International Journal of Thermal Sciences 76 (2014) 190–199

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Experimental study on natural convection in a cylindrical envelope with an internal concentric cylinder with slots

Kun Zhang [a,b], Mo Yang [b,*], Jin Wang [b], Yuwen Zhang [c]

[a] College of Mechanical Engineering, University of Lanzhou Jiaotong, Lanzhou 730010, China
[b] College of Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China
[c] Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO 65211, USA

ARTICLE INFO

Article history:
Received 4 April 2013
Received in revised form
7 September 2013
Accepted 14 September 2013
Available online 22 October 2013

Keywords:
Natural convection
Rayleigh number
Static bifurcation
Self-sustained

ABSTRACT

Detailed experimental analysis is presented for natural convection in a cylindrical envelope with an internal concentric cylinder with slots. For the case of $\varphi = 90^\circ$, where φ is the angle of slot opening from the vertical axis, and two types of temperature fields were obtained at the same Rayleigh number of 5.49×10^4. It is demonstrated that the steady state solution was not unique and was dependent on the initial conditions, which is related to static bifurcation. For the two cases of $\varphi = 0^\circ$ and $\varphi = 45^\circ$, the natural convection turned to unsteady, although the boundary conditions were not time-dependent. The most obvious oscillation regions were above the inner cylinder, and the amplitude increased with increasing Rayleigh numbers. The nonlinear characteristic of these problems led to the multiplicity of convections and self-sustained oscillation.

1. Introduction

Natural convection is a recurrent phenomenon in the world and most of these flows are unsteady. Studies of unsteady-state natural convections have attracted increasing interest over the last decades due to the desire to improve the phenomenological understanding of natural convection, especially those studies of unsteady flow patterns and temperature fields related to nonlinear characteristics. Natural convection in a cavity is one of the classical models to study nonlinear characteristics. Many helpful results from the researches of natural convection in a cavity indicated that laminar steady flow and heat transfer are observed for lower Rayleigh number, while unsteady convection is obtained at high Rayleigh numbers [1–3]. Debasish and Muralidhar [4] experimentally investigated Rayleigh–Benard convection in a cavity using interferometric tomography. The results showed a sequence of transitions from stable laminar flow to unsteady flow and ultimately to turbulent flow. Mukutmoni and Yang [5,6] simulated Rayleigh–Benard convection in a small cavity with aspect ratio and confirmed that the oscillation and chaos existed. Zhang et al. [7] numerically investigated three different types of static bifurcation at Ra = 5000 with different initial conditions. Tae et al. [8] studied mixed convection in the cavity with simulation and experiment. The temperature field fluctuated when buoyancy force was higher. Zhan et al. [9] numerically studied the nonlinear phenomenon of natural convection in a 3-D rectangular cavity. The results showed that the static and dynamic bifurcation appeared with different initial conditions. Experimental studies of this problem were also performed by them [10], and their results verified the conclusions in the numerical studies that the self-sustained phenomenon of flow fields occurred in the steady conditions. Deshpande and Srinidhi [11] numerically studied the mixed convection in a cavity and observed the certain features of dynamic systems like bifurcation, period doubling and chaos. Benouaguef [12] numerically studied the unsteady natural convection in an air-filled square enclosure. They plotted the temporal evolutions of the hot global Nusselt number and the attractors in a space trajectory, and discussed the effect of the Rayleigh number on the route to the chaos.

Many experimental investigations and numerical simulations have been conducted to study unsteady natural convection in horizontal cylindrical annuli in steady conditions. Powe et al. [13,14] visualized the flow patterns with smoke as a tracer and obtained the Rayleigh number at which the flow will change from a steady flow to an unsteady flow. Rao et al. [15] investigated the transient oscillatory phenomena and numerically determined the critical Rayleigh number at which unsteady flow occurs. Cheddadi et al. [16] numerically and experimentally studied the bifurcation

---

* Corresponding author.
E-mail address: yangm66@gmail.com (M. Yang).

1290-0729/$ – see front matter © 2013 Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.ijthermalsci.2013.09.005

Nomenclature

a	thermal diffusivity, m^2/s
D	gap width, m
K	Gladstone–Dale constant, m^3/g
m	ordinal of stripes
M	molecular mass of air, g/mol
g	gravitational acceleration, m/s^2
L	longitudinal length of outer cylinder, m
P_o	atmospheric pressure, Pa
Pr	Prandtl number
r_i	inner radius of slotted inner cylinder, m
r_j	outer radius of slotted inner cylinder, m
r_o	inner radius of envelope cylinder, m
R	universal gas constant, J/mol K
Ra	Rayleigh number
t	time, s
T	temperature, K
T_e	environmental temperature, K
T_i	temperature of slotted inner circle, K
T_o	temperature of envelope circle, K

Greek symbols

α	slotted angle, degree
β	coefficient of thermal expansion, 1/K
λ	wavelength of the light, m
Θ	dimensionless temperature
ν	kinematic viscosity, m^2/s
φ	inclined angle between central line of internal slotted cylinder and vertical axis, degree

phenomenon of natural convection at different initial conditions, and showed that the flow pattern was not unique and depended on the initial conditions at high Rayleigh number. However, the static bifurcation phenomenon was not observed in their experiments. Liu et al. [17] investigated the stability of natural convection by measuring the total heat transfer coefficient and the distribution of radiation temperature of water, air and silicone. The results indicated that the critical Rayleigh number dictated the transition from steady to unsteady. Mizushima et al. [18] numerically investigated the bifurcation phenomenon and obtained the critical Rayleigh number when the flow changes into multi-vortex. Yoo [19] investigated numerically the bifurcation sequences to the chaos for the natural convection in horizontal concentric annuli in detail.

Comparatively, little works have been reported on unsteady natural convection heat transfer in more complex domain, such as in a cylindrical envelope with an internal concentric cylinder with slots. Some early studies for those complex models have been focused on the convective heat transfer enhancement. Kuleek assumed that the heat transfer enhancement of a cylindrical envelope with an internal slotted cylinder was expected to be about 30–40% higher than that of the concentric cylindrical annuli [20]. Wang et al. [21] experimentally investigated natural convection in a cylindrical envelope with an internal slotted cylinder and found that the convective heat transfer coefficient with slots could be enhanced by as much as 50%. They indicated that the unsteady phenomenon occurs because of the experimental conditions and the value of heat transfer coefficient is a time average value. The oscillated phenomenon at $Ra = 10^6$ was not investigated in their experiments. Yang et al. [22] numerically investigated natural convection heat transfer using a two-dimensional steady model and obtained the convective heat transfer coefficient. Recently, Huang et al. [23] studied the unsteady flow and heat transfer on steady conditions by two-dimensional unsteady model. Zhang et al. [24] numerically investigated nonlinear characteristics of natural convection heat transfer. An asymmetric solution was obtained although the boundary conditions are symmetric, and the oscillatory flow undergoes several bifurcations and ultimately evolves to a chaotic flow.

The objective of this paper is to experimentally study natural convection heat transfer in a cylindrical envelope with an internal concentric cylinder with slots. The temperature fields for different Rayleigh numbers will be obtained by using laser holographic interferometry technique [25,26]. The effect of initial conditions on the final temperature fields and the multiplicity of solutions related to static bifurcation will be investigated. Numerical simulation of the natural convection at the same parameters will also be performed to compare with the experimental results. The self-sustained oscillated phenomenon on steady conditions will be investigated in detail.

2. Experimental systems

2.1. Experimental model

The problem under consideration, as shown in Fig. 1, is the natural convection heat transfer in a horizontal cylindrical envelope with an internal concentric cylinder with slots. The inner and outer cylinders are kept at uniform but different temperatures T_i and T_o, respectively, with $T_i > T_o$. As a result of the temperature difference between the two circles, density gradient occurs and leads to natural convection. It is assumed that the air in the enclosure is of Boussinesq type. The included angle φ is defined for the angle between central line of internal slotted cylinder and vertical axis. Three different inclined angles ($\varphi = 0°$ $\varphi = 45°$ and $\varphi = 90°$) are selected for those models in our experiments.

2.2. Experimental setup

The experimental setup consists of anti-seismic table, experimental section and optical system. A schematic diagram of the total experimental setup is presented in Fig. 2. The anti-seismic table was manufactured by University of Shanghai for Science and Technology (see Fig. 3) and the flatness is less than 0.10 mm/m^2. The experimental study was carried out using laser holographic

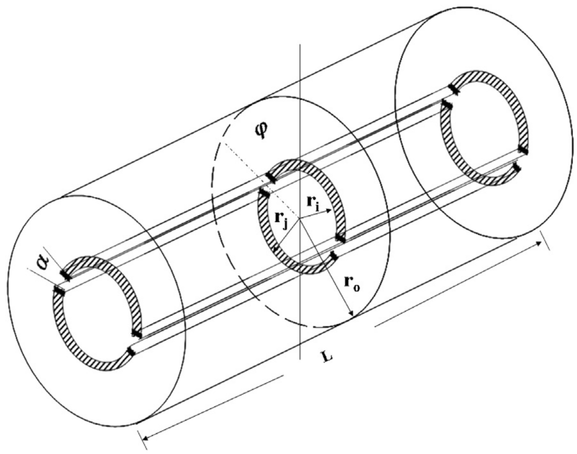

Fig. 1. Cylindrical envelope with an internal concentric cylinder with slots.