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# Flow visualization of natural convection in vertical channels with opposing buoyancy forces

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ABSTRACT

Natural convection inside an asymmetrically, isothermally heated vertical channel with opposing buoyancy forces was studied with flow visualization and laser interferometry. Opposing buoyancy forces occur inside the channel when the hot wall is warmer than the ambient temperature and the cold wall is cooler than the ambient. These opposing buoyancy forces can cause flow instability inside the channel. The flow- and temperature-fields are of interest for validation of numerical modelling. The flow-field was obtained with flow visualization using a laser sheet and a Dräger tube, which supplied the aerosol. The temperature-field was obtained using a Mach–Zehnder interferometer. Experiments were carried out over a range of temperature ratios between −0.25 and −0.75 using aspect ratios between 13.2 and 26.4. These conditions provided a modified Rayleigh number range of approximately 5–215. Flow- and temperature-field photographs were taken ranging from steady laminar to unsteady turbulent flow.


## 1. Introduction

Natural convection in an open-ended channel is a classical problem that has received a lot of attention in the literature, with the earliest studies dating back to the 1940s. However, the vast majority of previous studies have considered the situation where the buoyancy forces are in a single direction, generally producing a unidirectional flow. In contrast, the current study considers the case where one wall is warmer than the ambient and one wall is cooler than the ambient. The situation leads to highly complex flows, with fluid often being entrained and discharged at each end of the channel. For a representative set of cases, this work examines the character of the flow and temperature fields produced by this class of problems.

A schematic of the problem geometry is shown in Fig. 1. An open-ended vertical channel is formed by two vertical isothermal walls of height $L$ separated by a channel spacing $b$. The aspect ratio of the channel is defined as $A = L/b$. The fluid above and below the channel is quiescent and at the ambient temperature, $T_\infty$. The cold wall has a temperature $T_C$ and the hot wall has a temperature $T_H$. In this paper, the cold wall is on the left and the hot wall is on the right side of the channel. A temperature ratio was defined by Aung et al. [1] as:

$$R_T = \frac{T_C - T_\infty}{T_H - T_\infty} \quad (1)$$

Most existing studies of a heated vertical channel with a single buoyancy force are in the range $0 \leqslant R_T \leqslant 1$ (i.e. $T_C$, $T_H > T_\infty$). In this study, opposing buoyancy forces are investigated where the temperature ratio is in the range of $-1 < R_T < 0$ (i.e. $T_H > T_\infty$ and $T_C < T_\infty$).

There have been many studies on asymmetrically, isothermally heated vertical channels with positive temperature ratios [2–5]. Elenbaas [6] was one of the first to study natural convection inside a symmetrically ($R_T = 1$), isothermally heated vertical channel. He was able to obtain experimental data for a wide range of modified Rayleigh numbers using two square plates separated by various channel spacings. It was determined using analytical work that the Nusselt number approaches two asymptotes at the upper and lower modified Rayleigh numbers. Using the analytical work and experimental data, an overall channel average Nusselt number correlation was developed.

An asymmetrically heated vertical channel with uniform heat flux and uniform wall temperature was studied by Aung et al. [1]. Experiments were conducted to verify the results of a numerical study covering a wide range of modified Rayleigh numbers. For uniform wall temperatures, it was shown that a nearly universal curve can be used to relate the Nusselt numbers and the modified Rayleigh numbers for a wide range of temperature ratios. This is the case if the Nusselt number and Rayleigh number are defined

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## Nomenclature

| | |
|---|---|
| $A$ | aspect ratio (L/b) |
| $b$ | channel spacing (m) |
| $g$ | gravity (m/s$^2$) |
| $G$ | Gladstone Dale constant (m$^3$/kg) |
| $L$ | channel height (m) |
| $P$ | absolute pressure (Pa) |
| Pr | Prandtl number |
| $R$ | gas constant (J/kg K) |
| Ra($b/L$) | modified Rayleigh number |
| $R_T$ | temperature ratio |
| $T$ | temperature (°C) |
| $\overline{\Delta T}$ | characteristic temperature difference (°C) |
| $T_C$ | cold wall temperature (°C) |
| $T_H$ | hot wall temperature (°C) |
| $T_{ref}$ | absolute reference temperature (K) |
| $T_\infty$ | ambient temperature (°C) |
| $W$ | channel width in the laser beam direction (m) |
| $x,y$ | Cartesian co-ordinate system (m) |

*Greek symbols*

| | |
|---|---|
| $\beta$ | fluid thermal expansion coefficient (K$^{-1}$) |
| $\varepsilon$ | fringe shift order |
| $\lambda_0$ | laser light wavelength in a vacuum (m) |
| $\mu$ | fluid dynamic viscosity (N s/m$^2$) |
| $\rho$ | fluid density (kg/m$^3$) |

by using the appropriate characteristic temperature difference. This characteristic temperature difference is defined as:

$$\overline{\Delta T} = \frac{T_H + T_C}{2} - T_\infty \tag{2}$$

The modified Rayleigh number based on this temperature difference is:

$$\mathrm{Ra}(b/L) = \frac{g\beta\overline{\Delta T}\rho^2 b^3}{\mu^2}\mathrm{Pr}\frac{b}{L} \tag{3}$$

where Pr is the Prandtl number. All air properties were evaluated at the film temperature. The film temperature is defined as:

$$T_f = \frac{(T_H + T_C)/2 + T_\infty}{2} \tag{4}$$

Sparrow et al. [7] conducted a flow visualization study in order to investigate flow reversal in the upper portion of the channel. The vertical channel had the hot wall isothermally heated and the cold wall unheated ($R_T = 0$). The experimental model was set up in water at ambient temperature, into which the Thymol blue was injected. The heated wall was a source of buoyancy, so the fluid accelerated up the hot wall near the channel outlet. Fluid was drawn into the top of the channel adjacent to the unheated wall in order to satisfy mass conservation. They observed in a channel with Ra($b/L$) = 5270 and $A$ = 15.2 that some ambient water was drawn in from the top of the channel. The ambient water flowed about 25% down the cold wall and then re-circulated with the water flowing up the hot wall. Depending on the aspect ratio and modified Rayleigh number, the percentage of backflow down the cold wall varied. In general, flow reversal occurred when the modified Rayleigh number was greater than 2300.

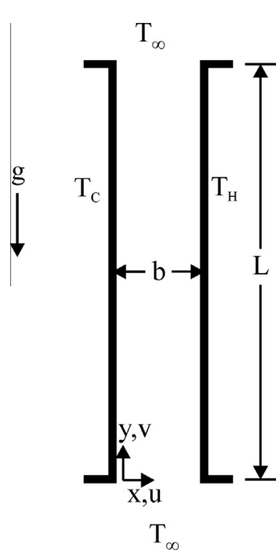


**Fig. 1.** Problem geometry and co-ordinate system.

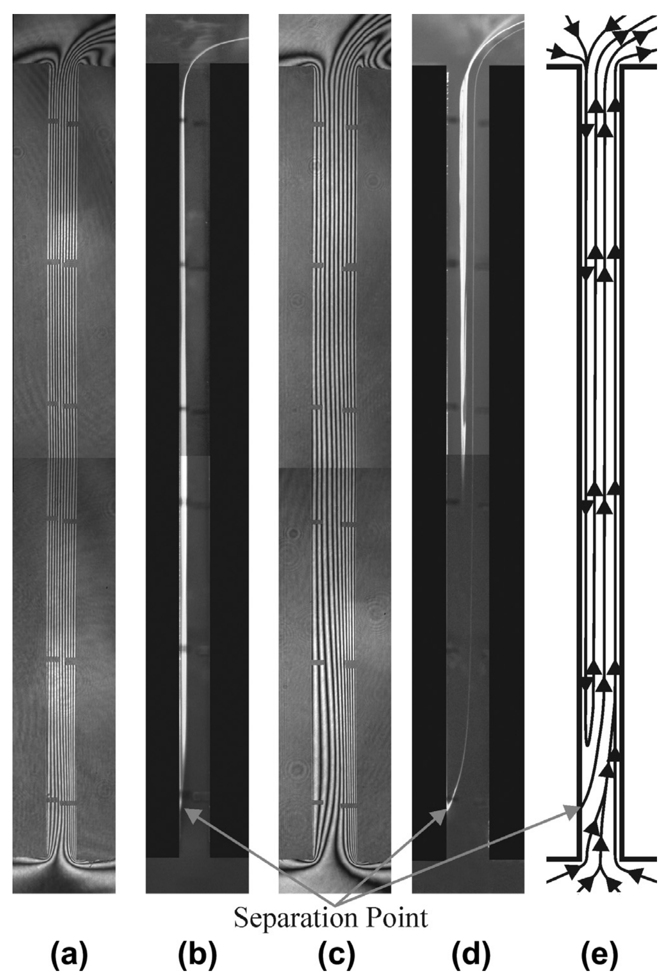


**Fig. 2.** (a) Interferogram and (b) streamlines for $R_T = -0.5$, Ra($b/L$) = 12.3 and $A$ = 26.4, (c) interferogram and (d) streamlines for $R_T = -0.5$, Ra($b/L$) = 67.5 and $A$ = 17.6 and (e) sketch of the flow pattern.