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Original Article

Analytical Modeling of Natural Convection in a Tall Rectangular Enclosure with Multiple Disconnected Partitions

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ABSTRACT

In this study, laminar natural circulation and heat transfer in a tall rectangular enclosure with disconnected vertical partitions inside were investigated. Analytical expressions were developed to predict the circulation flow rate and the average Nusselt number in a partially partitioned enclosure with isothermal side walls at different temperatures and insulated top and bottom walls. The proposed formulas are then validated against numerical results for modified Rayleigh numbers of up to 10^6. The impacts of the governing parameters are also examined along with a discussion of the heat transfer regimes.

1. Introduction

Enclosures divided by multiple vertical partitions are used in a wide variety of engineering applications such as mechanical, chemical, civil, and nuclear industries. Specifically, heat transfer through a partitioned enclosure has been of prime importance in the design of thermal insulators for nuclear reactors, buildings, cryogenic storage, etc.

The role of vertical partitions in suppressing the natural convection in enclosures heated from the sides has been extensively studied in the literature. Anderson and Bejan [1] conducted an experimental and theoretical study of natural convection in single and double partitioned enclosures, and reported that the heat transfer can be reduced by inserting vertical partitions. Nishimura et al. [2] investigated, both experimentally and numerically, laminar natural convection in rectangular enclosures with equally spaced vertical partitions inside. They showed that the heat transfer across the partitioned enclosure is inversely proportional to the number of fluid layers. A similar observation was made by Turkoglu and Yücel [3] for conducting partitions and side walls. Recently, Sambou et al. [4] presented a correlation to evaluate the average Nusselt number for partitioned enclosures with conducting side walls. There also have been several studies dealing with the effects of Rayleigh number, partition thickness and position, aspect ratio, and conductivity ratio of solid partition to fluid [5–8].

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Natural convection in enclosures with disconnected partitions inside has received little attention, although it is thought of as another major concern in practice. Costa et al. [9] conducted a numerical study on laminar free convection in enclosures with partial horizontal partitions. For enclosures with disconnected vertical partitions, Kim et al. [10] numerically investigated the thermal performance of the so-called wet thermal insulator installed in a system-integrated modular advanced reactor (SMART). When vertical partitions are disposed of inside the enclosure with gaps at the top and bottom ends to compensate for thermal expansion/contraction (see Fig. 1), buoyancy-driven flow circulates throughout the enclosure, i.e., fluid rises up in the hot-side layers, passing through the gap at the top, moving downward in the vertical channels near the cold side, and returning to the hot-side layers via the gap at the bottom. Compared to the case of connected partitions, in which natural circulation is confined within each fluid layer isolated by partitions, this often causes an undesirable increase in the circulation flow rate and heat transfer within the enclosure, significantly deteriorating the thermal insulation performance, as reported by Kim et al. [10]. Hence, if enclosures are used for thermal insulation purposes, it is desirable to remove the gaps by, for example, welding the partitioning plates to the top/bottom walls. However, owing to the limitations of the welding process associated with very thin partitioning plates and thermal expansion/contraction of materials in the case of integral-type nuclear reactors, it is often difficult in practice to eliminate the gaps and to ensure the perfect connection between them. Thus, in order to provide the proper requirements and/or recommendations for the design and manufacture of thermal insulator involving the selection of materials, we need to know in advance how the heat transfer performance is affected by the gaps, and to explore its functional dependence on the main governing parameters.

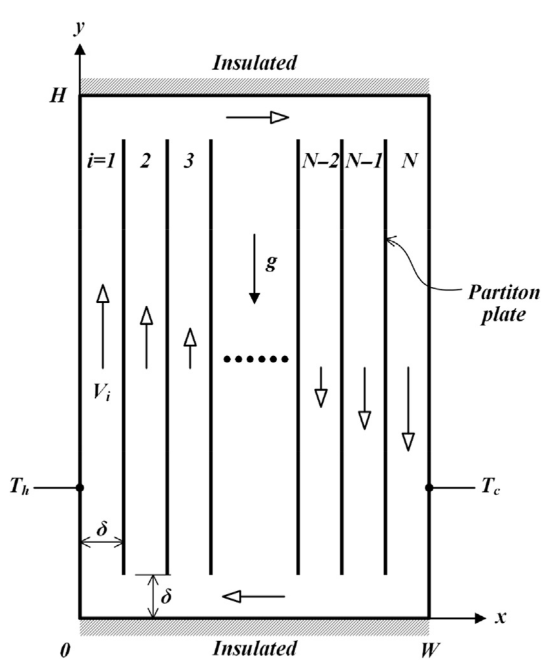

Fig. 1 – Schematic layout of a rectangular enclosure with multiple disconnected vertical partitions. δ, channel width; g, gravitational acceleration; H, enclosure height; i, layer index; N, number of fluid layers; T_c, cold wall temperature; T_h, hot wall temperature; V, mean velocity; W, enclosure width.

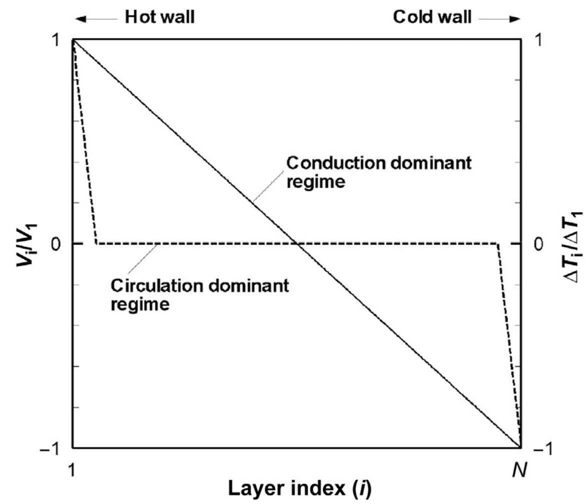

Fig. 2 – Illustration of velocity and temperature difference distributions in two limiting cases. ΔT, temperature difference; N, number of fluid layers; V, mean velocity.

In the present study, we investigated natural convection in a tall rectangular enclosure subjected to isothermal side boundary conditions with disconnected multiple vertical partitions of zero thickness. Under a fully developed laminar flow assumption, analytical modeling was performed to evaluate the flow rate of natural circulation and the average Nusselt number in a partially partitioned enclosure as a function of the main governing parameters such as the Rayleigh number, enclosure height/width ratio, and number of fluid layers. The validity and applicability of the proposed formulas are then established through comparisons with the numerical results. The impacts of the governing parameters on the emergence of natural circulation are also scrutinized along with a discussion of the heat transfer regimes.

2. Materials and methods

Fig. 1 shows a schematic diagram of the rectangular enclosure considered here, which is subjected to a horizontal temperature difference imposed over two isothermal side walls, with equally spaced vertical interior partitions separated from insulated top and bottom walls by a distance δ. To simplify the analysis, the following basic assumptions are made in this study, which are expected to be valid in many practical applications, such as multilayer insulation materials [11]: (1) the fluid channel width is small, such that $\delta \ll H$; (2) the vertical channel height is much larger than the enclosure width (i.e., $H \gg W$); (3) the interior partitions and exterior walls of the enclosure have no thickness; (4) the fluid properties are constant except for a linear density dependence on the temperature (Boussinesq approximation); (5) a steady, single-phase and fully developed laminar flow exists throughout the enclosure; (6) pressure losses in the miter bends and horizontal channels are negligibly small compared to