placed at the focal line. The efficiency of the solar power plant is mainly determined by the amount of energy collection at the trapezoidal cavity absorber. The amount of energy collection is usually obtained by subtracting the heat losses from the absorbed solar energy. Thus, the estimation of heat losses in a trapezoidal cavity absorber is an important input to the performance evaluation of the solar collector. Among the heat losses, conduction and radiation heat loss can be determined analytically, whereas it is difficult to quantify convection heat loss in a trapezoidal cavity absorber. Because the convection heat loss depends on the shape of the geometry, temperature and velocity fields in and around the cavity absorber. Moreover, the natural convection and surface radiation heat losses in a trapezoidal cavity absorber substantially reduce the efficiency of the system. Therefore, the heat loss characteristics in a trapezoidal cavity absorber need to be investigated.

Several experimental and numerical results have been presented to explain the phenomenon of combined natural convection and surface radiation in a closed cavity using Boussinesq approximation. In these aspects, Balaji and Venkateshan [1] numerically investigated the combined surface radiation and free convection in a square cavity with air as the intervening medium. Separate Nusselt number correlations have been developed for both free convective and radiative heat transfer for the Grashof number range of 10^3–10^6. Mahapatra et al. [2] presented a finite element solution on the interaction of surface radiation and variable property natural convection in a differentially heated square cavity. Cheng and Muller [3] performed numerical and experimental investigations on natural air convection coupled with thermal radiation in a vertical rectangular channel with one-side heated wall using the CFD code FLUTAN. Based on the experimental and numerical results, the semi-empirical Nusselt number correlation was developed for turbulent natural convection coupled with thermal radiation. Bouali et al. [4] studied numerically the effects of surface radiation and inclination angle on heat transfer and flow structures in an inclined rectangular enclosure with a centered inner body.

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Nomenclature

A_{abs}	area of absorber (m^2)
A_i	area of surface i (m^2)
A_j	area of surface j (m^2)
C_p	specific heat of the working fluid at constant pressure (J/kg K)
D	gap between top and bottom of the cavity absorber (m)
$q_{in,i}$	energy flux incident on the surface from the surrounding (W/m^2)
$q_{out,i}$	energy flux leaving the surface (W/m^2)
q_{Comb}	combined convective and radiative heat flux (W/m^2)
F_{ji}	view factor between surface j and surface i
Gr	Grashof Number
h_{Comb}	combined convective and radiative heat transfer coefficient, $W/(m^2\,K)$
k_f	thermal conductivity of the fluid (W/m K)
L	length of the cavity receiver (m)
NuC	convective Nusselt number
Nu_{Comb}	Combined convective and radiative Nusselt number
NuR	radiative Nusselt number
N_{rc}	radiation–conduction number
P	pressure (N/m^2)
Q_{Comb}	combined heat loss (W)
R	ideal gas constant (J/mol K)
S2S	surface-to-surface
T	temperature of the working fluid (K)
T_H	top surface temperature of the cavity absorber (K)
T_C	bottom surface (cover) temperature of the cavity absorber (K)
T_0	average of top and bottom surface temperature of the cavity absorber (K)
u	velocity at x-coordinates (m/s)
v	velocity at y-coordinates (m/s)
W	width of the top surface of the trapezoidal cavity absorber (m)

Greek symbols

θ	absorber angle, degree
ρ_f	density of the working fluid (kg/m^3)
ρ_0	reference density at T_0 (kg/m^3)
μ	dynamic viscosity (kg m/s)
μ_0	reference dynamic viscosity at T_0, (kg m/s)
ε_i	emissivity of surface i
σ	Stefan–Boltmann's constant, (5.67×10^{-8}, $W/m^2\,K^4$)
δ_{ij}	Kronecker delta

Subscripts

abs	absorber
Comb	combined
conv	convection
rad	radiation
C	cover
H	hot
in	inlet
out	outlet
rc	radiation–conduction
i, j, k	surfaces

Few researchers focused their studies on stability of natural convection flow in a tall vertical enclosure under non-Boussinesq conditions [5]. Tong and Koster [6] numerically studied 2-D natural convection in water with density inversion in a rectangular cavity using finite element model. Non-Boussinesq parabolic density – temperature relationship was incorporated in the model. It was found that interactive convection across the density inversion is dependent on aspect ratio and Rayleigh number. Mlaouah et al. [7] numerically investigated the behavior of transitional thermally driven flow in a two-dimensional differentially heated square cavity filled with a gas in cases where the temperature difference increases. Vierendeels et al. [8] computed the solutions for two-dimensional, laminar, steady state natural convection of a gas in a square cavity with large temperature differences. Non-Boussinesq or low-Mach number approximation was employed in the simulations. In addition to that, Boussaid et al. [9] studied heat and mass transfer problem in a trapezoidal cavity. The lower and top inclined parts of the cavity were considered as heated and cooled part. Using alternating direction implicit method (ADI), combined with a highly accurate fourth-order Hermitian method, the required heat and mass transfer equations were solved. Hammami et al. [10] performed three-dimensional numerical study of coupled heat and mass transfer by natural convection in a trapezoidal cavity using a finite volume technique. Based on these numerical results, thermal and hydrodynamic behavior of the binary mixture air–water vapor system was evaluated. It was observed that the aspect ratio increases, multi cellular flow patterns were formed. Moukalled and Darwish [11] carried out a numerical study to examine the effects on heat transfer of mounting two offset baffles onto the upper inclined and lower horizontal surfaces of the trapezoidal cavities. Based on the vertical wall in the left and right side of the trapezoidal cavity, two thermal boundary conditions were considered. It was observed that the decrease in heat transfer in the presence of baffles and increasing with increased Pr and baffle height. Natarajan et al. [12] investigated the influence of uniform and non-uniform heating of bottom wall on natural convection flows in a trapezoidal cavity using a finite element analysis. It was observed that the non-uniform of the bottom wall produces greater heat transfer rate at the center of the bottom wall than uniform heating. Separate power law correlations between Nusselt and Rayleigh numbers were developed for a wide range of Prandtl numbers.

Tmartnhad et al. [13] carried out a numerical study of mixed convection from a trapezoidal cavity. Two openings were adjusted on the plates of the cavity to study the effect of Reynolds number on the heat transfer by mixed convection. Arici and Sahin [14] numerically studied natural convection heat transfer in a partially divided trapezoidal enclosure using a control volume method. Summer and winter condition heat transfer results were examined in a partially divided trapezoidal enclosure. Negi et al. [15] experimentally determined the optical and thermal performance of the three identical tubular absorbers with black paint, cobalt oxide coatings and MAXORB foil for linear Fresnel reflector solar concentrator. Singh et al. [16] experimentally studied performance and the rise in oil temperature of the receiver with 10, 15 and 20 number of mirrors. It was observed that the rise in oil temperature was not directly related with number of mirrors. For the period of 30 min operation, the overall efficiency of the concentrator with 10, 15 and 20 number of mirrors was found to be 20.5%, 17.6% and 16.8% respectively. Khan [17] computed the thermal efficiency of rectangular absorber with two different coatings for prototype linear solar Fresnel reflecting concentrating collector. The absorber with selective electroplating copper oxide coating reached 49% thermal efficiency and other with black painted attained 48%. Mills and Morrison [18] evaluated the concept of CLFR for large scale solar thermal electricity generation plants. The absorber orientation, absorber structure, the use of secondary reflectors adjacent to the absorbers, mirror field configurations mirror packing densities, and