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Stability analysis of heat transfer in shallow enclosure applied in glass-covered PV-T system

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HIGHLIGHTS

- A numerical model of the shallow enclosure in glass-covered PV-T system was established.
- The critical tilt angle from steady to unsteady state was determined.
- Hysteresis phenomenon was found near the critical point.
- Main features from steady state to chaotic flow were displayed.

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ABSTRACT

The flow state undergoes a series of transitions with varing inclination of the shallow enclosure constituted in the glass-covered PV-T system. Based on this fact, a three-dimensional unsteady numerical model has been established to investigate the flow mechanism. The surface radiation and PV operating characteristic were taken into consideration. The critical tilt angle from steady to unsteady state was determined under different heating conditions and initial conditions. With the decreasing of inclination, main features including spectrum amplitude, velocity distribution and temperature contours were specified in three flow states. Results show that in general, the critical tilt angle is a positive function of total input heat flux q_t, the exception is the radiation uncoupled case of $q_t = 100\,\mathrm{W/m^2}$. When the reduction step size for inclination is fixed at only 1°, the derived critical tilt angle may be hysteretic. From the velocity contours, transverse roll in steady flow presents the dominant state. While during the transition process, the longitudinal flow is developed and superposed on the main flow step by step until the chaotic flow forms. In this state, continuous spectrum appears instead of several dominant frequencies observed in the periodic flow.

1. Introduction

In the last four decades, lots of attention has been paid to PV-T (photovoltaic-thermal) system, due to its advantages of generating electricity and thermal energy simultaneously [1]. In order to reduce heat loss to the ambient, the glass-plus-cavity design, namely a glass cover in association with a confined air cavity is essential [2]. It is a shallow enclosure with high aspect ratio, where heat transfer process is generated between PV cells and glass. It is necessary to study the flow mechanism in the enclosure as it affects the performance evaluation of the whole system.

Henderson et al. [3] have summarized the earlier work about the response of inclined cavity with different aspect ratios and angles. They pointed out that the intricate nature of flow itself would lead to the diverse regimes of researches, even for a simple inclined cavity. Through a series of investigations about a long rectangular channel, Ozoe et al. [4–7] concluded the critical inclination corresponding to the maximum or minimum Nusselt number is a strong function of the aspect ratio and a weak function of Rayleigh number *Ra*. A numerical investigation in the slender cavity was performed by Alvarado et al. [8]. Steady state results indicated that the flow pattern is appreciably modified by the surface radiation coupled with natural convection. As the enclosure shape changes from slender to shallow, Rahman and Sharif [9] discovered the convection strength increases at any

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Nomenclature

a	absorption coefficient, m^{-1}
A	aspect ratio
C_1, C_2, C_μ, $C_{1\varepsilon}$, $C_{3\varepsilon}$	coefficients in the turbulent model
c_p	specific heat capacity at constant pressure, J/(kg K)
f	dimensional oscillation frequency
g	gravitational acceleration, m/s^2
G_κ	generation of turbulent kinetic energy due to mean velocity gradients, $kg/(m\ s^3)$
G_b	generation of turbulent kinetic energy due to buoyancy, $kg/(m\ s^3)$
I	radiation intensity
I_0	incident irradiation, W/m^2
n	refractive index
Nu_c	convection Nusselt number
Nu_r	radiation Nusselt number
p	pressure, Pa
q_t	total input heat flux involving electricity and the lost heat, W/m^2
q	lost heat flux, W/m^2
$\vec{r}$	position vector
Ra	Raleigh number
$\vec{s}$	direction vector
$\vec{s}'$	scattering direction vector
S	average strain rate, s^{-1}
t	time, s
t'	dimensionless time
t_0'	dimensionless initial time of one period
t_p', t_{p1}', t_{p2}', t_{p3}'	dimensionless period
T	temperature, K
T_1	vertex temperature of the monitoring point, K
$\bar{T}$	average temperature of of cell 1, K
u'	dimensionless velocity
u_i, u_j, u_k	velocity component in i, j, k direction, m/s
u_1	vertex velocity of the monitoring point, m/s
Y_M	contribution of the fluctuating dilatation in turbulence to the overall dissipation rate, $kg/(m\ s^3)$

Greek symbols

α	tilt angles, °
$\alpha_{cri,u}$, $\alpha_{cri,d}$	critical tilt angles from steady to unsteady based on different initial conditions, °
α_{mul}	critical tilt angles for the occurrence of multimodal flow, °
$\Delta\alpha$	step decrease in the angle, °
δ_{ij}	Kronecker delta function
η_0	reference efficiency of PV cell
β	temperature coefficient, K^{-1}
ρ	density of air, kg/m^3
λ	thermal conductivity of air, W/(m K)
ν	kinematic viscosity of air, m^2/s
μ	dynamic viscosity, kg/(m s)
κ	turbulence kinetic energy, m^2/s^2
ε	turbulence dissipation rate, m^2/s^3
μ_t	turbulent eddy viscosity, kg/(m s)
σ	Stefan–Boltzmann constant
σ_T	effective Prandtl number for T
σ_κ	effective Prandtl number for κ
σ_ε	effective Prandtl number for ε
σ_s	scattering coefficient
Φ	phase function
Ω'	solid angle

particular inclination. Natural convection flow in an inclined rectangular enclosure with sinusoidal temperature profile on the left wall was analyzed by Cheong et al. [10]. In relation to application in building facade elements, Manz [11] concerned with natural convection heat transfer in the vertical cavities with aspect ratios of 20, 40 and 80. Inside a vertical rectangular enclosure with four discrete flush-mounted heaters, Ho and Chang [12] unveiled primarily the influence of aspect ratio both numerically and experimentally.

Apart from these, a number of researches [13–18] have mentioned the occurrence of the state transition when the variables, such as Ra and tilt angle change. An experimental investigation was carried out by Linthorst et al. [19] to determine the natural convection flow characteristics, including the transition from two-dimensional to three-dimensional flow and from stationary to nonstationary flow. A two-dimensional direct numerical simulation for free convection flow was raised by Arcidiacono and co-workers [20–22]. They analyzed the stability with three different aspect ratios and provided a summary map of flow regimes. In a rectangular container heated below, Koizumi [23] presented the bifurcation process to chaos and the effect of Grashof number Gr on the air flow pattern. Tso et al. [24] reported the flow and temperature fields become complex and distorted, when the rectangular enclosure with a 3 × 3 array of heaters is inclined. Numerical simulations from Williamson et al. [25,26] revealed the flow undergoes a bifurcation so that the fully developed flow becomes single mode and unsteady. At the high tilt angle, it is observed the flow consists of a large number of chaotic and irregular structures. Saury et al. [27] focused on the natural convection unsteadiness in an air filled cavity tilted from 0° to 180°. Results showed the transition from one mode to another is characterized by a critical Ra which varies with the inclination. By means of direct numerical simulation, Quéré and Behnia [28] have discussed the possible transition mechanisms to unsteadiness and fully chaotic natural convection. By the method of laser holographic interferometry photography, an experiment was conducted by Zhan et al. [29] to study the 3-D characteristics and self-sustained oscillation in a shallow cavity.

With respect to the theoretical modeling of PV-T system [2,30,31], Nusselt number formula from Hollands et al. [32] was frequently cited for the enclosed air space. The correlation was proposed under the condition of constant temperature, without the consideration of radiation participation. This situation, however, may not conform to the operating characteristic of PV cells in reality. In the numerical analysis related to PV-T system or solar collector [33–36], the instable air layer has been detected. Even so, a thorough research about the heat transfer mechanism has not been undertaken.

When applying the shallow enclosure in real PV-T system, two drawbacks could be extracted from the literature survey. Firstly, the existing literatures are mostly for the case of isothermal boundaries without radiation coupled. In the simulation part, two-dimensional modeling for the high aspect ratio cavity is in the majority. Nevertheless, the surface temperature of PV panel is possibly not uniform due to the negative function of the efficiency of PV cells. Besides, radiation interaction cannot be ignored because of the high emissivity of PV cells. The second point is associated with the transition process from steady to unsteady state. Stability investigations in above literatures have paid much attention on the square cavity, few are fitted well with the shallow enclosure. Moreover, the influence of the initial conditions has been rarely discussed in the existing 3D simulation.

Accordingly, the aim and novelty of the present paper is the stability analysis of heat transfer in the shallow glass-covered enclosure. Considering the operating characteristic of PV cells in reality, three-dimensional numerical model has been established. To further understand the transition process, firstly, analysis about the critical stability