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Resonant response of fluid flow subjected to discrete heating elements

Fu-Yun Zhao, Di Liu, Guang-Fa Tang *

College of Civil Engineering, Hunan University, Changsha, Hunan 410082, PR China

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Abstract

Two-dimensional calculation and theoretical analysis have been performed for laminar natural convection induced by two discrete heating elements flush mounted to one vertical wall of a square enclosure. Two cases are presented in this work. One is the upper elevation Heater-1 fluctuates its temperature as a sinusoidal function while the lower elevation Heater-2 maintains its temperature constant. The other case depicts the opposite situation of interchanging the boundary conditions of Heater-1 and Heater-2 in Case 1. A large range (0.01–10.0) of non-dimensional frequency is conducted numerically, and the results show the existence of resonance frequencies in both cases. Scale analysis over predicts the resonance frequency due to ignoring heat dissipation between the heaters. Mechanical details of the fluid flow and average heat transfer characteristics across Heater-1, Heater-2 and the centerline of the enclosure are scrutinized. The results indicate that in Case 1, the heat transfer of Heater-2 is little affected by the periodic change of temperature of Heater-1. However, the oscillatory behavior is largely intensified in Case 2 owing to the thermal wake generated on Heater-2 invigorating the global flow throughout the enclosure. The heatline concept, flow and temperature fields of the oscillating components are adopted to visualize the heat transport and fluid circulation.

Keywords: Thermal oscillation; Discrete heating elements; Resonance frequency; Scale analysis

1. Introduction

The study was inspired by an interesting design feature of effective cooling of electric devices. The electronic components are generally modeled as localized heating elements. The steady state performance of packages with discrete heat sources has been extensively studied [1–6]. The increasing interest of natural convection in an enclosure with time periodic boundary conditions is attributable to the relevance of such transient processes in many technological applications [7]. In addition to the apparatus design problem mentioned above, there is the behavior of air spaces (e.g. rooms) and bodies of water (reservoirs, lakes) in which the recirculation is driven periodically by the daily solar heating.

Natural convection affords a means of thermal control, which eliminates the fan or pump for forced convection and provides a noise free and vibration free environment. However, natural convection is not an effective mode of heat transfer, and compared to forced convection or boiling, the associated thermal resistances are large [2]. Resonance is the best way to improve the heat transfer performance of natural convection [8].

Just as stated by Kwak and Hyun [9], resonance is a phenomenon associated with the eigenmodes of a system, which are essentially independent of the kind of external forcing imposed. If the system is exposed to an external forcing with the correct natural frequency, resonance takes place in which the eigenmodes are excited and amplified.

The numerical studies of Kwak et al. [10] and Antohe and Lage [11] at high Rayleigh number clearly established the existence of resonance for periodic heating at the side wall. Semma et al. [12] studied a liquid enclosure analogous to the fluid phase of a vertical Bridgman configuration heated from the top temperature fluctuation. Oscillatory convection is studied numerically for different aspect ratios of the cavity, sizes of adiabatic zone and *Ra* numbers.

* Corresponding author. Tel.: +86 731 882 2760; fax: +86 731 882 2667.
E-mail address: zfycfdnet@163.com (G.-F. Tang).

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Nomenclature

A	amplitude of oscillating property
D	heat source length (m)
f	frequency (1/s)
g	gravitational acceleration (m/s^2)
H	height of enclosure (m)
N	Brunt–Vaisala frequency
Nu	total Nusselt number
Nu_{Local}	local Nusselt number
p	pressure (N/m^2)
P	dimensionless pressure
Pr	Prandtl number, Eq. (5d)
Ra	Rayleigh number, Eq. (5e)
S	heater pitch
t	temperature (K)
T	dimensionless temperature
u	velocity component in x-direction (m/s)
v	velocity component in y-direction (m/s)
U	dimensionless velocity component in X
V	dimensionless velocity components in Y
v_0	velocity scale in boundary layer
V_0	peripheral velocity of fluid wheel
W	width of enclosure (m)
x, y	Cartesian coordinates (m)
X, Y	dimensionless Cartesian coordinates

Greeks

α	thermal diffusivity (m^2/s)
β	volume expansion coefficient (1/K)
ε	dimensionless oscillation amplitude
ν	kinematic viscosity (m^2/s)
ω	dimensionless oscillation frequency
Ψ	stream function
ξ	heat function
ϕ	time-dependent property
Δ	amplitude
δ_T	thermal boundary thickness
ρ	density (kg/m^3)
τ	dimensionless time
τ_0	time (s)
τ_{0P}	period (s)
c	cold wall
C	center line
h	hot wall
L	left (cold) wall
r	resonance
R	right (hot) wall
R1	Heater-1
R2	Heater-2
max	maximum
ss	non-oscillating

Superscripts

*	relative oscillation
′	residual

However, studies on the resonance characteristics in an enclosure with multiple heating elements are scarce. Accounts of unsteady natural convection in discretely heated enclosures in which boundary conditions undergo continuous temporal variations are observed by a few researchers [13,14].

The present study aims to analyze, theoretically and numerically, the transient flow characteristics of two heating elements with time dependent temperature conditions. The details of fluctuating flow and temperature fields over a cycle will be thoroughly observed. Emphasis will be placed on obtaining a physical interpretation of the nature of the convective resonance phenomenon with discrete heating elements. Transient interactions of the two heat sources are investigated to maximize the overall heat transfer rate.

2. Mathematical formulation

2.1. Physical modeling

The flow configuration and coordinate system under consideration, as shown schematically in Fig. 1, is a rectangular cavity (width W, height H) filled with incompressible Boussinesq liquid, which satisfies $\rho = \rho_0[1 - \beta(t - t_c)]$, β being the thermal expansion coefficient and subscript 0 denoting the reference state. All the physical properties are taken to be constant. We set $W/H = 1$ in order to be

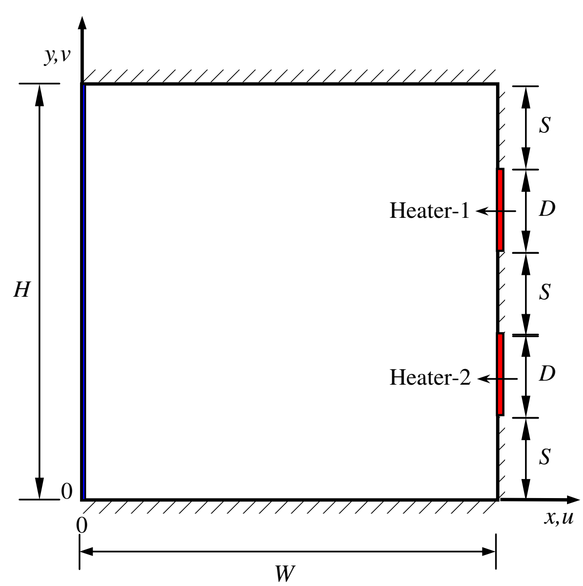

Fig. 1. Sketch of the flow configuration.