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Characteristics of temperature field in a closed cavity with centrifugal acceleration

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ABSTRACT

A closed temperature chamber with multiple distributed heat sources, used in a multi-parameter combined environmental test, was presented. Coupling effects in it between centrifugal acceleration and temperature fields were studied. Fluid governing equations in non-inertial coordinate system were given. Flow and temperature fields of the air in the closed centrifugal cavity was analyzed. Numerical simulation was done by the FLUENT software and corresponding experiments were carried out. The results show that thermal buoyancy, centrifugal buoyancy and Coriolis force affect the temperature distribution obviously, and the temperature distributions differ as the magnitude of centrifugal acceleration changes. Non-uniformity of the air temperature increases with the magnitude of centrifugal acceleration. Moreover, the convective heat transfer is enhanced by the centrifugal acceleration. This study will provide theoretical basis for the multi-parameter combined environmental test concerned with centrifugal acceleration and temperature.

1. Introduction

Sensors and electronic devices on spacecraft suffer from complex combined environmental factors, including linear acceleration, vibration, temperature, pressure and noise, etc. In order to test the reliability of these devices, it is essential to setup multi-parameter combined environmental test devices on the earth. However, different environmental factors may affect each other seriously. Generally, linear acceleration is simulated by centrifugal acceleration, which is generated by centrifuges in the laboratory. In a multi-parameter combined environmental test device that includes a centrifuge with a temperature chamber on the end of it [1], temperature field will be affected by centrifugal acceleration. In detail, fluid in the cavity is affected by the thermal buoyancy, centrifugal bouyancy as well as the Coriolis force, which makes the flow and temperature fields very complicated.

Convection in a rotating cavity concerned with different thermal boundaries has been studied widely in the past. A typical problem is the rotating Rayleigh–Bénard convection [2,3], which focuses on the flow and temperature fields in a rotating cavity with vertical temperature difference. Much attention has been paid to the onset of convection caused by temperature gradient and the stability of the flow as well as the flow pattern [4]. A similar problem to the rotating Rayleigh–Bénard convection is the convection in the rotating cubic cavity heated differentially on its vertical walls. In other words, the temperature gradient exists in the horizontal direction. Lin et al. studied this problem and found that when the Coriolis and centrifugal forces are high enough, significant effects on the flow and heat transfer appears [5]. The experimental data suggested that the rotation of the cavity results in flow stabilization at low rotation speed and the flow can be destabilized when the cavity is in fast rotation [6]. The oscillation of temperature field was discussed as well [7]. Jin et al. [8] found that rotation reduces heat transfer performance in the low rotation speed range and increases it in the relatively high speed range. Ji [9] studied the characteristic of fluid flow and heat transfer with centrifugal effect by the field synergy principle [10]. Also the synergic relation among velocity field, pressure field and temperature field of the fluid was discussed.

These studies mainly focused on the effects of rotation on the onset of convection and the overall heat transfer at different Rayleigh numbers. Most of the concerned cavities rotate about their symmetric axes and fixed temperature difference of different walls is always assumed. We have ever set up a combined environmental test device, in which the coupling effects between heat transfer and centrifugal acceleration has been studied [11]. However, only one inner heat radiator was placed in an unclosed cavity and the

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Nomenclature

a_{cen}	centrifugal acceleration, $R\Omega^2$
c_p	specific heat at constant pressure
c_s	specific heat of the solid
$\boldsymbol{f}$	shear stress
g	magnitude of gravity acceleration
$\mathbf{g}$	gravitational acceleration vector
k	thermal conductivity of air
k_s	thermal conductivity of the solid
L	reference length
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
P	thermodynamic pressure
P_m	motion pressure
q	local heat flux
Q_V	heat flux of heat source in the air
Q_V^s	heat flux of heat source in the solid
$\mathbf{r}$	position vector defined in the rotating reference frame
R	distance between origins of the static and moving reference frame
Ra	Rayleigh number, $g\beta\Delta TL^3\rho c_p/\nu k$
Ra_ω	rotational Rayleigh number, $\Omega^2(2R+H)\beta\Delta TL^3\rho c_p/\nu k$
t	time
T	temperature of air
T_0	reference temperature
T_a	Taylor number, Ω^2H^4/ν^2
T_h	temperature of the hot wall
T_s	temperature of solid
T_{wall}	wall temperature
$\boldsymbol{w}$	velocity vector of the fluid in the rotating reference frame
Greek symbols	
α	surface heat transfer coefficient of the air wall
α_s	surface heat transfer coefficient of the solid wall
β	thermal expansion coefficient
ν	kinematic viscosity
ΔT	temperature difference
Ω	magnitude of angular rotation speed
$\boldsymbol{\Omega}$	vector of angular rotation
ρ	density of air
ρ_0	air density at temperature T_0
ρ_s	density of the solid
Φ	viscous dissipation
$\partial\Omega$	boundary of the computational domain

uniformity of the temperature field could hardly be realized. Thus a new temperature chamber with multiple heat sources on its surrounded walls for the multi-parameter combined environmental test device is designed, in which the temperature chamber rotates about an axis parallel to its symmetric axis. In this case, the structure and thermal boundary conditions are different from the present researches. In this study, effects of centrifugal acceleration on the temperature field in a closed cavity will be discussed by numerical simulations and experiments, focusing on the non-uniformity of the temperature field and the evolution of Nusselt number with varied centrifugal acceleration.

2. Modeling and solution method

2.1. Physical model

Fig. 1 shows the top view of the temperature chamber, in which inner air and the aluminum enclosure are shown. Four heaters are distributed on the out wall and eight temperature sensors named as S1–S8 are distributed in the cavity. The origin of rotating reference frame *Oxyz* lies in the center of the fluid. The axes of static Cartesian reference frame $O'x'y'z'$ are parallel with the axes of *Oxyz*, respectively. The whole model rotates at a constant angular speed $\boldsymbol{\Omega}$ about the z' axis. S2(1) suggests that the x and y coordinates of sensors 1 and 2 are the same and sensor 1 lies below sensor 2, as well as the other six sensors.

In order to obtain the temperature distribution and characteristics of heat transfer, the following assumptions are made: (a) the specific heat of the air is constant. (b) The radiation of the air is neglected. (c) As the Boussinesq approximation [12] is adopted, the change of density can be approximately expressed as

$$\rho - \rho_0 = -\rho_0\beta(T - \mathrm{T}_0). \tag{1}$$

2.2. Governing equations

Fluid in the rotating reference frame is affected by the Coriolis and centrifugal force. The governing equations of transient and incompressible flow can be described as follows.

Differential continuity equation is

$$\frac{\partial\rho}{\partial t} + \operatorname{div}(\rho\boldsymbol{w}) = 0. \tag{2}$$

Differential momentum equation is

$$\rho\frac{\partial\boldsymbol{w}}{\partial t} + \rho\boldsymbol{w}\cdot\nabla\boldsymbol{w} = -\nabla P + \boldsymbol{f} - 2\rho\boldsymbol{\Omega}\times\boldsymbol{w} + \rho[\mathbf{g} - \boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{r})]. \tag{3}$$

Considering the gradient of static pressure

$$\nabla P = \nabla P_m + \rho_0[\mathbf{g} - \boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{r})] \tag{4}$$

and applying the Boussinesq approximation, the differential momentum equation can be rewritten as

$$\rho\frac{\partial\boldsymbol{w}}{\partial t} + \rho\boldsymbol{w}\cdot\nabla\boldsymbol{w} = -\nabla P_m + \boldsymbol{f} - 2\rho\boldsymbol{\Omega}\times\boldsymbol{w} + \rho_0\beta(T - \mathrm{T}_0)[\mathbf{g} - \boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{r})]. \tag{5}$$

Differential energy equation is

$$c_p\rho\left(\frac{\partial T}{\partial t} + \boldsymbol{w}\cdot\nabla T\right) = \boldsymbol{w}\cdot\nabla P + \operatorname{div}(k\cdot\nabla T) + Q_V + \Phi, \tag{6}$$

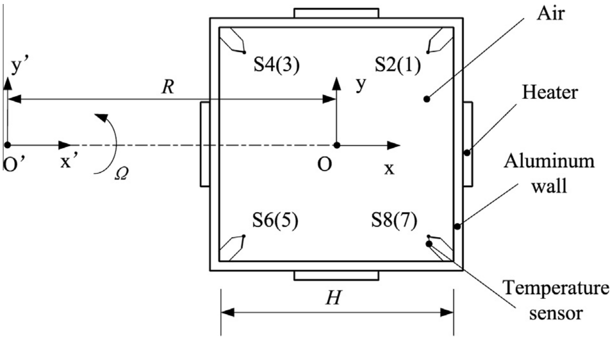

Fig. 1. Top view of the temperature chamber rotating about z' axis.