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# Natural convection heat transfer characteristics in vertical cavities with active and inactive top and bottom disks

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ABSTRACT

Natural convection heat transfer was investigated in vertical cavities where either all surfaces were active, or only the vertical surface was active for four different geometries, which were varied by placing a disk at the top and/or bottom of the cavity. A cupric acid–copper sulfate electroplating system was employed for mass transfer experiments exploiting the analogy with heat transfer. The Rayleigh number was varied in the range $4.55 \times 10^9 \leqslant Ra_{Lw} \leqslant 3.79 \times 10^{13}$. Preliminary tests for a vertical pipe, upward- and downward-facing horizontal disks showed good agreement with existing correlations. The measured Nusselt numbers in the vertical cavities with all surfaces active were always greater than those with only the vertical surface active, which is attributed to greater hydrodynamic interaction of the flows generated by different surfaces. When all surfaces were active, the bottom-closed cavity exhibited the largest heat transfer rates, followed by both-closed, top-closed, and both ends open cavities; this trend was observed with laminar and turbulent flows. With only the vertical surface active, similar trends were observed except that the heat transfer rates were almost identical for both-open and top-closed cavities, which is attributed to the weak influence of the top disk on the heat transfer characteristics. Using these results, empirical correlations were derived for both laminar and turbulent flow conditions.



## 1. Introduction

Natural convective flows in a vertical cavity are relevant to many practical applications in the design of both heat and mass transfer devices, especially the passive safety system design of nuclear power plants under hypothetical accident conditions. Much data are available for natural convection in a vertical cavity where both ends are open (i.e., a vertical heated pipe) over a wide range of Rayleigh numbers [1–3]; however, most practical problems related to engineering fields concern vertical cavities with arrangements other than a simple vertical heated pipe.

The vertical cavity consists of a vertical cylindrical wall and horizontal circular disks. The horizontal circular disks seal the cavity at the top and/or bottom, and may be either active or inactive, where the term active corresponds to a heated wall and inactive to an adiabatic wall. The geometry of the vertical cavities may be classified into four cases: both ends open, bottom-closed (with an open top), top-closed (with an open bottom), and with both ends closed. There have been some reports of natural convection in vertical cavities [4–6], whereby the authors used the cavities with either all surfaces active (i.e., both the vertical walls and horizontal disks were heated), or where only the vertical surfaces were active. These works were restricted mainly to laminar flows and the bottom-closed and top-closed cavity geometries. The heat transfer behavior of the cavity geometry with both ends closed has been less well studied. Furthermore, the available data in the literature lack consistency in terms of the size of the vertical cavities, and the authors did not provide detailed phenomenological explanations of the flow interactions in the vertical cavities. For these reasons, detailed investigations are required to understand the heat transfer behavior of vertical cavities by exploring further geometrical arrangements with consistent sizes of cavity with both laminar and turbulent flows.

This study investigated natural convection heat transfer due to hydrodynamic interactions in vertical cavities with various geometrical arrangements and with Rayleigh numbers in the range $4.55 \times 10^9$ to $3.79 \times 10^{13}$. These ranges are sufficient to cover laminar and turbulent flows. The Nusselt number was measured for the four geometries of vertical cavities with all surfaces were active, and only the vertical surfaces were active. Exploiting the analogy between heat and mass transfer, we used a sulfuric acid-copper sulfate ($H_2SO_4$—$CuSO_4$) electroplating system with the limiting-current technique to characterize the heat transfer coefficients.

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**Nomenclature**

| | |
|---|---|
| $C_b$ | concentration in the bulk [mol/m$^3$] |
| $C_p$ | specific heat at constant pressure [J/kg K] |
| $d$ | diameter [m] |
| $D_m$ | mass diffusivity [m$^2$/s] |
| $D_o$ | cylinder diameter [m] |
| $F$ | Faraday constant, 96,485 [C/mol] |
| $g$ | gravitational acceleration, 9.8 [m/s$^2$] |
| $Gr_H$ | Grashof number [$g\beta\Delta TH^3/\nu$], [$(gH^3/\nu^2)\cdot(\Delta\rho/\rho)$] |
| $H$ | height of cathode [m] |
| $h_h$ | heat transfer coefficient [W/m$^2$ K] |
| $h_m$ | mass transfer coefficient [m/s] |
| $I$ | electric current [A] |
| $I_{lim}$ | limiting current density [A/m$^2$] |
| $L$ | length of horizontal surface [m] |
| $L_W$ | surface area / perimeter projected onto a horizontal plane ($H + d/4$) [m] |
| $M$ | molarity [mol/l] |
| $k$ | thermal conductivity [W/m K] |
| $n$ | number of electrons in charge transfer reaction |
| $Nu_d$ | Nusselt number [$h_hd/k$] |
| $Nu_H$ | Nusselt number [$h_hH/k$] |
| $Nu_{Lw}$ | Nusselt number [$h_hL_W/k$] |
| $Pr$ | Prandtl number [$\nu/\alpha$] |
| $Ra_H$ | Rayleigh number [$g\beta\Delta TH^3/\nu$], [$(gH^3/D\nu)\cdot(\Delta\rho/\rho)$] |
| $Sc$ | Schmidt number [$\nu/D_m$] |
| $Sh_H$ | Sherwood number [$h_mH/D_m$] |
| $Sh_d$ | Sherwood number [$h_md/D_m$] |
| $Sh_{Lw}$ | Sherwood number [$h_mL_W/D_m$] |
| $t_n$ | transference number |
| $U$ | uncertainty |
| *Greek symbols* | |
| $\alpha$ | thermal diffusivity [m$^2$/s] |
| $\beta$ | volume expansion coefficient [1/K] |
| $\gamma$ | dispersion coefficient |
| $\mu$ | viscosity [kg/m s] |
| $\nu$ | kinematic viscosity [m$^2$/s] |
| $\rho$ | density [kg/m$^3$] |
| $\delta$ | velocity boundary layer thickness [m] |
| $\delta_T$ | thermal boundary layer thickness [m] |

Phenomenological explanations of the effects of the geometry on the flow interactions and heat transfer rates are provided, and empirical correlations based upon the results are derived for the four arrangements with laminar and turbulent flow conditions.

## 2. Natural convection heat transfer in a vertical cavity

Table 1 lists a summary of previous studies on natural convection heat transfer in vertical cavities. For the case with both ends open, the thermal boundary layer that developed along the hot wall was thinner than the cylinder radius, and the heat transfer phenomena were similar to those for a vertical plate [1]. With this geometry, the Nusselt number can be calculated using correlations for vertical plates. Kang and Chung [7,8] showed this result experimentally and reported that a transition to turbulent flow occurred with a Grashof number of approximately $Gr_H = 10^9$, corresponding to a Rayleigh number of $Ra_H = 10^{12}$ when a Prandtl number was $Pr = 2000$. Their results were in good agreement with Le Fevre's correlation for laminar flow [9] and Fouad's correlation for turbulent flow [10].

There have been several reports of the heat transfer characteristics in bottom-closed and top-closed cavities. These cavities consist of a vertical wall and a horizontal disk either at the bottom or top. Some of the previous studies have used mass transfer experiments exploiting the analogy between heat and mass transfer systems. Somerscales and Kassemi [4] measured the natural convection heattransfer in bottom-closed cavities with all surfaces active for Rayleigh numbers in the range $7.1 \times 10^7 \leqslant Ra_d \leqslant 6.9 \times 10^9$, where the diameter was used as the characteristic length. Krysa et al. [5] carried out experiments using bottom-closed cavities for Rayleigh numbers in the range $2 \times 10^7 \leqslant Ra_d \leqslant 1.2 \times 10^{10}$ and visualized the flows emerging from the cavity openings for a short cavity. Two types of bottom-closed cavities were formed with all surfaces active and with only the vertical surface active. Two characteristic lengths were used depending

**Table 1**
Previous studies for the vertical cavities.

| Authors | $H$ (m) | $d$ (m) | Range of $Ra$ | Arrangement | Surface condition | Correlations | |
|---|---|---|---|---|---|---|---|
| Le Fevre [9] | – | – | $Gr_H \leqslant 10^9$ | Both ends open | – | $Nu_H = 0.67(Gr_HPr)^{0.25}$ | (1) |
| Fouad [10] | – | – | $Gr_H \geqslant 10^9$ | Both ends open | – | $Nu_H = 0.31(Gr_HPr)^{0.28}$ | (2) |
| Somerscales and Kassemi [4] | 0.00635, 0.0127, 0.0254 | 0.0127 | $7.1 \times 10^7 \leqslant Ra_d \leqslant 6.9 \times 10^9$ | Bottom-closed (open top) | All surfaces active | $Nu_d = 0.232(d/H)^{0.191}Sc^{0.056}Ra_d^{0.28}$ | (3) |
| | 0.0127, 0.0254, 0.0508 | 0.0254 | | | | | |
| | 0.019, 0.0381, 0.0762 | 0.0381 | | | | | |
| Krysa et al. [5] | 0.003–0.0381 | 0.0135 | $2 \times 10^7 \leqslant Ra_{Lw} \leqslant 1.2 \times 10^{10}$ | Bottom-closed (open top) | All surfaces active | $Nu_{L_w} = 0.559Ra_{L_w}^{0.265}$ | (4) |
| | | | | | Only vertical surface active | $Nu_H = 0.480Ra_H^{0.265}$ | (5) |
| Sedahmed et al. [6] | 0.005, 0.01, 0.015, 0.025, 0.03 | 0.0172 | $1 \times 10^8 \leqslant Ra_{Lw} \leqslant 5.02 \times 10^9$ | Bottom-closed (open top) | All surfaces active | $Nu_{L_w} = 0.257Ra_{L_w}^{0.333}$ | (6) |
| | 0.02 | 0.02, 0.0296, 0.032, 0.041 | | Top-closed (open bottom) | | $Nu_{L_w} = 0.187Ra_{L_w}^{0.297}$ | (7) |