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Experimental and numerical study of Buoyancy-driven low turbulence flow in rectangular enclosure partially filled with isolated solid blockages

Draco Iyi [a,*], Reaz Hasan [b], Roger Penlington [b]

[a] *Department of Mechanical Engineering, School of Engineering, Robert Gordon University Aberdeen, AB10 7GJ, United Kingdom*
[b] *Department of Mechanical and Construction Engineering, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, United Kingdom*

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ABSTRACT

This paper considers the natural convection inside an air filled enclosure having several isolated cylindrical blockages distributed within it, and arranged parallel to two vertical walls of the enclosure. These two walls are maintained at different temperatures resulting in a natural convection process inside the enclosure. The objectives are to provide experimental temperature data and to investigate the influence of the blockages proximity within and outside the active vertical wall hydrodynamic boundary layer of the natural convection flow and heat transfer. Experiments were designed with high degree of accuracy to provide reliable temperature data-bank for a range of blockages proximity to the active vertical walls. The test enclosure is an air filled rectangular cavity fixed at 0.97 m × 0.4 m × 1 m, corresponding to the height, width and depth respectively. The top and bottom walls are conducting surface and the temperature difference between the active vertical walls was maintained at 42.2 °C resulting in a characteristic Rayleigh number of 4.04×10^9 based on the enclosure height. All the walls of the enclosure were insulated externally while the inner surfaces were covered with conducting plate. The test cavity capability of establishing low turbulence natural convection flows was verified. All temperature data were obtained at steady state and it was verified to be reproducible by repeating the experiment at different times. Also, two-dimensionality was verified via rigorous temperature readings over a period of time. Additional temperature readings were recorded for the air and cylinder surfaces at several distinct locations. Further investigations were conducted using a numerical approach to supplement and validate the experiments.

Experimental temperature data collated at various locations within the enclosure show excellent comparison with numerical results and as such provide a useful experimental benchmark temperature data for the validation of low turbulence natural convection flow in enclosure partially filled with isolated solid objects. Our result shows that a significant increment or reduction in air temperature and wall heat transfer could be achieved by varying the blockages proximity, and especially when the blockages are positioned within the hydrodynamic boundary layers of the active vertical walls.

1. Introduction

Buoyancy-driven flow and heat transfer in cavities partially filled with isolated solid products is important in the design of a wide range of industrial and engineering applications such as thermal management of indoor environments, cooling of electronic panels, drying of agricultural products and stacking of items in cold storage etc. The flow in such a confined space develops as a result of temperature gradient between two adjacent vertical walls of the cavity. The flow phenomenon has been the subject of extensive research due to its relevance in many practical applications [1–3]. As a result, there has been a growing demand for experimental data which will aid the development of more robust numerical method in order to achieve most approximate estimation of the transfer processes inside the cavity.

The basic set up for such flows that has also attracted most attention from researchers, is an air filled rectangular cavity without solid products whose opposing vertical walls is heated differentially [4–7]. Detailed data on the flow, turbulence and wall heat transfer coefficients have been collected through various experiments [8–10]. The experimental data available in literature have enabled the continuous development of numerical approach and methods by conducting validation and exploratory studies

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* Corresponding author.
E-mail address: d.iyi@rgu.ac.uk (D. Iyi).

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Nomenclature

C_p	specific heat at constant pressure, J/(kg-K)
D	depth of the cavity, m
g	gravitational acceleration, m/s^2
H	height of the cavity, m
$\bar{k}$	average thermal conductivity, W/(mK)
L	width of the cavity, m
Nu	local Nusselt number, $= Q_i L/(\bar{k}\Delta T)$
$\overline{Nu}$	average Nusselt number, $= \bar{Q}L/(\bar{k}\Delta T)$
$\Delta\overline{Nu}$	change in average Nusselt number, $= \overline{Nu}_\delta - \overline{Nu}_f$
$\%\Delta\overline{Nu}$	percentage change in average Nusselt number, $= 100 \times \Delta\overline{Nu}/\overline{Nu}_f$
Q	local heat flux, W/m^2
$\bar{Q}$	integral average heat flux, W/m^2
f	empty enclosure (Reference cavity)
δ	blockages proximity from active vertical wall
Ra_L	Rayleigh number, $= g\beta(T_{hot} - T_{cold})L^3/(\alpha\nu)$
Ra_H	Rayleigh number based on height, $= g\beta(T_{hot} - T_{cold})H^3/(\alpha\nu)$
T	temperature (K, °C)
T^*	non-dimensional temperature, $= (T - T_{cold})/\Delta T$
ΔT	temperature difference, $= T_{hot} - T_{cold}$
u^*	near-wall velocity, $= C_\mu^{1/4}k^{1/2}$
v_x	fluid velocity component in x-direction, m/s
v_y	fluid velocity component in y-direction, m/s
x, y, z	Cartesian coordinates
y^+	non-dimensional wall distance, $= (u^*\Delta y)/\nu$
Δy	distance to the nearest wall

Greek symbols

α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, (1/K)
ε	turbulent dissipation rate, m^2/s^2; Emissivity
ρ	fluid density, kg/m^3
μ	dynamic viscosity kg/m-s

on this very topic [11]. The interest seems to be on-going because more challenging situations are emerging with time [12,10]. In the case of a rectangular cavity of height H, the natural convection heat transfer from hot to cold walls is characterized by the formation of a slow moving vortex along the solid walls and the intensity of the flow can be conveniently expressed by the Rayleigh number [13,12] as defined by Eq. (1). Depending on the Rayleigh number the flow can be treated as turbulent or laminar, where $Ra \leqslant 10^8$ indicate buoyancy-induced laminar flow, with transition to turbulence occurring over the range of $10^8 \leqslant Ra \leqslant 10^{10}$ [14].

$$Ra = \frac{g\beta(T_h - T_c)L^3}{\nu\alpha} \tag{1}$$

Another trend in buoyancy driven flow research has been focused on the examination of enclosures partially filled with solid products [15–19]. Similar to that of the empty cavity, the flows in such confined spaces develop as a result of temperature gradient but complicated by the interactive effects of the solid products which act as blockages (obstacles) to the airflow and heat transfer. Unlike porous media [18,20,15], these obstacles are not in contact with each other, but are close enough to influence the transfer processes inside the enclosure.

The majority of the studies in this category is based on the steady state laminar flow of Rayleigh number from 10^4 to 10^8. Typical example of studies in this category is the work by Das and Reddy [19], Defrayed and Lauriat [21] and Basak et al. [20], all of which are limited to steady state two-dimensional laminar natural convection flow of the Rayleigh number ranging from 10^5 to 10^8. Das and Reddy [18] and Yoon et al. [22] have reported the fluid flow and heat transfer in a differentially heated rectangular cavity containing just one disconnected solid product, while Bragas and de Lemos [23,16], Hooman and Merrikh [17] investigated the cavity filled with several obstacles. The key findings from these research works show that when a limited number of solid products are involved, the fluid flow is predominantly confined between the vertical walls and the first column of the objects.

It is important to mention that investigations have been reported for an air-filled empty box [13,9,24] and box partially filled with isolated solid products [25,23]. However, no study have been reported for isolated solid products arranged in clusters in such a way that it interact with the flow near the active vertical walls of the chamber. This configuration has its relevance either cold or warm storage and in the design and location of clustered heating elements, etc. The aim of this paper is therefore to explore the effect of isolated blockages proximity from the enclosure active vertical walls on the natural convection flow and heat transfer.

2. Problem description

A natural convection experimental test rig whose flow domain is a rectangular box with a constant temperature gradient between the active vertical walls and conducting surface for both horizontal surfaces was designed and fabricated to obtain temperature data at various strategic positions within the enclosure. The test rig is capable of establishing low Rayleigh number natural convection flow inside the enclosure with or without the solid cylindrical blockages. The enclosure without blockages was used as a reference to that with blockages in order to quantify the influence of the blockages proximity from the active vertical wall. The enclosure flow domain size is fixed at 0.97 m high, 0.4 m wide and 1 m deep, with aspect ratios of $AR_x = 2.425$ (=H/L) and $AR_y = 2.5$ (=D/L). The temperature difference between the isothermal vertical walls was maintained at 42.2 °C. The Rayleigh number based on these dimensions and the temperature gradient between the active vertical walls was evaluated as 4.04×10^9, therefore a weak natural convection turbulent flow is expected inside the cavity. The schematic of the flow domain set-up for cavity with blockages is shown is Fig. 1.

One of the key objectives of this paper is to provide high quality temperature benchmark data for the validation of numerical method. To achieve this, rigorous attempts were made to scrutinize various factors that are likely to influence the experimental conditions. The factors scrutinized are: the two-dimensionality of the flow domain at three cavity depths, the energy balance of the cavity, and uniformity of temperature distribution on the inner surface of the active vertical wall and the repeat of measurements for air temperature data at different locations within the fluid domain. After satisfactory temperature data were obtained for steady state situation, isolated cylindrical pipes (blockages) were systematically positioned inside the enclosure. With the same experimental conditions, the set up was left to run for 42 h to allow the establishment of natural convection flow and temperature data were collated at steady state. The experimental temperature data were complemented by conducting detailed numerical simulations using experimental boundary conditions which enabled us to validate our experimental temperature data elsewhere in the domain.