International Journal of Heat and Mass Transfer 89 (2015) 444–453

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Conjugate free convection with surface radiation in open top cavity

Dwesh K. Singh [a], S.N. Singh [b,*]

[a] HT Lab, Mechanical Engineering, ISM Dhanbad, Jharkhand 826004, India
[b] Mechanical Engineering, ISM Dhanbad, Jharkhand 826004, India

ARTICLE INFO

Article history:
Received 31 January 2015
Received in revised form 8 April 2015
Accepted 8 May 2015
Available online 5 June 2015

Keywords:
Open cavity
Volumetric heat generation
Surface radiation
Conjugate
Convection

ABSTRACT

This paper reports the numerical study of two-dimensional, steady, incompressible, conjugate, laminar, natural convection with surface radiation in open top cavity having air as the intervening medium for different locations of uniform volumetric heat generating source at the left wall. For surface radiation calculations, radiosity–irradiation formulation has been used, while the view factors required therein, are calculated using the Hottel's Crossed-string method. The analysis has been done for a constant property of fluid, with the Boussinesq approximation assumed to be valid. The effects of the magnitude of heat source, location, the material and surface properties of the heat source on both heat transfer and fluid flow have been studied and discussed. An important contribution from the present work is to find the location of heat source for efficient cooling and it is found at the top of the left wall. Based on a large set of numerical data, correlations have been developed for maximum non-dimensional temperature of heat source for three different locations at the left wall.

1. Introduction

Open cavities are encountered in various engineering systems, such as open cavity solar thermal receivers, uncovered flat plate solar collectors having rows of vertical strips, electronic chips, passive systems, etc. The thermal performance of electronic packages containing a number of discrete heat sources has been studied extensively in the literature. The design problem in electronic packages is to maintain cooling of chips in an effective way to prevent overheating and hot spots. This is achieved generally by effective cooling by natural convection, mixed convection, surface radiation and finally by better design. In the latter case, the objective is to maximize heat transfer density so that the maximum temperature specified for safe operation of a chip is not exceeded. Thus, optimum placement of discrete heat source may be required. To date, many literature shows that there are numerous studies on heat transfer by natural convection numerical as well as experimental and by conjugate heat transfer.

An excellent review of laminar natural convection has been presented by Ostrach [1]. Benchmark numerical solutions for natural convection in a square enclosure with two isothermal and two adiabatic walls have been obtained by de Vahl Davis and Jones [2]. Ho and Chang [3] studied the effect of aspect ratio for natural-convection heat transfer in a vertical rectangular enclosure with 2-dimensional discrete heating. Tou and Zhang [4] performed three-dimensional numerical simulation of natural convection in an inclined liquid-filled enclosure with an array of discrete heaters. Similarly, experimental studies have been performed using open cavities with an aspect ratio of one [5–8]. In the above literatures, only heat transfer by natural convection is considered, i.e. conduction and radiation are neglected.

Theoretical conjugate heat transfer by natural convection and radiation has been studied in various other configurations. Balaji and Venkateshan [9] studied interaction of radiation with free convection in an open cavity. Dehghan and Behnia [10] studied both numerically and experimentally conjugate heat transfers in an open-top upright cavity having discrete heater and with the bottom side insulated. Gururaja Rao et al. [11] investigated for conjugate mixed convection with surface radiation from a vertical electronic board equipped with a movable flush-mounted discrete heat source and determined the best position for the heat source. Singh and Venkateshan [12] reported the results of numerical study of natural convection with surface radiation in side vented open cavities using mixed boundary condition for the opening above the right wall. Kuznetsov and Sheremet [13] performed a numerical study of two-dimensional transient natural convection in a rectangular enclosure having finite thickness heat-conducting walls. Martyushev and Sheremet [14,15] numerically studied transient laminar natural convection with surface radiation in a square and cubical enclosure with heat-conducting

* Corresponding author. Tel.: +91 3262235491; fax: +91 3262296563.
E-mail addresses: singhdwesh@gmail.com (D.K. Singh), snsingh631@yahoo.com (S.N. Singh).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.05.038
0017-9310/

Nomenclature

A	aspect ratio, H/d
$A1$	geometric ratio, d/t
d	spacing m
$F_{i,j}$	view factor between element i and j
g	acceleration due to gravity m/s^2
G'	elemental irradiation W/m^2
G	elemental dimensionless irradiation, $G'/\sigma {T_{ref}}^4$
H	height of the cavity, m
h	height of the heat source m
J'	elemental radiosity W/m^2
J	elemental dimensionless radiosity, $J'/\sigma {T_{ref}}^4$
k	conductivity of air W/m-K
k_s	conductivity of left wall W/m-K
Nu_c	local convection Nusselt number, $-\frac{1}{\theta}\left(\frac{\partial\theta}{\partial X}\right)$
$\overline{Nu_c}$	average convection Nusselt number, $\int_0^{Y_h} Nu_c dY$
$\mathrm{Nu_r}$	local radiation Nusselt number, $\frac{1}{\theta} N_{rf}\zeta$
$\overline{Nu_r}$	average radiation Nusselt number, $\int_0^{Y_h} Nu_r dY$ $\overline{Nu_t}$ $\overline{Nu_c}+\overline{Nu_r}$
N_{rf}	radiation flow parameter, $\sigma {T_{ref}}^4 d/[\Delta T_{ref} k]$
m,n	number of grid points in horizontal and vertical direction
Pr	Prandtl number, υ/α
p	pressure Pa
P	non-dimensional pressure, $(p-p_\infty)H^2/\rho\alpha^2$
q_v	uniform volumetric heat generation rate, W/ m^3
q_c, q_r	convective and radiative heat flux W/m^2
Ra^*	modified Rayleigh number, $g\beta\Delta T_{ref}H^3/(\upsilon\alpha)$
t	thickness of left wall m
T	temperature K
T_{ref}	reference temperature of left wall K
T_∞	ambient temperature K
u,v	vertical and horizontal velocity m/s
U,V	dimensionless vertical and horizontal velocity, uH/α and vH/α
ΔT_{ref}	modified reference temperature difference, $q_v Ht/k_s$ K
x,y	horizontal and vertical coordinate m
X,Y	dimensionless horizontal and vertical coordinate, x/H and y/H
Y_h	dimensionless height of the heat source, h/H
ΔY	dimensionless height of the wall element
ΔY_h	dimensionless height of the heat source element

Greek symbols

α	fluid thermal diffusivity m^2/s
β	isobaric coefficient of volumetric thermal expansion, 1/T 1/K
ε	emissivity of the walls
γ	thermal conductance parameter, $kd/k_s t$
ζ	dimensionless radiative heat flux, $q_r/\sigma T^4_{ref}$
υ	kinematic viscosity of the fluid m^2/s
θ	dimensionless temperature, $(T-T_\infty)/\Delta T_{ref}$
$\theta_{\max}$	dimensionless maximum temperature, $(T-T_\infty)/\Delta T_{ref}$
Ψ'	stream function m^2/s
Ψ	dimensionless stream function, ψ'/α
σ	Stefan Boltzmann constant, 5.67×10^{-8} W/m^2 K^4

Subscripts

∞	ambient
i,j	any two arbitrary area element
rf	radiation flow

solid walls of finite thickness. Bejan and Sciubba [16] presented experimental work to optimize the spacing between two parallel plates using laminar forced convection. Hajmohammadi et al. [17] applied two reliable methods to cope with the rising temperature in an array of heated segments exposed to forced convective boundary layer flow. Hajmohammadi et al. [18] studied for controlling the heat flux distribution by changing the thickness of heated wall. Hajmohammadi et al. [19] investigated for improvement of forced convection cooling due to the attachment of heat sources to a conducting thick plate. da Silva et al. [20] used constructal theory for optimal distribution of discrete heat sources on a plate with laminar forced convection. Lindstedt and Karvinen [21] performed a simple analytical study for a flat plate cooled on one surface by forced or natural convection while the other side remains at uniform temperature. Hajmohammadi et al. [22] applied semi-analytical method for conjugate heat transfer. Hajmohammadi and Nourazar [23] reported the results of conjugate forced convection heat transfer from a heated flat plate of finite thickness and temperature-dependent thermal conductivity. A conjugate analysis with finite volume approach is performed by Hajmohammadi et al. [24] to study the effects of a thick plate on the excess temperature of an iso-heat flux heat source cooled by laminar forced convection flow.

From a careful review of the literature, it is clear that a very few works have been done in the present geometry having displaced volumetric heat generating source at the left wall and dissipates heat due to adjacent fluid due to conjugate free convection with surface radiation So, the main objectives of the present study are to investigate the influence of local volumetric heat generating discrete heat source on flow and heat transfer and subsequently fixing the best location of the same for cooling purposes. Based on a large set of numerical data, a correlation for maximum non-dimensional temperature has been also developed.

2. Mathematical formulation

2.1. Formulation for convection and conduction

The two-dimensional, steady, incompressible, laminar natural convection heat transfer from left wall with very thin volumetric heat generating source in open top cavity with fixed height H, spacing d, is considered using the system of coordinates as shown in Fig. 1. There is a volumetric heat generating source of height h (25% of the left wall) and thermal conductivity, k_s in which heat conduction is one-dimensional and thickness t provided in the left vertical wall of the cavity. Conductivity of heat source is independent of temperature level. It is possible to change the location of the heat source along the left wall of the cavity such that the heat source can take up three different position viz. (a) bottom (b) mid (c) top in the cavity. The governing equations for mass, momentum and energy for a constant property fluid under the Boussinesq approximation, in the non-dimensional form are:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\Pr\left[\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right] \tag{2}$$