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Evolution to chaotic natural convection in a horizontal annulus with an internally slotted circle

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ABSTRACT

The characteristics of transition from laminar to chaotic natural convection in a two-dimensional horizontal annulus with an internally slotted circle is analyzed using Lattice Boltzmann method (LBM). The aim of this paper is to identify the route(s) to chaos, and to illustrate the dynamical response of the flow with the change of the control parameter (*Ra*). The results obtained for a range of the Rayleigh number, *Ra*, from 5×10^3 to 2×10^6 at $Pr = 0.71$, and the slot degree, S_f, from 0.1 to 0.4. The numerical results show that slot ratio, slot configuration, and Rayleigh number are influential to oscillation phenomenon in this model; the flow inside the annulus may be: (1) a stable base-two-cells regime, (2) a multi-cellular flow with four-stable-symmetrical-secondary cells regime, (3) a multi-cellular flow with four-oscillatory-secondary cells regime, and (4) an asymmetrical oscillation regime. The results also show that the oscillatory flow undergoes several bifurcations and ultimately evolves to a chaotic flow after the first bifurcation. In addition, certain features of nonlinear dynamical systems like bifurcation, self-sustained oscillations are also observed. The simulation results also show that slot degree S_f is relevant to oscillations. Furthermore, with the larger slotted ratio, the flow is more unstable, and the configuration with top and bottom slot seems to be the most unstable among the given four models.

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1. Introduction

In the recent years, there has been a growth of interest in the behavior of chaos dynamic systems. Chaos theory is defined as the qualitative study of unstable aperiodic behavior in deterministic nonlinear systems. The particular interest is in how a deterministic system behaves in a complicated way (what we could conventionally call "random" or "stochastic" behavior, now we could call "chaotic" behavior) owing to some element of nonlinearity [1]. In addition, an important route to chaos is by means of a cascade of period-doubling bifurcations. This route has universal properties, and is observed in real dynamic systems, most importantly (from our point of view) in certain types of thermally generated turbulence (i. e. natural convection instability). Now the idea that the "soft" or "weak" turbulence can be connected to chaos theories based on a small number of degrees of freedom is being accepted by the researchers.

Transitions to oscillatory or chaotic convections are very interesting phenomena, and researches to clarify the route(s) to turbulent convections are in progress. The instability of natural convections has attracted wide attentions in the past decades, due to a desire to improve the phenomenological understanding of natural convection, and the pressing need for numerical models capable of predicting the corresponding flow structures and related heat transfer processes. A great deal of literature relevant to natural convection has concentrated on the transition process to unstable periodic flow and route to chaos. Benouaguef et al. [2] studied the unstable natural convection in an air-filled square enclosure. The temporal evolution of the hot global Nusselt number and the attractors in a space trajectory were plotted, and the effects of the Rayleigh number on the route to chaos were discussed. Paolucci and Chenoweth [3] numerically studied the transition from laminar to chaotic flow in a differentially heated vertical cavity. They obtained the critical Rayleigh number as a function of aspect ratio and developed expressions relating the fundamental frequencies of the oscillatory flow to the Rayleigh number and aspect ratio. Erenburg et al. [4] numerically studied the multiplicity, stability, and bifurcations stable natural convection in a two-dimensional rectangular cavity with partially and symmetrically heated vertical walls; the observed phenomena also occurred at larger Prandtl numbers, which was illustrated for $Pr = 10$. Gelfgat [5] studied the oscillatory regime of natural convection of air in an 8:1 two-dimensional rectangular cavity with a global Galerkin method.

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Nomenclature

c	particle speed
c_s	speed of sound in lattice scale
e_a	discrete lattice velocity
f_a	velocity distribution function
F_y	force term of vertical direction (N/kg)
g	gravitational acceleration (m/s^2)
g_a	temperature distribution function
keq	equivalent thermal conductivity
r_i	inner radius
r_o	outer radius
S_f	slotted ratio
T_i, T_o	dimensionless temperature at inner and outer cylinder
u, v	velocity components at horizontal and vertical direction (m/s)
$\mathbf{u}$	velocity vector

Greek Symbols

Θ	dimensionless temperature
δ	thickness of slotted annulus
δ_{a2}, δ_{a4}	Kronecker function
γ	slotted angle
ρ	density (kg/m^3)
τ	dimensionless time
τ_f, τ_T	lattice relaxation time
Δt	lattice time step

Subscript

i	inner cylinder
α	discretization direction
o	outer cylinder

Superscript

eq	equilibrium distribution function

Chen [6] performed a numerical study of external electrical and magnetic effects on the thermal instability in natural convection flow over a heated horizontal plate. Cheng [7] systematically investigated the flow and heat transfer from laminar to chaos in a 2-D square cavity where the flow is induced by a shear force resulting from the motion of the upper lid combined with buoyancy force due to bottom heating. Sheu and Lin [8] numerically studied the rich and complex buoyancy-driven flow field due to natural convection over a wide range of Rayleigh numbers in a cubic cavity by virtue of the simulated bifurcation diagram, limit cycle, power spectrum, and phase portrait. Saury et al. [9] carried out an experimental study on the natural convection unsteadiness occurring in an air-filled cavity having two opposite walls respectively heated and cooled at constant and uniform temperature. Oscillation and chaos in combined heat transfer by natural convection, conduction, and surface radiation in an open cavity was solved numerically by Wang et al. [10]. Louisos et al. [11] computationally investigated the nonlinear dynamics of unstable natural convection in a 2D thermal convection loop with heat flux boundary conditions.

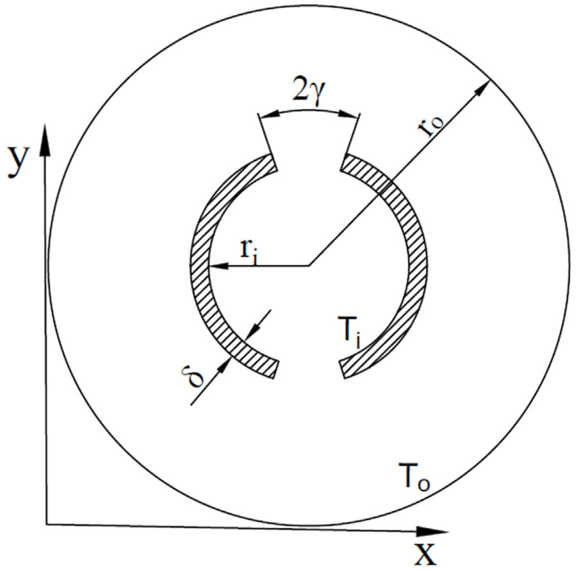

Fig. 1. Physical domain.

Most recently, Mercader et al. [12] and Sánchez et al. [13] studied the thermal convection in a laterally heated horizontal cylinder rotating about its axis, and analyzed the linear stability; several secondary flows originated from the instabilities were computed. Dou and Jiang [14] numerically investigated the physical mechanism of flow instability and heat transfer of natural convection in a cavity with thin fin(s). Cimarelli and Angeli [15] analyzed the transition to turbulence of natural convection flows between two infinite vertical plates by Direct Numerical Simulations (DNS). The first bifurcation from the laminar conduction regime to stable convection and then chaotic flow regime were captured. Naghib et al. [16] investigated the unstable natural convection in a water-filled, open top tank with a black bottom subjected to radiative heating from a halogen theatre spotlight by laboratory-scale experimental study. Cho et al. [17] numerically investigated the two-dimensional natural convection in a square enclosure with different arrays of two inner cylinders. They found that the flow and temperature fields eventually reached stable or unstable states, depending on the distance between the cylinders.

Because of its wide engineering applications, such as solar collectors, thermal energy storage systems and large-current busbar. The busbar consists of two metal cylinders: an inner hollow cylinder (current busbar: the cross-section can be circular, hexagon, or octagon) and an outer metal cylinder. The heat generated in the

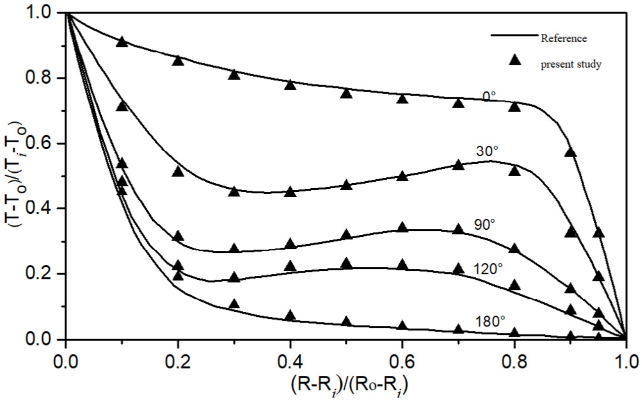

Fig. 2. Comparison of radial dimensionless temperature profiles at $Ra = 5 \times 10^4$, $Pr = 0.7$.

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