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Unsteady buoyancy driven flows and heat transfer through coupled thermal boundary layers in a partitioned triangular enclosure

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ABSTRACT

A numerical investigation has been carried out for the coupled thermal boundary layers on both sides of a partition placed in an isosceles triangular enclosure along its middle symmetric line. The working fluid is considered as air which is initially quiescent. A sudden temperature difference between two zones of the enclosure has been imposed to trigger the natural convection. It is anticipated from the numerical simulations that the coupled thermal boundary layers development adjacent to the partition undergoes three distinct stages; namely an initial stage, a transitional stage and a steady state stage. Time dependent features of the coupled thermal boundary layers as well as the overall natural convection flow in the partitioned enclosure have been discussed and compared with the non-partitioned enclosure. Moreover, heat transfer as a form of local and overall average Nusselt number through the coupled thermal boundary layers and the inclined walls is also examined.

1. Introduction

Natural convection in enclosures is a topic of considerable interest for the engineers. This is applicable to many situations in nature and engineering, e.g. thermal design of buildings, to cryogenic storage, solar collector design, nuclear reactor design, and others. There exists several excellent reviews [1,2] in the literature. Most of the studies devoted to an enclosure with no partitions. However, there have been several studies on the effect of vertical partition in the rectangular enclosure in suppressing natural convection, including the case of a porous medium [3–10]. This problem is of fundamental importance for a variety of reasons. For engineers who deal with insulation in the building, it is important for them to know the net heat transfer rate across solid walls and windows separating a warm room from a colder environment or vice versa. Moreover, from the point of view of fundamental research in heat transfer and fluid mechanics, it is also important to understand the interaction of two convective systems coupled across a partially conducting wall. Previous studies have shown that for a laminar flow regime even though the partition is perfectly conducting, it depresses natural convection in the cavity in comparison with that in a non-partitioned cavity and thus heat transfer through the cavity is significantly reduced [11–14].

Some other studies which considered the natural convection in rectangular enclosures with multiple vertical partitions [14–16] are also available in the literature. The effect of multiple thin partitions has been investigated both experimentally and numerically by Nishimura et al. [14]. The experiments were performed in enclosures with aspect ratios, $A = 4$ and 10, for the range $10^6 \leqslant Ra \leqslant 10^8$ and the range of partitions $1 \leqslant N \leqslant 4$. The authors concluded that the average Nusselt number is inversely proportional to $(1 + N)$. Anderson and Bejan [15] calculated the rates of heat transfer for double partitions which were placed in the middle of an enclosure. Their results showed that the heat transfer rate for double partitions is 20% less than that for a single partition. Jones [16] demonstrated numerical results considering laminar buoyancy driven flows in rectangular enclosures with multiple partitions. It is revealed from their studies that the effect of dividing the enclosure into six cells reduces the heat transfer rate by a factor of 6.

In addition to the rectangular or square cavity the attention has also been given to the triangular enclosure [17–21] recently for its various engineering applications. An extensive review of natural convection in the triangular cavity is reported in [22]. The main application is the fluid flow and heat transfer in the attic space. Heat transfer through an attic space into or out of buildings is seen as an important study for attic shaped houses in both hot and cold climates. One of the key objectives for design and construction of houses is to provide thermal comfort for occupants. In the present energy-conscious society, it is also a requirement for houses to be

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Nomenclature

A	aspect ratio
g	acceleration due to gravity
H	height of the enclosure
l	length of the enclosure
Nu_L	local Nusselt number
Nu	overall Nusselt number
P	dimensional pressure
p	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh Number
t	dimensional time
T	dimensional temperature of the fluid
T_c,T_h	dimensional temperatures of the cold and hot inclined walls
ΔT	dimensional temperature difference between the hot and cold inclined walls
u,v	dimensionless velocities in the x- and y- direction respectively
U,V	dimensional velocities in the X- and Y- direction respectively
x,y	dimensionless Cartesian coordinates
X,Y	dimensional Cartesian coordinates

Greek letters

β	thermal expansion coefficient
δ_T	thickness of the thermal boundary layer
κ	thermal diffusivity
ρ	density of the fluid
ν	kinematic viscosity
θ	dimensionless temperature
τ	dimensionless time
τ_s	dimensionless steady state time
$\Delta\tau$	dimensionless time step

energy efficient, i.e. the energy consumption for heating or air-conditioning houses must be minimized.

The studies related to attic space have been mostly devoted to two types of boundary conditions; day time or summer time condition [18,20], where the top inclined surfaces are heated and the horizontal bottom surface is cooled or adiabatic and night time or winter time condition [17,21], where the upper inclined surfaces are cooled and the bottom surface is heated or adiabatic. However, a realistic diurnal temperature condition was also considered by Saha et al. [19]. It was found that the heat transfer through the inclined walls are weaker during the day or summer time condition and stronger during at night or winter time. The reason for strong heat transfer is the formation of convecting plumes which are generated adjacent to both inclined walls and the horizontal wall. Natural convection due to differential heating of two inclined walls of an attic space is conducted by [23,24]. They investigated for quite a large values of Grashof number (Gr = Ra/Pr). The range of Gr considered by [23] for their experimental study was $2.9 \times 10^6 < \mathrm{Gr} < 9.0 \times 10^6$ and the range of Gr considered by [24] for their numerical study was $10^3 < \mathrm{Gr} < 10^8$ where they assumed that the flow is laminar.

The issue of heat transfer through the top surfaces of the attic spaces is the main concern of building a house to give thermal comfort to the occupants. To the best of the authors' knowledge there exists no study on partition triangular cavities to suppress of heat transfer through the inclined walls. The lack of such investigation has motivated the current study to compare the heat transfer phenomena for partitioned and non-partitioned triangular enclosures. The obtained results could help the builders for their insulation system in the attic shaped houses. The emphasis has been given to the transient process of natural convection resulting from a suddenly generated temperature difference between the fluids on the two sides of a conducting partition which has been placed along the geometric centre line of the enclosure. The impact of the partition on transient heat transfer is also discussed in this study.

2. Problem formulation

Under consideration is a triangular cavity of height H, half length of the base l, containing a Newtonian fluid, air, which is initially at quiescent. A partition is placed along the geometric centre line of the enclosure. Two interiors of both sides of the partition together with adjacent inclined walls receive different temperature with the left side receiving cold and the right side receiving hot temperature after time $\tau = 0$. In order to avoid the singularities at the tips in the numerical simulation, the tips are cut off by 5% and at the cutting points (refer to Fig. 1) rigid non-slip and adiabatic vertical walls (height = $H/20$) are assumed. The bottom surface is also considered as adiabatic and rigid non-slip. We anticipate that this modification of the geometry will not alter the overall flow development significantly. The origin of the coordinate is the intersection point of the partition and the bottom surface.

The development of natural convection inside an attic space is governed by the following two-dimensional Navier–Stokes and energy equations with the Boussinesq approximation:

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

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{1}{\rho}\frac{\partial P}{\partial X} + \nu\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right), \tag{2}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{1}{\rho}\frac{\partial P}{\partial Y} + \nu\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + g\beta(T - T_c), \tag{3}$$

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = \kappa\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right), \tag{4}$$

where U and V are the velocity components along X- and Y- directions, t is the time, P is the pressure, ν, ρ, β and κ are kinematic viscosity, density of the fluid, coefficient of thermal expansion and thermal diffusivity respectively, g is the acceleration due to gravity and T is the temperature.

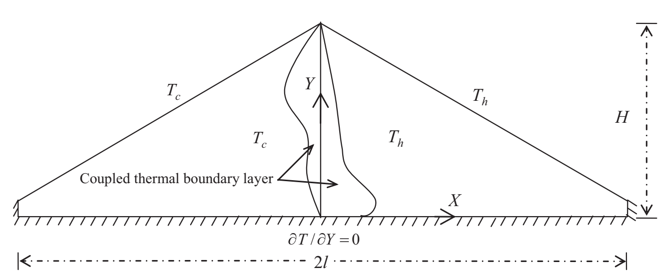

Fig. 1. Schematic of the computational domains and boundary conditions.