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Direct numerical simulation of Rayleigh-Bénard-Marangoni convection of cold water near its density maximum in a cylindrical pool

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A R T I C L E I N F O

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A B S T R A C T

In order to understand the influence of Marangoni effect on Rayleigh-Bénard convection, a series of three-dimensional numerical simulations of Rayleigh-Bénard- Marangoni convection of cold water near its maximum density in a cylindrical pool heated from below and with a free surface at the top were carried out by using the finite volume approach. Results show that the flow pattern is strongly influenced by the Rayleigh number, as well as by the Biot number. When the Biot number is small, the critical Rayleigh number for the onset of convection is low due to the strong Marangoni effect on the free surface. As the Biot number increases, the Marangoni effect becomes weaker. Therefore, the critical Rayleigh number becomes much larger and more flow patterns can be observed at different density inversion parameters. Furthermore, the average Nusselt number is influenced by the Rayleigh number, the Biot number and the density inversion parameter. Specifically, the average Nusselt number increases with the increase of the Rayleigh number and the decrease of the density inversion parameter. Meanwhile, as the Biot number goes up, the average Nusselt number increases at first and then decreases. In addition, there exists a sudden increase of the Nusselt number when the flow pattern transits from a relative stable state to a violent state, which means the flow pattern can also influence the heat transfer ability.

1. Introduction

For a cavity heated from the bottom and with a free surface at the top, when the temperature difference between the bottom and top is large enough, the flow driven by the buoyancy and the surface tension gradient will happen, which is named as Rayleigh- Bénard-Marangoni (R-B-M) convection [1]. Because of its wide existence in industrial applications, such as cold storage air conditioning, crystal growth, welding process etc. [2–4], this convection has been widely concerned, especially in recent decades.

The pioneering work on Bénard convection was carried out by Bénard [5]. According to his experiment, it was found that the fluid keeps stationary at a small temperature difference; however, the hexagon flow pattern appears when the temperature difference exceeds a certain value. After that, Block [6] pointed out that the hexagonal cell pattern may be caused by the surface tension gradient. Ondarcuhu et al. [7] investigated the effect of the temperature difference on the flow pattern of Bénard-Marangoni convection in a rectangular cavity by experiments. Results indicated that when the temperature difference is small, the flow pattern appears as the pentagon and square patterns. With the gradual increase of the temperature difference, the pentagon pattern disappears at first, and then reproduces. Dijkstra [8] numerically analyzed the stability of two-dimensional steady flow patterns in rectangular containers, and obtained the bifurcation diagram of flow patterns. Similar studies of a volatile fluid in a sealed and confined rectangular container were carried out by Qin et al. [9,10]. Then, Xu et al. [11] studied R-B-M convection in a cylinder heated laterally and cooled at top by using higher order finite difference scheme. They found that the critical Grashof number increases with the increase of the Marangoni number. Nezar and Rahal [12] numerically investigated the effect of gravity and surface tension gradient on the flow patterns. It was concluded that with the increase of the thickness of liquid layer, the flow pattern would bifurcate from hexagonal cells to stationary longitudinal rolls. Rahal et al. [13] conducted a series of experiments to study the effect of the Marangoni number, Biot number and Prandtl number on the free surface deformation, and found that the flow will bifurcate to a time-dependent flow when the Biot number is large enough. Sakhy et al. [14] carried out a series of three-dimensional numerical simulations on R-B-M convection in a cylindrical container heated from below by a non-uniform heat flux, the results showed that

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Nomenclature

Bi	Biot number
d	depth of cylindrical pool, m
$\mathbf{e}_z$	z-directional unit vector
g	gravitational acceleration, m/s^2
h	heat exchange coefficient on the free surface, W/(m^2·K)
Ma	Marangoni number
Nu	Nusselt number
P	dimensionless pressure
Pr	Prandtl number
q	exponent in Eq. (1)
r	radial coordinate or radius, m
R	dimensionless radius
Ra	Rayleigh number
T	temperature, °C
$\mathbf{V}$	dimensionless velocity vector
z	axial coordinate
Z	dimensionless axial coordinate

Greek symbols

α	thermal diffusivity, m^2/s
γ	thermal expansion coefficient, (°C)$^{-q}$
γ_T	surface tension coefficient, N/(m·K)
λ	thermal conductivity, W/(m·K)
Γ	aspect ratio
μ	dynamic viscosity, kg/(m·s)
ν	kinematic viscosity, m^2/s
θ	azimuthal coordinate, rad
Θ	dimensionless temperature
ρ	density, kg/m^3
σ	surface tension, N/m
τ	dimensionless time

Subscripts

0	initial
ave	average
cri	critical
e	environment
h	hot wall
m	density inversion point
t	top free surface

the flow patterns depend on the Rayleigh number, Marangoni number, Biot number and the ratio of thermal conductivities. Boeck [15] investigated the effect of homogeneous magnetic field on Bénard convection in a rectangular domain, and the transition from stationary hexagonal pattern to time-dependent convection was explored for the fluid with zero Prandtl number. Guo and Narayanan [16] performed a linear stability analysis of R-B-M convection of a silicone oil in the annular cavity. It was found that the depth of the cavity rather than the width of the gap has an important effect on the Marangoni convection. Furthermore, the critical wavelength generally decreases with the decrease of the scaled gap.

For all reports mentioned above, the density of working fluid was supposed to be a linear function of temperature. However, cold water is a typical fluid which has the maximum density at the temperature around 4 °C, this special property makes the flow become more complicated [17]. Sasaguchi et al. [18] carried out numerical analyses on the influence of eccentricity on natural convection of cold water in a rectangular cavity and found that when the initial water temperature is 4 °C, the relative positon of the cylinder and rectangular cavity has a significant effect on the average Nusselt number. When the initial water temperature exceeds 4 °C,a downward flow pattern can be observed at first, and then changes to upward flow pattern gradually. Osorio et al. [19] numerically simulated natural convection of cold water in a square cavity and discussed the effect of the density inversion parameter on the flow pattern. Furthermore, Nishimura et al. [20] investigated R—B convection of cold water in a rectangular enclosure whose aspect ratio was 1.25. Results showed that the flow pattern and the temperature field are symmetric; however, a sinking cell is formed at the center of the enclosure because of the influence of the density inversion. Lin and Nansteel [21] simulated natural convection of cold water in a square enclosure heated and cooled on opposite vertical walls, and found that there is a multicellular flow pattern. Furthermore, the flow pattern is independent on the Rayleigh number at $10^3 \le Ra \le 10^6$. Yuan and Li et al. [22,23] performed a series of numerical simulations on natural convection of cold water in the horizontal annulus and the horizontal eccentric annulus, and discussed the effect of Rayleigh number and density inversion parameter on the flow patterns. Li et al. [24] also found some new flow patterns in R—B convection of cold water at a fixed aspect ratio. Hu et al. [25] performed numerical simulations of cold water in complex configurations and obtained the heat transfer correlations in different cavities.

However, when both the buoyancy and the surface tension gradient are taken into account, the formation of the flow pattern is very complicated and different. Therefore, the aim of present work is to obtain various flow patterns of R-B-M convection of cold water in a cylindrical container. Furthermore, we also focus on the effects of Rayleigh number, Biot number and density inversion parameter on the heat transfer and evolution of flow patterns.

2. Model formulation

2.1. Basic assumption and governing equations

The physical model is schematically shown in Fig. 1. We consider a cylindrical pool with the aspect ratio $\Gamma = r_0/d = 1.5$, which is filled with cold water near its maximum density. Where, r_0 is the radius and d is the depth of the cylindrical pool. The sidewall is regarded as perfectly adiabatic. The bottom of the pool is kept at constant temperature T_h, while the top is a free surface with a variation temperature. The existence of free surface means that there is the heat exchange between cold water and the environment. The heat transfer coefficient and the

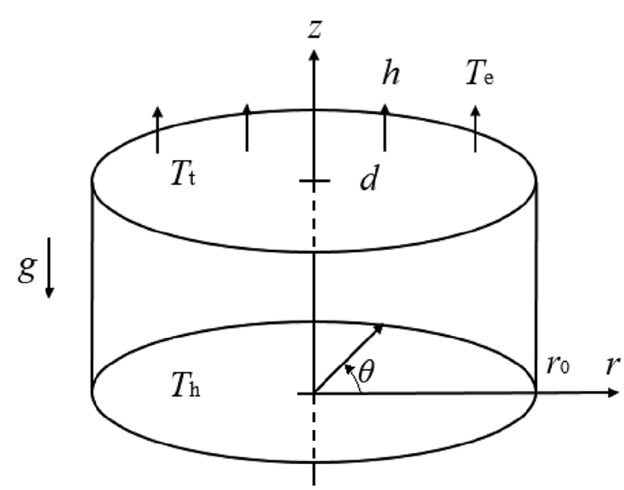

Fig. 1. Physical model and the coordinate system.