International Journal of Heat and Mass Transfer 70 (2014) 119–127

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Natural convection in an enclosure containing a sinusoidally heated cylindrical source

R. Roslan [a], H. Saleh [b], I. Hashim [b,c,*], A.S. Bataineh [d]

[a] Faculty of Science, Technology & Human Development, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia
[b] School of Mathematical Sciences, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[c] Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[d] Department of Mathematics, Faculty of Science, Al Balqa Applied University, 19117 Salt, Jordan

ARTICLE INFO

Article history:
Received 22 November 2012
Received in revised form 18 September 2013
Accepted 5 October 2013
Available online 20 November 2013

Keywords:
Natural convection
Square enclosure
Inner cylinder

ABSTRACT

The problem of unsteady natural convection induced by a temperature difference between a cold outer square enclosure and a hot inner circular cylinder is studied in this paper. The cylinder temperature is assumed to vary sinusoidally with time about a fixed mean temperature. The coupled momentum and energy equations have been solved numerically over a wide range of values of the amplitude and the frequency of the source temperature signal, as well as the source radius. It is found that the heat transfer rate tends to increase by oscillating the source temperature signal. The maximum heat transfer augmentation was obtained for frequency between 25π and 30π for a high amplitude and a moderate source radius.

1. Introduction

Fluid flow and natural heat transfer from a heated body, especially cylinder inside enclosures has long been studied and has received much attention due to its direct relevancy to many engineering applications such as flooding protection for buried pipes, solidification processes, heat exchangers, electronic packaging and chemical reactors. House et al. [1] investigated the effect of a centered, conducting body and concluded that heat transfer process across the enclosure may be increased or decreased by a conducting body with a thermal conductivity ratio lower or greater than unity, respectively. Ghaddar [2] studied a uniformly heated horizontal cylinder placed in a large air-filled rectangular enclosure and found the maximum air velocity was at a distance of about nine cylinder diameters along the vertical centerline above the heated cylinder. Moukalled and Acharya [3] and Shu and Zhu [4] analyzed the effect of the radius of the inner cylinder and the aspect ratio to the fluid flow and heat transfer rate. Cesini et al. [5] performed a numerical and experimental analysis of a horizontal cylinder and reported in general the numerical and experimental result were in good accordance. Shu et al. [6] employed the differential quadrature method and showed that the global circulation, flow separation and the top space between the square outer enclosure and circular inner cylinder have an important influence on the flow and thermal fields. A heated cylinder kept in a square enclosure with different thermal boundary conditions was presented by Roychowdhury et al. [7].

Angeli et al. [8] developed a correlation for the average Nusselt number as a function on both the Rayleigh number and the cylinder diameter. The heat transfer enhancement by increasing the cylinder size and/or surface emissivity was obtained by Mezrhab et al. [9]. Kim et al. [10] and Lee et al. [11] showed that the cylinder position could affect heat transfer quantities. The changes in heat transfer quantities at Rayleigh number of 10^7 was presented by Yoon et al. [12] and Yu et al. [13]. Hussain and Hussein [14] studied a uniform heat source applied on the inner cylinder in a square air filled enclosure in which all boundaries are assumed to be isothermal. They obtained a two-cellular flow field and found that the total average Nusselt number behaves nonlinearly as a function of locations. The existence of local peaks of the Nusselt number along the surfaces of the cylinder and the enclosure was investigated by Lee et al. [11]. Recently, Nabavizadeh et al. [15] studied a heated sinusoidal cylinder at various amplitudes and undulations. They concluded that increasing amplitude or number of undulations or changing the angle might change the heat transfer coefficient which then influence the temperature and velocity fields. Very recently, Sairamu and Chhabra [16] considered a heated tilted square cylinder placed at the center of a square enclosure.

The transient behavior of fluid flow and heat transfer in an enclosure has been extensively studied due to the relevance to many industrial applications. For example, in the cooling of electronic

* Corresponding author at: School of Mathematical Sciences, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia. Tel.: +60 3 8921 5758; fax: +60 3 8925 4519.

E-mail address: ishak_h@ukm.my (I. Hashim).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.10.011

Nomenclature

a, A	amplitude, dimensionless amplitude
F	dimensionless oscillating frequency
g	gravitational accleration
n	normal direction to the walls
ℓ	width and height of enclosure
p, P	pressure, dimensionless pressure
Nu	Nusselt number
Pr	Prandtl number
r, R	cylinder radius, dimensionless cylinder radius
Ra	Rayleigh number
t	time
T	temperature
$\overline{T}_h$	mean value of hot temperature
u, v	velocity components in the x- and y-directions
U, V	dimensionless velocity components in the X- and Y-directions
W	surface area of walls
x, y & X, Y	space coordinates & dimensionless space coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
ν	kinematic viscosity
θ	angle of circular cylinder
Θ	dimensionless temperature
τ	dimensionless time
$\ddot{\tau}$	dimensionless time at stable state
τ_p	dimensionless periodic time of cylinder temperature
ρ	density
ω	oscillating frequency
$\overline{Nu}_{ss}$	average Nusselt number at basic steady state
$\overline{\overline{Nu}}$	time-averaged Nusselt number

subscripts

c	cold
h	hot
ss	steady

equipment, the electrical components are periodically energized intermittently and, therefore, the heating is an unsteady manner. Kazmierczak and Chinoda [17] investigated natural convection of water in a square enclosure by sinusoidal heating. Antohe and Lage [18] reported the convection intensity within the enclosure increases linearly with heating amplitude, while the resonance frequency was shown to be independent of the heating amplitude. Abourida et al. [19] and El Ayachi et al. [20] indicated that the heat transfer in a system could be enhanced by a proper choice of the considered parameters. Cheikh et al. [21] concluded that the periodical heating case causes an increase of the mean heat transfer in comparison to the constant heating case. Liu et al. [22] studied a square conducting body placed at the center of the enclosure. It was found that the resonant frequency decreases by increasing the body size and thermal conductivity ratio. In the problem of chaotic natural convection, Al-Taey [23] found the appearance of a new chaotic form in the stream function pattern and temperature distribution when he studied a heated square enclosure with time periodic boundary conditions. Recently, Zhang et al. [24] proposed the high-accuracy solutions of the sinusoidal heating profile. The aim of the present work is to investigate numerically the problem of unsteady natural convection from a sinusoidally heated cylinder embedded in a square enclosure. The sinusoidal heating is predicted to contribute the heat transfer enhancement due to the pulsating local flow response around the cylinder, for example the periodically on/off circular light in a room would enhance the heat transfer mechanism across the room.

2. Mathematical formulation

A schematic diagram of a cold square enclosure having an inner hot circular cylinder is shown in Fig. 1(a). The cylinder with radius r is located in the center of the enclosure and its temperature varies sinusoidally in time about a mean hot temperature $\overline{T}_h$, with amplitude a and frequency ω. The cylinder or source temperature is hotter than the wall temperature at all times, as graphically depicted in Fig. 1(b). Under the influence of the vertical gravitational field, the cylinder and walls at different levels of temperature lead to a natural convection problem. The fluid is assumed Newtonian and viscous dissipation and radiation effects are negligible. We assumed the cylinder and walls were made from materials having very low emissivity such as the polished aluminium, so that radiation has a very small effect on the temperature of the cylinder and walls. The governing equations are described by the NavierStokes and the energy equations, respectively. The governing equations are transformed into dimensionless forms under the following non-dimensional variables

$$\tau=\frac{t\alpha}{\ell^2},\quad X=\frac{x}{\ell},\quad Y=\frac{y}{\ell},\quad U=\frac{u\ell}{\alpha},\quad V=\frac{v\ell}{\alpha},\quad \Theta=\frac{T-T_c}{\overline{T}_h-T_c},$$
$$R=\frac{r}{\ell},\quad Pr=\frac{\nu}{\alpha},\quad Ra=\frac{g\beta(\overline{T}_h-T_c)\ell^3}{\nu\alpha},\quad P=\frac{p\ell^2}{\rho\alpha},\quad A=\frac{a}{\overline{T}_h-T_c},$$
$$F=\frac{\omega\ell^2}{\alpha}. \tag{1}$$

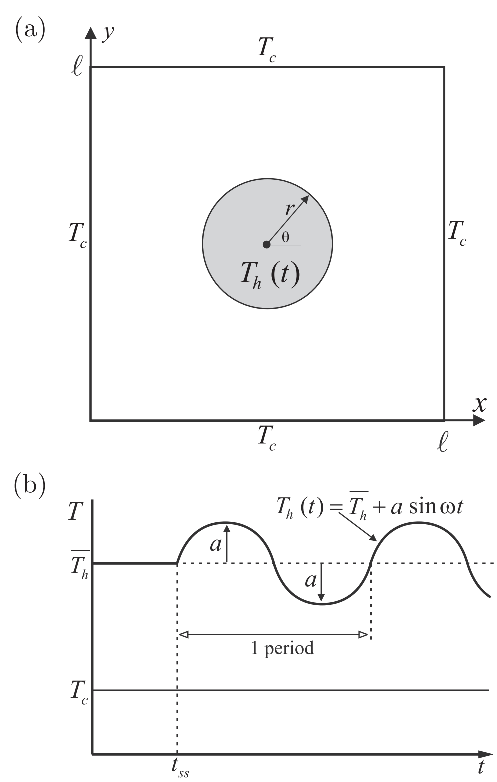

Fig. 1. Schematic representation of the model.