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A heatline approach on the analysis of the heat transfer enhancement in a square enclosure with an internal conducting solid body

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ABSTRACT

In this article, conjugate heat transfer in a square enclosure heated and cooled at the adjacent walls with an internal conducting solid body is studied. The effect of a square body on the steady state heat transfer in the enclosure is investigated for a Prandtl number of 7.0 in a range of Rayleigh number from 10^3 to 10^6, the ratio of the enclosure and body dimensions (ζ) from 0.1 to 0.9 and the ratio of the thermal conductivities of the solid and fluid (k^*) from 0.01 to 100. A heatline approach is used on the analysis of the conjugate heat transfer in the enclosure. The heat transfer process in the enclosure is governed by the Rayleigh number, the size of the solid and thermal conductivity. For dimensionless body sizes of $\zeta < 0.3$, the heat transfer in the enclosure is not affected by the body and the Nusselt number remains a function of the Rayleigh number. As the body size increases, the Nusselt number also becomes dependent on the size of the body and its thermal conductivity. In the range of $\zeta > 0.8$ and $k^* > 10$, the dependence of the Nusselt number on the Rayleigh number weakens and the heat transfer in the enclosure approaches the limit of pure conduction.

1. Introduction

Natural convection in enclosures is a fundamental problem in heat transfer and has been intensively studied numerically and experimentally since the 1950s. The problem in its classical form, when the enclosure interior is filled only with a fluid, is applied in different fields of engineering such as in the design of solar thermal collectors, in the cooling of electronic components and in conserving energy in buildings. On some occasions, obstacles may be introduced within the enclosure in the form of baffles or partitions in order to better reproduce the geometric characteristics of a particular case, e.g. the protuberances of an electronic component or different rooms in a building that are connected by a doorway.

Although consolidated literature on these configurations may be found, i.e. on fluid-filled and partitioned enclosures [1], it was only in the early 1990s that enclosures with an internal solid completely surrounded by a fluid began to receive attention [2,3]. Natural convection in an enclosure with different (fluid–solid) constituents is of particular importance in situations such as grain storage, packed-bed reactors and freezing or melting in soils. In order to model these types of process, a macroscopic approach, i.e. one that considers the fluid–solid constituent as a porous medium, is traditionally used [4], [p. 543]. On the other hand, when the size of the solid particle is large and detailed information on each constituent is of interest, the discrete assessment of the fluid and solid regions, i.e. a microscopic approach, is preferred. This is the case, for example, of casting processes in which the core (solid) is surrounded by liquid metal, the tubes (solid) in heat exchangers surrounded by a fluid, the rods (solid) of the nuclear reactors surrounded by water or the dough (solid) in oven filled with air in a baking process in the food industry.

Some studies have been developed involving natural convection in enclosures within which there is a single solid or several discrete solids. House et al. [2] investigated the effect of the size and thermal conductivity of a single solid body positioned in the centre of an enclosure heated and cooled from its sides. The heat transfer in the enclosure is governed by Rayleigh and Prandtl numbers, the size of the body and its thermal conductivity. Following the work of House et al., further studies were carried out on enclosures which have one of the two fundamental boundary conditions in which a flow of natural convection can occur at steady state, i.e. enclosures heated and cooled from the side and heated from the bottom and cooled

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Nomenclature

g	gravity acceleration
H	enclosure height
$\mathscr{H}$	heat function
k	thermal conductivity
L	enclosure length
n	iteration order
N	normal direction from a surface
Nu	averaged Nusselt number
p	pressure
Pr	Prandtl number
Ra	Rayleigh number
T	temperature
u, v	velocity in x and y direction
var	absolute relative error
W	body length
x, y	horizontal and vertical coordinates

Greek symbols

α	thermal diffusivity
β	coefficient of volumetric thermal expansion
ε	residual error
ζ	dimensionless size of the body
ν	kinematic viscosity
ρ	specific mass
ϕ	generalized dimensionless variable
ψ	stream function

Subscripts

0	cold wall
1	hot wall
f	fluid
rt	ratio
s	solid

Superscripts

*	dimensionless variable

from the top. The studies were typically performed using a body of fixed size where the body itself might be heat-generating [5–9], adiabatic [10,11] or conductive [12–14].

In Oh et al. [5] an enclosure heated and cooled from the sides with an internal heat generating body of fixed size was studied. In this configuration the heat transfer in the enclosure is governed by the temperature difference of the enclosure walls and that of the enclosure wall and the heat generating body. Ha et al. [6] studied the same enclosure as in Ref. [5] in order to assess the transient behaviour of the heat transfer of the enclosure. The authors showed that the dimensionless temperature difference is an important parameter to define which temperature difference is governing the heat transfer in the enclosure. Liu and Phan-Thien [7] added the heat transfer by radiation to the problem of the enclosure heated from the sides with an internal heat generating body. The authors showed the effect of the emissivity of the body on the global flow and the total heat transfer of the enclosure. Lee and Ha [8] studied the enclosure heated from the bottom and cooled from the top with an internal heat generating body. A chaotic behaviour of the Nusselt number was verified for high Rayleigh numbers as the heat generated by the body increases. The effect of the heat generating body was also studied in Zhao et al. [9] on an enclosure heated with a fixed heat flux and cooled at a constant temperature defined at the sides of the enclosure.

Ha et al. [10] and Ha et al. [11] studied the effect of an adiabatic body in an enclosure heated from the bottom and cooled from the top. The authors showed that there is a range of Rayleigh number for which the Nusselt number achieves a steady behaviour after a few number of oscillations. This steady behaviour becomes periodic oscillatory as the Rayleigh number increases.

The enclosure with an internal heat conducting body was studied in Mezrhab et al. [12]. The authors show that the conductivity of the body has little in the heat transfer of the enclosure, however, a fixed size of body was considered. The effect of a conducting body and the angle of inclination on the heat transfer of the enclosure were studied in Das and Reddy [13]. The authors showed that the Nusselt number remains constant for a Rayleigh number of 10^3 and different inclination angles which indicates a heat transfer dominated by conduction at this Rayleigh number. In Zhao et al. [14] the effect of a conducting body was also studied. The authors showed that the heat transfer in the enclosure decreases when the width of the channel between the enclosure wall and the body approximates the width of the thermal boundary layer formed on the enclosure wall.

In Bhave et al. [15], the effect of an adiabatic body of different sizes was studied and a correlation predicting the optimal body size was proposed which enhances heat transfer in the enclosure. The correlation was based on the geometric aspect of the streamlines of the enclosure without the body.

As to considering an enclosure filled with a matrix of discrete solid bodies, it is only more recently that there have been studies on its natural convection based on the microscopic approach. Merrikh and Mohamad [16] studied heat transfer in an enclosure heated and cooled from the side and the boundary effects associated with inserting a matrix of discrete solid bodies within it. Later, in Merrikh and Lage [17], the macroscopic and microscopic approach were applied and compared with respect to an enclosure filled with discrete bodies which was heated and cooled from the side. Further studies focused on the heat transfer [18,19] and correlations for the Nusselt number [20,21] in enclosures which were filled with discrete solid bodies and heated and cooled from the side.

In the literature mentioned so far, few studies of an enclosure with a single body have focused on the effect of the body size on the heat transfer in the enclosure [2,15]. Further, only two configurations of enclosure were studied, i.e. heated and cooled from the side; and heated from the bottom and cooled from the top. In these configurations, the thermal gradient imposed by the boundary conditions is, respectively, perpendicular or parallel (in the same direction) to the gravity acceleration vector, resulting therefore in the two basic configurations in which the natural convection flow occurs. This article sets out the effect of the size of the body and its conductivity on the heat transfer in an enclosure heated and cooled at its adjacent walls. The particular interest in this configuration lies in the simultaneous imposition of the two basic configurations between the thermal gradient and the gravity acceleration vector for which a natural convection flow is generated. In the vertical wall, a perpendicular configuration is imposed whereas in the horizontal adjacent wall, a parallel configuration is imposed [22]. Also, a novel approach to explain the heat transfer enhancement found in the enclosure due to the insertion of the body is proposed by applying the heatline method of visualization for convective heat transfer firstly proposed by Kimura and Bejan [23].