International Journal of Heat and Mass Transfer 72 (2014) 572–584

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Comparison investigation on natural convection of cold water near its density maximum in annular enclosures with complex configurations

Yu-Peng Hu, You-Rong Li *, Chun-Mei Wu

Key Laboratory of Low-grade Energy Utilization Technologies and Systems of Ministry of Education, College of Power Engineering, Chongqing University, Chongqing 400044, China

ARTICLE INFO

Article history:
Received 4 November 2013
Received in revised form 13 January 2014
Accepted 15 January 2014
Available online 13 February 2014

Keywords:
Natural convection
Heat transfer
Density maximum
Numerical simulation
Complex configuration

ABSTRACT

In order to compare the characteristics of natural convection of cold water near its density maximum in annular enclosures with various complex configurations, a series of numerical simulations were carried out using the finite volume method. The effects of the Rayleigh number, the density inversion parameter and the aspect ratio on natural convective flow and heat transfer were analyzed, and the variations of local and average Nusselt numbers were discussed in these enclosures. The results show that the flow pattern depends mainly on geometrical configurations of the enclosures, the Rayleigh number and the density inversion parameter. The Rayleigh–Bénard convection cells appear in the top or bottom region for the R-C, T-C, E-S and E-T configurations at a large Rayleigh number. With the increase of the aspect ratio, the number of the vortex in the flow cell increases and the cell splitting phenomenon happens at a large aspect ratio in the R-C, D-C, T-C, E-S and E-T configurations. The heat transfer correlations for various configurations have been proposed, and the enclosure with the best heat transfer performance among various configurations is assured based on the simulation results.

1. Introduction

Natural convection in annular enclosures has become a very important and interesting topic because it is frequently encountered in many industrial applications, including thermal storage systems, cooling of electronic equipments, and drying etc. As one of the most representative cases, natural convection in horizontal annular enclosures between horizontal cylinders has received increasing attention. Kuehn and Goldstein [1] carried out the first experimental and theoretical work on natural convection of water and air in an annular enclosure between horizontal concentric cylinders in 1976. From then on, many investigations on the flow evolution and heat transfer in the concentric and eccentric annulus were performed [2–6].

Recently, due to the increasing application demand of the annular enclosures with various complex configurations of non-circular cross-sections in engineering, many efforts have been made to study natural convection in these complicated enclosures. The flow pattern and heat transfer characteristics of natural convection of different fluids were exhibited by numerical simulations and experiments in various enclosures, including the annulus between an outer square wall and an inner cylinder [7–12], the triangular enclosure containing a circular cylinder [13–15], the circular enclosure with the elliptical inner wall [16–17] and a sinusoidal cylinder [18,19], the elliptic annuli [20,21] and the rhombic annuli [22,23] etc. The effects of the Rayleigh (*Ra*) number, Prandtl (*Pr*) number, aspect ratio, eccentricity and enclosure gap on the flow pattern and heat transfer were discussed.

In all these investigations mentioned above, a linear relation between the density and temperature of the fluid was assumed. However, cold water is a special fluid which is often used as the working fluid in the thermal energy storage system. Its density increases with the increase of temperature up to about 4 °C, then decreases with further increase of temperature. This characteristic is called as the density inversion phenomenon. Therefore, understanding the effect of this feature of cold water on natural convection is very necessary. There are a few studies on natural convection of water near its density maximum in an annulus. Vasseur et al. [24] simulated natural convection with density inversion in an annulus and found that the flow pattern behaves two counter rotating cells. Raghavarao and Sanyasiraju [25] performed the same work with the annulus radius ratio of 1.5 and 2.0 and concluded that the density inversion parameter influences the flow patterns and heat transfer rates greatly. Recently, Li et al. [26–28] performed a series of investigations on natural convection of water near its density maximum in horizontal concentric and eccentric annuli and revealed that the density inversion phenomenon has

* Corresponding author. Tel.: +86 23 6511 2284; fax: +86 23 6510 2473.
E-mail address: liyourong@cqu.edu.cn (Y.-R. Li).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.01.047
0017-9310/

Nomenclature

a	length of semi-major axis of ellipse, m
A	aspect ratio, $A = r_i/b$
b	length of semi-minor axis of ellipse, m
$\mathbf{e}$	the unit vector
g	gravitational acceleration, m/s^2
L	perimeter, m
n	normal direction to the inner wall
Nu	Nusselt number, $Nu = \frac{\partial\Theta}{\partial n}\|_{wall}$
P	dimensionless pressure
Pr	Prandtl number, $Pr = \nu/\alpha$
q	exponent in density–temperature relation
r	radius, m
Ra	Rayleigh number, $Ra = g\gamma(T_iT_o)^q(br_i)^3/(\nu\alpha)$
s	local coordinate, m
S	dimensionless local coordinate
T	temperature, °C
$\mathbf{V}$	dimensionless velocity vector

Greek symbols

α	thermal diffusivity, m^2/s
ε	deviation
γ	thermal expansion coefficient, (°C)$^{-q}$
Θ	dimensionless temperature, $\Theta = (T - T_o)/(T_i - T_o)$
ν	kinematic viscosity, m^2/s
ξ	elliptical ratio, $\xi = (1 - b^2/a^2)^{1/2}$
ψ	dimensionless stream function

Subscripts

ave	average
i	inner wall
o	outer wall
m	density inversion point
max	maximum

an important effect on both the flow pattern and the heat transfer. With the development of engineering technology, the demand of the annular enclosures with various complex configurations increases in energy storage systems. However, the understanding on natural convection of water with the density maximum in the annular enclosures with various complex configurations is much lacked. Only Sasaguchi et al. [29,30] studied natural convection in a rectangular enclosure containing a circular cylinder by adjusting the temperature of water at 4, 6, 8 and 12 °C. The various complicated flow patterns and the variation of the average Nusselt number on the inner cylinder with temperature were obtained.

This work was contributed to natural convection of water with density maximum in annular enclosures with various complex configurations of both inner wall and outer wall. Comparisons on the flow pattern and heat transfer in different annular enclosures with various configurations were performed. The effects of the Rayleigh number, density inversion parameter and aspect ratio were discussed.

2. Problem statement

2.1. Physical description

The physical model and reference frame for the present work are sketched in Fig. 1. Consider an annular enclosure with a circular inner wall and an elliptical outer wall which is filled with cold water near its density maximum. The inner and outer walls keep at constant temperatures T_i and T_o ($T_i > T_o$), respectively. The radius of the inner wall is r_i, and the lengths of the semi-major and semi-minor axis of the elliptical outer wall are a and b respectively. The aspect ratio A is defined as the ratio of the radius of the inner wall to the semi-minor axis of the outer wall, $A = r_i/b$. The elliptical ratio is expressed as $\xi = (1 - b^2/a^2)^{1/2}$ and it is fixed at $\xi = 0.50$ in this work. The local coordinate along the inner wall is normalized by dividing its own perimeter as $S = s/L$.

In order to study the effect of the configuration of the enclosure on natural convection of water near the density maximum, change the cross-section geometry of the outer wall and the inner wall by fixing their perimeters. The obtained enclosures with different configurations are elliptical outer wall with circular inner wall (denoted as E-C), rectangular outer wall with circular inner wall (R-C), diamond outer wall with circular inner wall (D-C), equilateral triangular outer wall with circular inner wall (T-C), elliptical outer wall with square inner wall (E-S), elliptical outer wall with

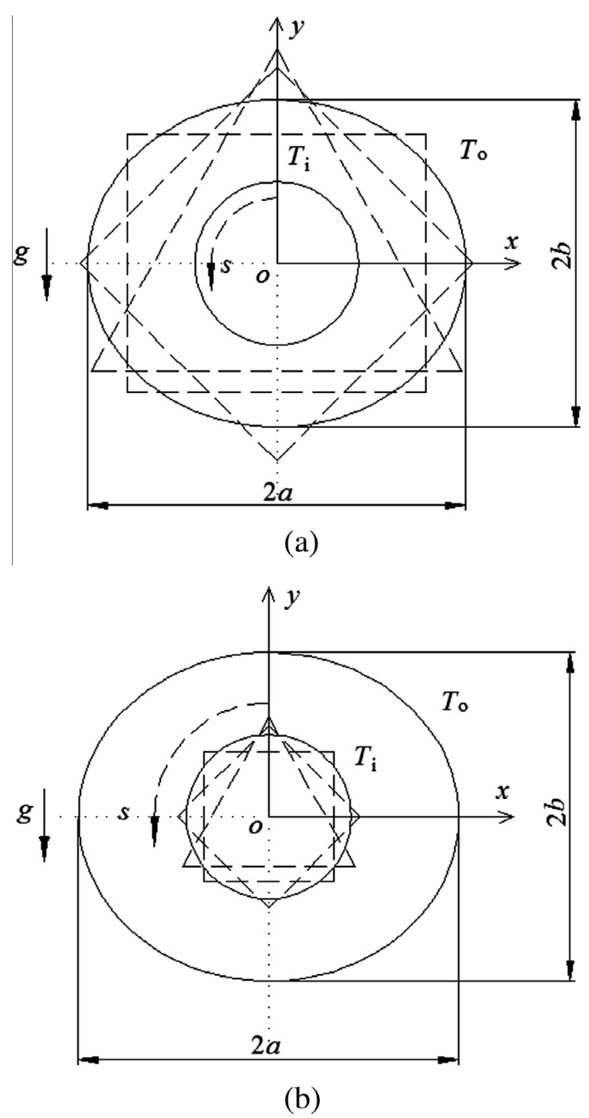

Fig. 1. Physical model. (a) Different outer wall configuration; (b) Different inner wall configuration.