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Theoretical investigation of natural convection heat transfer in inclined and fully divided CO_2 enclosures on Mars

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ABSTRACT

This work presented extensive numerical studies on fluid flow and heat transfer in inclined and fully divided CO_2 enclosures with partitions on Mars. An atmospheric pressure of 1000 Pa, a gravitational acceleration of 3.62 m/s^2, and a Prandtl number of 0.77 were considered in the computation. The hot and cold walls were maintained at uniform temperatures of T_h = 240 K and T_c = 200 K, while the others were assumed as adiabatic, and the boundary condition of partitions was assumed as coupled. The velocity fields, temperature contours, and heat flux through CO_2 enclosures were presented for a Rayleigh number of 7270, an aspect ratio of 7.14, tilt angles from 0° to 90°, and partition numbers of 0, 1, 2, and 3. It was observed that three flow regimes formed successively when the tilt angle increased, namely the Rayleigh–Bénard convection, transition convection, and single-cell convection. The transition regime was the most unstable regime. The values of two critical tilt angles between the three flow regimes were also obtained. With increasing angle, the heat flux slightly decreased in the first regime, significantly decreased in the second regime, and initially increased and then slightly decreased in the third regime. The opposite effect of partitions on the first and the third regimes was explained by the field synergy principle. The partition advanced the formation of the single-cell convection to a lower angle and also alleviated the fluctuation in the heat flux for various tilt angles, which contributes to the future thermal design of Mars rovers operating on rugged Mars surface.

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1. Introduction

Enclosures are widely used in several industrial applications for heat conservation such as design of solar collectors, multilayered walls, electronic equipment cooling, and double pane windows. Furthermore, natural convection inside the vertical and horizontal enclosures is extensively examined in different operating environments. However, in addition to being influenced by the different conditions in which enclosures are located, fluid flow and heat transfer inside the enclosure also significantly differ when the inclination of the enclosure changes or when the enclosure is divided by partitions. Therefore, several studies focused on the effect of the tilt angle and partitions attached to the enclosure on heat transfer. In typical applications, air-filled cavities on the Earth were mostly reviewed as discussed below.

The investigations of heat transfer in classical enclosures are presented in several studies [1–7], including the horizontal enclosure with heated bottom wall, cooled top wall, and two adiabatic vertical walls or the vertical enclosure with heated left wall, cooled right wall, and two adiabatic horizontal walls.

After investigating the classical cases, a few studies indicated that the diverse tilt angle of the enclosure also significantly impacted heat transfer through the enclosure. Soong et al. [8] examined natural convection and hysteresis phenomena in an air rectangular enclosure for different Rayleigh numbers ranging from 10^3 to 2×10^4 and angles from 0° to 90°. They indicated that the flow pattern was related to the initial state of the flow contours. Tzeng et al. [9] investigated the effect of the inclination on fluid flow in a two-dimensional tilted air rectangular enclosure. He pointed out that natural convection in enclosures was extremely sensitive to the inclination of the enclosure at a few critical conditions and heat transfer rate was bound with the cellular flow pattern. Girgis [10] conducted a similar study as Tzeng et al. [9]. He obtained the Nusselt number correlations. Miroshnichenko and Sheremet [11] performed an investigation of the turbulent natural convection in a square enclosure with a local heat source when the tilt angle increased from 0° to 180°. They indicated that heat transfer rate reached the maximum when the tilt angle was 150°.

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Nomenclature

AR	enclosure aspect ratio
c_p	specific heat capacity (J/g·K)
d	enclosure deep (mm or m)
g	gravitational acceleration (m/s^2)
H	thickness of enclosure (mm)
Kn	Knudsen number
k	thermal conductivity (W/m·K)
L	length of the layer (mm or m)
l	characteristic length (m)
N	partition number
p	pressure (Pa)
Q	heat transfer rate(W)
q	heat flux (W/m^2)
Ra	Rayleigh number
T	temperature (K)
T_0	operating temperature (K)
u	velocity components in x direction (m/s)
$\vec{V}$	velocity vector
$\vec{\nabla T}$	temperature gradient vector
v	velocity components in y direction (m/s)
x	x coordinate location (mm)
y	y coordinate location (mm)

Greek symbols

β	thermal expansion coefficient (1/K)
λ	mean free path (m)
μ	dynamic viscosity (kg/m·s)
ρ	density of fluid (kg/m^3)
ρ_0	constant density of the flow (kg/m^3)
ΔT	difference in temperatures $\Delta T = T_h - T_c$ (K)
$\Delta\tau$	residual tolerance
θ	tilt angle (degree)
θ_{crit1}	critical angle between the first and second regimes (degree)
θ_{crit2}	critical angle between the second and third regimes (degree)
θ_{syn}	synergy angle (degree)

Subscripts

c	cold
h	hot
max	maximum
min	minimum
p	partition

Several studies focused on heat transfer and fluid flow in the enclosure with different partitions. Most of them studied partially divided enclosures and considered different locations of partition. Jetli et al. [12] performed numerical investigation of natural convection in an air square enclosure with two baffles attached to the top and bottom walls. They found that when the top baffle got closer to the cold wall and bottom baffle got closer to the hot wall, the Nusselt number decreased. Kelkar and Patankar [13] and Sun and Emery [14] proposed that the effect of the baffle on heat transfer was negligible when the height of baffle was shorter than the half of the enclosure height. Sankhavara and Shukla [15] numerically analyzed fluid flow in partially divided horizontal air rectangular enclosures with partitions attached to the vertical walls. They pointed out that the convection dominated heat transfer for higher Rayleigh numbers, while conduction dominated heat transfer for lower Rayleigh numbers. Ilis et al. [16] numerically investigated natural convection heat transfer in an air square cavity with a ceiling-mounted barrier. They found that the influence of the barrier on heat transfer decreased with increasing Rayleigh number. Yucel and Ozdem [17], Nardini et al. [18], and Bae et al. [19] indicated that heat transfer increased with increasing Rayleigh number in partially partitioned enclosures, and this was identical to that in classical cases.

A few studies focused on the fully divided enclosures. Bejan [20] numerically investigated the influence of obstructions on natural convection in two-dimensional air layers. He proposed that the horizontal adiabatic partitions increased heat transfer rate in a convection-dominated regime. Turkoglu and Yücel [21] numerically analyzed heat transfer in divided air rectangular enclosures with conducting partitions. They pointed out that the Nusselt number increased with increasing Rayleigh number, and the effect of aspect ratio on heat transfer was limited in the cases considered in the study. Kahveci [22] used polynomial differential quadrature (PDQ) method to investigate the natural convection in an air rectangular enclosure with a vertical partition. He found that a transition from the unicellular flow to multicellular flow occurred when the aspect ratio increased, and this increased the convective heat transfer coefficient. Williamson and Armfield [23] investigated fluid flow in a two-dimensional air rectangular cavity with a vertical partition placed at the middle of the cavity. They observed that when the Rayleigh number increased, an additional regime existed between the convectively unstable regime and turbulent regime unlike that in the classical cavity. Khatamifar et al. [24] numerically studied the conjugate natural convection flow in an air square cavity divided by a partition with limited thickness. They indicated that the Nusselt number increased with decreases in the partition thickness and was negligibly influenced by the partition position.

The number of reported studies that combine the effect of both tilt angle and partition number on heat transfer inside the enclosure is still very limited. Acharya and Tsang [25] numerically investigated the natural convection in an inclined air rectangular enclosure with a complete partition attached to the middle of the enclosure at tilt angles of 30°, 45°, 60°, and 90°. They indicated that the temperature of partition increased monotonically along its length, and the influence of Rayleigh number on the partition temperature was limited when the tilt angle was 45°. Tsang and Acharya [26] performed a numerical study on the natural convection in an inclined air rectangular enclosure with an off-center complete partition at tilt angles of 30°, 45°, 60°, and 90°. They pointed out that the effect of partition location on the partition temperature distribution decreased with increasing Rayleigh number. Mamou et al. [27] focused on the natural convective in a slanting air rectangular cavity consisting of multiple layers divided by baffles. They predicted the critical Rayleigh number for the transition from pure heat conduction to nature convection.

For the aim of exploring Mars, an increasing number of Mars rovers will work on the Mars surface in the future. Given the fact that the atmosphere on Mars surface is predominantly composed of Carbon Dioxide (CO_2) with low pressure (1000 Pa) and low temperature (200 K), thermal insulation materials and CO_2 gas enclosures are always adopted to insulate and protect the internal equipment. Hence, heat transfer characteristics of CO_2 enclosures are a key factor in the thermal design of Mars rover. Furthermore, when the Mars Rover executes the task on Mars surface covered with various sags and crests, the enclosures of the Mars Rover tilt into different angles from 0° to 90°. Occasionally, in order to improve the strength of the enclosure or divide the enclosure into

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