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The thermal diode and insulating potentials of a vertical stack of parallelogrammic air-filled enclosures

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This paper focuses on the interaction and the contribution of the three modes of heat transfer in a stack of parallelogrammic air-filled cavities separated by solid partition walls. The thermal diode potential and the high insulating character of such structures are the main interests of this investigation. The inclination angle, the emissivity of the inner boundaries of the cavity as well as the thickness and the thermal conductivity of the partition walls are the parameters varied in this study. Their respective contributions to the total Nusselt number are assessed. The two-dimensional fluid cavities studied in this work are characterized by an aspect ratio of 1. The vertical boundaries of the enclosures are considered isothermal at specified hot and cold temperatures, and the inclination angle of the partition walls is varied from -60° to 60° with respect to the horizontal. Numerical simulations are carried out using a finite-volume solver. It is shown that the total Nusselt number is highly sensitive to the emissivity of the inner boundaries of the cavities and thus, to the heat transfer through radiation. Moreover, it is found that the conduction heat transfer in the partition walls also plays an important role in most of the cases investigated. The importance of these two modes of heat transfer results in a significant decrease in both the thermal diode potential and the insulating character of the enclosures compared to the classic case for which only convection heat transfer is considered. Nonetheless, this study suggests that a vertical structure composed of a stack of parallelogrammic air-filled enclosures could be successfully designed to provide a practical and economically interesting alternative to polystyrene panels.

1. Introduction

Over the past decades, several investigations have been directed towards the development of approximate solution methods for applications involving natural convection. The particular case of free convection in cavities, which is quite prevalent in practice, has mainly retained the attention. Many authors have performed theoretical studies on natural convection heat transfer across cavities [1–3]. Early on in the numerical simulation era, the differentially heated square cavity became a classic numerical problem.

Indeed, natural convection in closed cavities has been investigated in numerous occasions and many different geometries have been studied over the years. For example, many authors have oriented their research towards cylindrical shapes [4,5], while others worked on triangular cavities [6,7]. Nevertheless, the most widely studied geometry in the literature remains the 2D square, rectangular or parallelogrammic cavity.

For these types of cavity, the effects of many parameters, such as the Rayleigh number (Ra), the Prandtl number (Pr) and the aspect ratio (h/L), have already been extensively studied [1,8–11]. Generally, a higher Rayleigh number results in an increased heat transfer across the cavity and can eventually lead to unsteady phenomena and turbulence, while moderate variations of the Prandtl number does not significantly influence the general behavior of the flow in the cavity [12–14].

From a more practical point of view, several papers have dealt with the impact of the inclination angle (ϕ) of the partition walls bounding the upper and lower parts of the parallelogrammic cavity [10,15–18]. It has been shown that the convection heat transfer is highly affected by the inclination angle of the partition walls. As shown in Fig. 1, the convective motion of the fluid is much more important when the vertical hot boundary is located *below* the vertical cold boundary (positive ϕ), while a vertical hot boundary *above* the cold one (negative ϕ) can even lead to a complete stratification in the cavity and, ultimately, to essentially pure conduction heat transfer in a stagnant fluid. Therefore, the heat transfer through a given inclined cavity has two different values depending on the side of the hot boundary. This attractive behavior has been

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Nomenclature

$\boldsymbol{e_g}$	unit gravity vector = $(0, -1)$
F_{ij}	view factor matrix
g	gravitational acceleration [m s^{-2}]
h	height of the hot and the cold boundaries of the cavity [m]
J	radiosity [W m^{-2}]
k_f	thermal conductivity of the fluid [W m^{-1} K^{-1}]
k_s	thermal conductivity of the solid partition walls [W m^{-1} K^{-1}]
L	distance between the hot and the cold boundaries [m]
$\boldsymbol{n}$	local unit vector normal to a boundary and directed towards the considered region
p	pressure [Pa]
$\overline{q'}_{cond}$	mean conduction heat transfer rate per unit depth in the partition walls, Eq. (10) [W m^{-1}]
$\overline{q'}_{conv}$	mean convection heat transfer rate per unit depth in the fluid cavity, Eq. (8) [W m^{-1}]
$\overline{q'}_{rad}$	mean radiation heat transfer rate per unit depth in the fluid cavity, Eq. (9) [W m^{-1}]
q'_{ref}	reference conduction heat transfer rate per unit depth in the enclosure, Eq. (7) [W m^{-1}]
q''_r	radiative thermal heat flux, Eq. (4) [W m^{-2}]
t	thickness of the solid partition walls [m]
T	temperature [K]
T_0	mean temperature = $(T_H + T_C)/2$ [K]
T_C	temperature of the cold boundary [K]
T_H	temperature of the hot boundary [K]
$\boldsymbol{u}$	velocity vector = (u, v) [m s^{-1}]
$\boldsymbol{x}$	position vector = (x, y) [m]
α	thermal diffusivity of the fluid [m^2 s^{-1}]
β	coefficient of volumetric expansion of the fluid [K^{-1}]
θ	temperature difference scale = $T_H - T_C$ [K]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]
σ	Stefan-Boltzmann constant [W m^{-2} K^{-4}]
ψ	stream function [m^2 s^{-1}]

Dimensionless physical parameters

h/L	aspect ratio of the cavity
k_s/k_f	thermal conductivity ratio
Pr	Prandtl number = ν/α
Ra	Rayleigh number = $g\beta\theta L^3/\alpha\nu$
t/L	thickness ratio of the solid partition walls
T_0^*	normalized mean temperature = T_0/θ
ϵ	emissivity
$\frac{\sigma T_0^4}{k_f\theta/L}$	relative radiation level
ϕ	inclination angle of the solid partition walls with respect to the horizontal

Dimensionless coefficients

Nu	Nusselt number
ξ_{60}	thermal diode coefficient

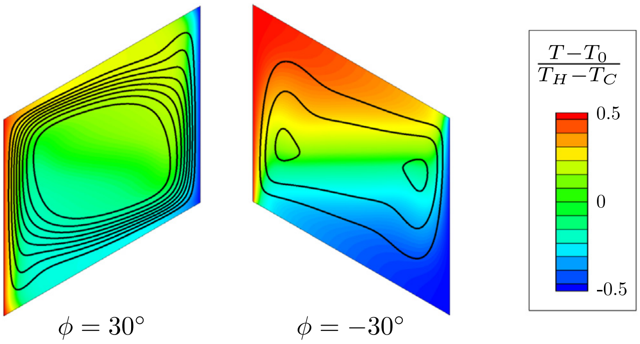

Fig. 1. Temperature fields (colored background in the online version) and stream functions (black lines, $\Delta\psi^* = 0.0041$) for air-filled cavities with adiabatic upper and lower boundaries and isothermal vertical boundaries (the hot boundary is located on the left).

confirmed by many authors who refer to the parallelogrammic cavity as a thermal diode cavity [15,18,19]. Indeed, several numerical and experimental studies have shown that the convection Nusselt number is strongly reduced when the inclination angle (ϕ) is negative [10,11,17].

In addition to the applications that could benefit from the thermal diode behavior of such cavities, it could also be interesting in practice as an insulating wall. The idea of using a stack of piled-up air-filled cavities instead of a full panel of insulating material is very attractive. Indeed, a wall composed of air-filled cavities that would have the same thermal properties as an insulating material would have major economic and environmental advantages due to the reduction of the amount of material needed. To investigate this possibility, the three modes of heat transfer must be considered in a structure composed of multiple piled-up cavities.

Most of the studies in the field have investigated the case of a single cavity with adiabatic upper and lower boundaries. Only a few authors have considered more than one fluid cavities [11,18,20,21], either fully or partially separated by conductive solid partition walls, even if one expects to use walls composed of several such cavities. Moreover, most of the studies that have been performed on the thermal diode cavity have not considered radiation even if it has been shown that this heat transfer mode can become quite significant [21–23]. To the authors' best knowledge, the study of multiple cavities involving the three modes of heat transfer has not yet been investigated in the literature despite its relevance in many applications.

The objective of the present study is to assess the individual contribution of each of the three heat transfer modes, as well as how they interact with each other in an infinite stack of parallelogrammic cavities separated by conductive solid partition walls, as shown in Fig. 2. This general problem is governed by nine dimensionless parameters (see nomenclature), which makes it a formidable challenge. In this initial phase of our investigation, we have fixed five of these nine parameters to focus on the general trends first. Thus, we have varied the inclination angle (ϕ), the thickness and the thermal conductivity ratios of the solid partition walls (t/L and k_s/k_f) and the emissivity of the inner boundaries of the cavities (ϵ) in order to show their effect on the thermal diode potential and on the total heat transfer.

In order to analyze the importance and the contribution of the three heat transfer modes separately, we proceed in three steps. First, a single cavity with adiabatic upper and lower boundaries is presented (Fig. 3a). The pure-convection heat transfer is briefly discussed using a cavity without partition walls and without considering radiation. This simple case, which has been studied thoroughly in the literature, is used as a reference to evaluate the impact of the other heat transfer modes. In a second step, the