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Aspect ratio effect on the prediction of boundary layer interference in steady natural convection inside heterogeneous enclosures

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ABSTRACT

Flow interference, caused by solid obstacles placed within an enclosed fluid undergoing natural convection, can have a tremendous impact on the flow pattern and heat transfer process. Disconnected, conductive, solid square blocks uniformly distributed inside a rectangular, horizontally heated enclosure are used as a platform to investigate this flow interference, which can be caused: (1) adjacent to the enclosure walls – when the (hot or cold) vertical fluid stream boundary layers grow enough to reach the solid blocks; and, (2) along the enclosure horizontal surfaces – when the top (or bottom) horizontal fluid streams get impeded by the adjacent blocks. Analytical equations, based on scale analysis, are derived for predicting the minimum number of blocks beyond which vertical and horizontal interferences take place, as function of the Rayleigh number (Ra), fluid volume fraction (porosity ϕ), and the enclosure length-to-height aspect ratio (A). The analytical predictions are validated against numerical simulation results, covering the ranges $10^5 \leqslant Ra \leqslant 10^8$, $0.36 \leqslant \phi \leqslant 0.84$, and $0.25 \leqslant A \leqslant 4$. The predictions prove the horizontal interference predominates in relation to the vertical interference in shallow ($A > 1$) enclosures.

1. Introduction

Several common engineering processes involve the natural convection of an enclosed fluid flowing around discrete solid bodies. Containerization, such as the storage of grains for maritime transportation, is one practical example in which the natural convection of the enclosed fluid (usually air) takes place around the grains, which play the role of discrete solid bodies. The natural convection inside the enclosure is typically driven in these cases by an external (to the enclosure) mechanism, such as solar radiation heating the external surfaces of the container. Another practical example is found in the bakery industry, where the large scale baking of bread and pastry is commonly accomplished by uniformly distributing several pieces of dough over perforated racks placed in rows inside large convection ovens. Similar configurations are found in batch ovens for treating (i.e., aging, curing, drying, preheating, etc.) large quantities of small solid parts, and in autoclaves for sterilizing equipment and supplies. Notice the last three examples differ from the first in which the solid bodies in the first example (the grains) are usually connected (i.e., touching each other and the surfaces of the enclosure), while in the other cases the solid bodies are usually disconnected, placed distant from one another and from the surfaces of the enclosure.

Although of great practical interest, the fundamental study of the natural convection phenomenon inside enclosures containing solid bodies is still in its infancy, primarily by the geometrical complexity brought about by the presence of the solid bodies. The solid bodies, which form a "heterogeneous medium" with the enclosed fluid, can affect the heat transfer process inside the enclosure (as compared to the process without any solid bodies) in two primary ways: (1) by providing a different conductive path to the thermal energy being transported; and, (2) by impeding –for being impermeable and nonslip– the otherwise free convective fluid flow inside the enclosure. This means the solid body interfaces with the fluid play a fundamental role in the heat transfer process inside the enclosure. The need to access and map the fluid–solid interfaces, to account for their effects, is what causes the geometrical difficulties when studying this type of configuration, particularly when several solid bodies are present inside the enclosure.

It was apparently not until 1990 when the first numerical study considering a heterogeneous enclosure undergoing natural convection was pursued, by House et al. [1], with the study of thermal conductivity effects on the natural convection in a fluid filled

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Nomenclature

A	enclosure aspect ratio
c_p	specific heat, J/kg K
D	dimensionless block side length
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
H	enclosure height, m
k	thermal conductivity, W/mK
K	solid-to-fluid thermal conductivity ratio
L	enclosure width, m
n	coordinate normal to the boundary
N	number of solid blocks
Nu	Nusselt number
p	dimensional pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
q''	heat flux at the vertical heated wall, W/m^2
Ra	Rayleigh number
S	dimensionless distance from enclosure surface to adjacent solid blocks
S_δ	dimensionless boundary layer thickness scale
T	temperature, K
V	volume, m^3
u, v	Cartesian velocity components along x and y directions, m/s
U, V	dimensionless Cartesian velocities
x, y	horizontal and vertical Cartesian coordinates, m
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity, m^2/s
β	isobaric coefficient of volumetric thermal expansion, 1/K
ϕ	porosity
γ	number of lattices
μ	dynamic viscosity of fluid, kg/ms
ν	kinematic viscosity, m^2/s
θ	nondimensional temperature
ρ	density, kg/m^3
Σ	nondimensional vertical length scale
ω	number of lattices in horizontal direction

Subscripts

C	cold
f	fluid
h	horizontal
H	hot
min	minimum
s	solid
T	total
v	vertical

enclosure containing a centered, single solid square block. Later on, Oh et al. [2] extended this study considering the enclosure heated vertically and the solid block generating thermal energy. More recently, Lee and Ha [3], considered heating the enclosure from below with the solid block as either conducting or adiabatic (thermally nonparticipating). Lee and Ha [4] looked at the effects of the fluid-to-solid thermal conductivity ratio and the temperature difference ratio, while Zhao et al. [5] and [6] considered variations in the internal thermal condition of the block. Kumar De and Dalal [7] studied the natural convection around an inclined heated square cylinder placed inside a rectangular enclosure, while Bhave et al. [8] presented interesting and useful correlations predicting the optimum block size for maximizing the heat transfer inside the enclosure. All these studies were conducted following the continuum modeling approach, in which the continuum balance equations for the fluid and, separately, for the solid body inside the enclosure were solved numerically, together with compatibility conditions imposed along the fluid–solid interfaces. Noteworthy in these studies is the use of a single solid block inside the enclosure, yielding a relatively easy to map fluid–solid interface.

However, the geometrical and consequent numerical difficulty increases rather quickly when the number of solid bodies placed inside the enclosure increases. This hindrance, however, can be sidestepped when the number of solid bodies inside the enclosure is very large and their size is consequently small. In this case, the resulting fine structure of the heterogeneous enclosure is such that the alternative porous-continuum modeling approach, defined as such by Merrikh et al. [9], can be used. This approach does not require mapping the fluid–solid interfaces inside the enclosure, which in this case would be quite demanding; rather, their local effects are lumped and accounted for by porous-continuum properties, such as the permeability, form coefficient, effective thermal conductivity and effective heat capacity of the medium. The overcoming of the geometrical difficulty this approach provides, however, comes with a price: the loss of information inherited by the lumping (averaging) process. Notwithstanding, the porous-continuum approach, for its simplicity and relative robustness, has until recently been the preferred choice for studying natural convection in heterogeneous (porous) enclosures when several solid bodies are present (Nield and Bejan [10], Vafai [11], Bejan and Kraus [12]).

The porous-continuum approach, however, is not suitable for configurations in which the number of solid obstructions is small and their size is large because in this case the lumping process becomes very inaccurate (in technical terms, this would yield a representative elementary volume comparable to the domain size). Albeit this difficulty, the availability of more powerful computation tools in recent times has allowed the use of the continuum approach for studying enclosures with internal geometries more complex than that of a single solid body placed in it. Merrikh and Mohamad [14], for instance, considered the natural convection effects caused by the presence of multiple solid blocks (up to 144) inside a heated enclosure. Their observations were supported and expanded by Merrikh and Lage [15]. The effect of varying the geometry of the blocks, pioneered by Braga and de Lemos [16], highlighted the advantage of using square blocks (instead of circular bodies) in enhancing the heat transfer inside the enclosure because of the extra mixing induced by the flow separation at the sharp edges of the blocks. The natural convection in an enclosure with randomly distributed solid bodies was recently studied by Pourshaghaghy et al. [17], who observed an oscillatory (in time) solution for the local Nusselt number.

When several solid blocks are distributed inside a heated enclosure, the possibility of a new fundamental phenomenon emerges: that of *flow interference* by the solid blocks placed near the heated and cooled walls of the enclosure. Because the vertical natural convection streams formed along the hot and cold walls of the enclosure diffuse momentum as they flow, the region occupied by them tends to grow along the flow direction, possibly reaching the nearby solid blocks. If this happen the interaction with the blocks