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Numerical simulation of flow instability and heat transfer of natural convection in a differentially heated cavity

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ABSTRACT

This paper numerically investigates the physical mechanism of flow instability and heat transfer of natural convection in a cavity with thin fin(s). The left and the right walls of the cavity are differentially heated. The cavity is given an initial temperature, and the thin fin(s) is fixed on the hot wall in order to control the heat transfer. The finite volume method and the SIMPLE algorithm are used to simulate the flow. Distributions of the temperature, the pressure, the velocity and the total pressure are obtained. Then, the energy gradient theory is employed to study the physical mechanism of flow instability and the effect of the thin fin(s) on heat transfer. Based on the energy gradient theory, the energy gradient function K represents the characteristic of flow instability. It is observed from the simulation results that the positions where instabilities take place in the temperature contours accord well with those of higher K value, which demonstrates that the energy gradient theory reveals the physical mechanism of flow instability. Furthermore, the effects of the fin length, the fin position, the fin number, and Ra on heat transfer are investigated. It is found that the effect of the fin length on heat transfer is negligible when Ra is relatively high. When there is only one fin, the most efficient heat transfer rate is achieved as the fin is fixed at the middle height of the cavity. The fin blocks heat transfer with a relatively small Ra, but the fin enhances heat transfer with a relatively large Ra. The fin(s) enhances heat transfer gradually with the increase of Ra under the influence of the thin fin(s). Finally, a linear correlation of K_{max} with Ra is obtained which reveals the physical mechanism of natural convection from different approaches.

1. Introduction

Transient natural convection flows in a cavity are common in industrial applications such as in heat exchangers, solar collectors and nuclear reactors etc, and in our daily life such as in light emitting diode (LED) street lights, computers, mobile phones etc. In the early stages, the steady-state flow has been extensively explored in Refs. [1–3]. Actually, most buoyancy-driven flows in nature and industrial applications are unsteady, and consequently more and more experimental and numerical studies are gradually focusing on unsteady-state flows [4,5]. Patterson and Imberger [6] studied theoretically the transition of unsteady natural convection in a rectangular cavity and found that the whole base flow during the transition includes a vertical boundary layer, a horizontal intrusion and the flow in the core.

The transition of natural convection flows in the cavity differentially heated has been given considerable attention over the last three decades [7–9], and more practical applications based on transient natural convection heat transfer face the problem that it is difficult to enhance or depress the heat transfer rate. It is known that the heat transfer rate will be enhanced when the base flow in the cavity loses its stability [10]. Based on the previous research results, one of the simplest ways to control the heat transfer rate is to fix a solid block on either the hot or the cold side of the differentially heated cavity.

Xu et al. made their efforts to investigate the physical mechanical of natural convection by imposing a thin fin on the hot side of the differentially heated cavity [11–15]. In the following description, we will briefly review the investigation progress and the relevant conclusions. Xu et al. [11] made some experiments to validate the transition of unsteady natural convection using a shadowgraph technique and measured the convection phenomenon using fast-response thermistors. They observed that the transition from initiation by suddenly heating to a quasi-steady state undergoes a number of stages as analyzed by Patterson and Imberger [6]. They also observed separation and oscillations of the thermal flow above the fin and demonstrated that

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Nomenclature

A	aspect ratio of the cavity (dimensionless)
$\overline{A}$	amplitude of the disturbance distance, m
c_p	specific heat, $m^2\ s^{-2}\ K^{-1}$
E	total mechanical energy per unit volumetric fluid, $J\ m^{-3}$
F	function (dimensionless)
g	gravity acceleration, $m\ s^{-2}$
H_1	height of the cavity, m
H	loss of total mechanical energy, $J\ m^{-3}$
k	thermal conductivity factor, $W\ m^{-1}\ K^{-1}$
K	dimensionless function expresses the ratio of transversal energy gradient and streamwise energy gradient
l	length of fin, m
L	length of cavity, m
n	coordinate in transverse direction, m
Nu	Nusselt number along a vertical straight line (dimensionless)
p	pressure, $N\ m^{-2}$
p_0	total pressure, $N\ m^{-2}$
Pr	Prandtl number (dimensionless)
Ra	Rayleigh number (dimensionless)
s	coordinate in streamwise direction, m
t	time, s
T	temperature, K
T_0	temperature of the fluid, K
T_c	temperature of the cold wall, K
T_h	temperature of the hot wall, K
u, v	velocity components in x, y directions respectively, $m\ s^{-1}$
v'_m	amplitude of the disturbance of velocity in transverse direction, $m\ s^{-1}$
x, y	coordinates, m

Greek symbols

β	coefficient of thermal expansion, $(10^{-6})\ K^{-1}$
λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
μ	dynamic viscosity, $N\ m^{-2}\ s$
ν	kinematic viscosity, $m^2\ s^{-1}$
ρ	density of fluid, $kg\ m^{-3}$
ω_d	frequency of the disturbance, $rad\ s^{-1}$
ΔE	energy difference along transverse direction, $J\ m^{-3}$
ΔH	energy difference along streamwise direction, $J\ m^{-3}$
ΔT	temperature difference, K
Δx	grid mesh sizes, m

these oscillations trigger instability of the downstream thermal boundary layer flow and enhance the convection. Based on the related experimental results, Xu et al. [12] numerically studied the transition to a periodic flow induced by a thin fin. They find that in the early stage of the flow development following suddenly heating, a lower intrusion front is formed under the fin, and a starting plume arises after the lower intrusion front bypasses the fin. The starting plume induces strong perturbations and even turbulence in the downstream vertical boundary layer. They confirmed that the presence of the thin fin changes the flow regime by triggering intermittent plumes at the leeward side which in turn enhances heat transfer rate. Later, Xu et al. [13] made some further research of transient natural convection flows around a thin fin by both scaling analysis and direct numerical simulations. Both results indicate that the thickness and velocity of the transient natural convection flows around the fin are determined by different dynamic and energy balances which depend on the Rayleigh number, the Prandtl number and the fin length. Furthermore, Xu et al. [14] still performed some experiments to measure the temperature of the thermal flows. They clarify that the oscillatory property of the boundary layer is a key to developing processes by which the boundary layer may be triggered into transition to turbulence, and the consequent enhancement of the total heat transfer. Recently, Xu et al. [15] numerically investigated the relationship between the conductivity of the thin fin and the heat transfer rate of the unsteady natural convection flow adjacent to the finned sidewall of a differentially heated cavity. They observe that the conducting fin improves the transient convection flows in the cavity and enhances heat transfer by up to 52% in comparison with the case without a thin fin.

During the same period, other researchers made lots of contribution in investigation of transient natural convection. Bilgen [16] carried out a numerical study in differentially heated cavities using following parameters: Rayleigh number from 10^4 to 10^9, dimensionless thin fin length from 0.1 to 0.9, dimensionless thin fin position from 0 to 0.9, dimensionless conductivity ratio of thin fin from 0 to 60. He finds that Nusselt number is an increasing function of Rayleigh number, and a decreasing function of fin length and relative conductivity ratio. Moreover, the heat transfer may be suppressed by up to 38% by choosing appropriate thermal and geometrical fin parameters. Oztop and Bilgen [17] numerically investigated the heat transfer in a differentially heated, partitioned, square cavity containing heat generating fluid. They clarify that the flow field was modified considerably with partial dividers and heat transfer was generally reduced particularly when the ratio of internal and external Rayleigh number is from 10 to 100. Mezrhab et al. [18] studied the heat transfer in an inclined square cavity, differentially heated by using numerical coupling between the Lattice-Boltzmann equation and finite-difference for the temperature. He finds that when Ra is low ($Ra \leqslant 10^5$), the average hot wall Nusselt number is higher in inclined cavities than in vertical one; while at large Ra ($Ra = 10^6$), the opposite phenomenon occurs. Varol et al. [19] numerically analyzed the natural convection in solid adiabatic thin fin attached to porous right triangular enclosures. They find that the thin fin can be used as a passive control element for flow field, temperature distribution and heat transfer. Mahmoudi et al. [20] numerically investigated the natural convection cooling of a heat source horizontally attached to the left vertical wall of a cavity filled copper–water. They observe that the increase of Rayleigh numbers strengthens the natural convection flows which leads to the decrease in heat source temperature.

As mentioned above, the researchers have handled so many ways to control the heat transfer mainly by triggering the base flow to lose its stability [6,11–20]. However, the dynamic mechanisms of flow instability of natural convection around a fin and the relation between instability and heat transfer rate is still not fully understood. These observations motivate the study in this paper.

After almost 20 years of investigation, Dou and co-authors [21–29] proposed an energy gradient theory which describes the rules of fluid material stability from the viewpoint of mechanical energy field. It is claimed that the instability of material system could not be resolved by Newton's three laws, for the reason of a material system moving in some cases is not simply due to the role of forces, but due to the gradient of the total mechanical energy. This approach explains the mechanism of flow instability from physics and derives the criteria of turbulent transition. Accordingly, this method dose not attribute Rayleigh–Benard problem to forces exerted on fluid, but to the gradient of total mechanical energy