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An investigation of unsteady flow reversal of natural convection in vertical parallel plates by the modified local one-dimensional inviscid relations method

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ABSTRACT

An unsteady flow reversal of natural convection in vertical parallel plates with an asymmetrically heated wall is investigated numerically. For clarifying the occurrence of flow reversal, the width of the plates is regarded as a variable, and the non-reflecting boundary condition is adopted at apertures. The methods of the Roe scheme, preconditioning and dual time stepping matching LUSGS are simultaneously used to solve governing equations which are available for a low speed compressible flow problem. The flow reversal is observed under broad width situations and absent under narrow width situations. Distributions of the pressure differences at the apertures are revealed to indicate the occurrence of flow reversal. The present Nusselt numbers, which mean time and area-averaged ones, display relatively good agreement with those of the existing works.

1. Introduction

The subject of natural convection in vertical parallel plates still attracts lots of experimental and numerical studies [1–24] because of its wide applications in both academic and industrial research, such as heat dissipation fins, solar cells, and air conditioned systems. In some situations of this subject, a special phenomenon called flow reversal, in which surrounding fluids through the outlet flow into the vertical parallel plates, is found when the ratio of the width to the length of the plates exceeds a certain threshold. The flow reversal also appears in some mixed convection systems under a situation of the dominance of natural convection [25–29]. According to the phenomenon, the occurrence of the flow reversal implies that due to the limitation of geometric and thermal conditions of natural convection, the total mass flow rate via the inlet sucked into the plates is less than the critical mass flow rate which is the largest quantity of mass flow rate to be sucked into the plates by the buoyancy force in spite of via an inlet or an outlet. The shortage of mass flow rate between the total mass flow rate and the critical mass flow rate is then supplemented from the outlet. The mass flow rate through the outlet flowing downward into the plates inevitably impinges on the mass flow rate through the inlet flowing upward into the plates. The equilibrium between both upward and downward impulses caused by two mass flow rates strongly affects phenomena of the impingement to be steady or not. In generally, unsteady phenomena of the impingement easily happen when the impulse of the mass flow rate flowing through the outlet is much larger than that of the mass flow rate flowing through the inlet, and vice versa.

In the past, Sparrow et al. [2] conducted experimental and numerical studies to investigate natural convection in vertical parallel plates and flow reversal. The flow reversal was formed by a pocket of recirculating flow when Ra/A ratio exceeded a certain magnitude. Numerical solutions obtained by a parabolic finite difference scheme yielded Nusselt numbers in good agreement of the experimental results. An experimental work of natural convection in two vertical plates was conducted by Al-Azzawi [3]. One of the plates regarded as a heat wall was heated electrically, and the other was made of glass. The height of plates are 1 m and 2 m, respectively. The width between two plates varies from 25 to 150 mm. The thermal conditions of the heated wall were a uniform heat flux and a constant wall temperature, respectively. An experimental equation was derived to reveal a relationship between the Nusselt number and modified Rayleigh number.

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Nomenclature

A	area (m^2)
b	width of the plate (m)
e	internal energy (J/kg)
g	acceleration of gravity (m/s^2)
h	height of the plate (m)
k	thermal conductivity (W/m K)
k_0	surrounding thermal conductivity (W/m K)
w	length of the plate (m)
$\dot{M}_y$	local mass flow rate (kg/s)
$\overline{\dot{M}_y}$	total mass flow rate (kg/s)
Nu_x	local Nusselt number defined in Eq. (39) $Nu_x = \frac{h}{k_0(T_h-T_c)}[k(T)\frac{\partial T}{\partial y}]$
$\overline{Nu}_x$	time-average local Nusselt number defined in Eq. (40) $\overline{Nu}_x = \frac{1}{t}\int_t Nu_x dt$
$\overline{Nu}_A$	area-average local Nusselt number defined in Eq. (44) $\overline{Nu}_A = \frac{1}{A}\int_w \int_h Nu_x dxdz$
$\overline{Nu}$	time and area-average Nusselt number defined in Eq. (45) $\overline{Nu} = \frac{1}{A}\int_w \int_h \overline{Nu}_x dxdz$
P	pressure (Pa)
P_0	surrounding pressure (Pa)
Pr	Prandtl number
R	gas constant (J/kg/K)
Ra	Rayleigh number defined in Eq. (26) $Ra = \Pr \frac{g\rho_0^2(T_h-T_c)h^3}{T_0\mu(T)^2}$
Ra^*	modified Rayleigh number defined in Eq. (27) $Ra^* = Ra \times \frac{h}{b}$
t	time (s)
t^*	dimensionless time $t^* = t\frac{\alpha}{h^2}$
T	temperature (K)
T_0	temperature of surroundings (K)
T_h	temperature of heat surface (K)
u, v, w	velocities in x, y and z directions (m/s)
x, y, z	Cartesian coordinates (m)
X, Y, Z	dimensionless Cartesian coordinates $X = \frac{x}{h}$, $Y = \frac{y}{h}$ and $Z = \frac{z}{h}$
Greek symbols	
α	thermal diffusivity rate (m^2/s)
ρ	density (kg/m^3)
ρ_0	surrounding density (kg/m^3)
μ	viscosity ($N\ s/m^2$)
μ_0	surrounding viscosity ($N\ s/m^2$)
γ	specific heat ratio

Chang and Lin [5] performed a numerical study to investigate the reversed flow and oscillating wake in an asymmetrically heated channel. The Boussinesq assumption and an extended domain were adopted. The phenomenon of flow reversal was indicated near the upper adiabatic wall. The larger the Rayleigh number was, the more remarkable phenomenon was revealed. Kihm et al. [8] performed a numerical study matching smoke visualization to investigate a problem of flow reversal of natural convection in isothermal vertical walls. The Boussinesq assumption and an extended boundary were adopted. The phenomenon of flow reversal was observed in the upper central region because of isothermal vertical walls, and variations of the entrance lengths with the Rayleigh numbers were indicated. Ospir et al. [21] conducted an experimental study to investigate an evolution of flow reversal from a single cell to a final eight-shaped structure. Results showed that the increase in the modified Rayleigh number resulted in an increment in the penetration of the flow reversal. Recently, Li et al. [22] firstly added an effect of radiation on investigating the flow reversal of natural convection in asymmetrically heated vertical channels numerically. Experimental results of Webb and Hill [4] were used as boundary conditions at the inlet and outlet of the channel, and then the governing equations of an elliptic nature were solved and an extended boundary adopted in the above literature was not necessary. The flow reversal and distributions of streamlines and isotherms under a steady situation were indicated. The mass flow rate kept constant when the wall spacing exceeded a certain magnitude. The onset of flow reversal delayed upon the effect of surface radiation and enhancement of the cooling of the heated wall by radiation were shown. Desrayaud et al. [23] used eight different methods to study natural convection between parallel plates with an asymmetrically heated wall. The flow reversal was observed and results obtained by the above method were in good agreement. Because an elliptic natural of the problem was solved in the above literature, the results were mainly indicated by steady situations. Due to the solution method mentioned above, indications of variations of pressures, which are driving forces caused by the buoyancy force and cannot be assigned in advance like forced convection, are difficult to be revealed. Indeed, according to the result of a distribution of pressures, the characteristics of the flow reversal can be easily predicted.

Therefore, the aim of the study is to investigate unsteady phenomena of the flow reversal of natural convection in parallel vertical plates numerically. In order to simulate the situation more realistically, the compressibility and viscosity of the working fluid are considered, and the non-reflecting boundary condition, which causes the Boussinesq assumption to be no longer necessary, held at the inlet and outlet of the plates is adopted. For solving a low speed compressible flow problem, the methods of the Roe scheme [30], preconditioning [31] and dual time stepping [32] matching the LUSGS [33] are simultaneously used to solve the governing equations. Then the magnitudes of the velocity, temperature, pressure and density at the inlet and outlet of the plates are simultaneously calculated. The flow reversal is found when the width exceeds a certain magnitude. Further, an unsteady flow reversal, which is mainly caused by a drastic impingement occurring between the mass flow rates flowing through the inlet and outlet, appears under a larger magnitude of the width of the plates. Distributions of pressures in the plates are indicated to validate the flow orientation at the inlet and outlet. Both numerical results of this study and existing experimental results [3] display relatively good agreement.

2. Physical model

A physical model of vertical parallel plates is indicated in Fig. 1. The length and height of the physical model are w and h, respectively. The temperature of the heated wall is T_h and equal to 400 k, and the right wall is adiabatic. The width of the plates is b, and the direction of gravity is opposite to the direction of X. Boundary conditions on both apertures are non-reflecting boundary conditions and both sides of the length are periodic conditions. The pressure and temperature of the surrounding are 101,300 Pa and 298 K, respectively.

For facilitating the analysis, the following assumptions are made.