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Natural convection and heat transfer in a valley shaped cavity filled with initially stratified water

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ABSTRACT

Fog is omnipresent in the natural environment, namely valleys and mountains. A strong comprehension of the fluid flow dynamics pertaining to fog formation is of crucial importance. In the present study, the two-dimensional numerical method is used to investigate the transient natural convection in a valley-shaped triangular cavity initially filled with stratified water. A wide range of Rayleigh numbers (2.26×10^5–2.26×10^9) and aspect ratios (0.1–1.0) are considered. The numerical results are verified against experimental results. The development of natural convection flows in the cavity from the start up to the steady state is classified into two stages: an early stage and a transitional stage. Transient natural convection flows in the cavity are described. Spectral analysis is performed for different governing parameters. A simple scaling analysis is performed for the thermal boundary layer and the time scale of the stratification breakup describing the disappearance of fog in the valley is obtained and validated by numerical results. Additionally, mass and heat transfer in the cavity is measured and the scaling relation between the Nusselt number and the Rayleigh number for different aspect ratios are presented.

1. Introduction

Fog is widely present in nature, especially in a valley. Fog is prevalent in the lower regions of the valley where the air is cold and dense. Once the warmer air flows into the lower region of the valley, the stratification of air in the valley is destroyed, which in turn leads to the disappearance of fog [1]. Accordingly, the appearance and disappearance of fog in the valley has steadily gained attention, and a number of studies have delved into this fog formation. In the early 1970's, fog on a large scale field near a valley was observed [2,3]. Later, the field observation program of radiation fog was also carried out [4]. Additionally, the valley fog test was performed [5]. These tests have revealed the extent of physical and chemical properties of fog. However, it is clear that the field measurement of fog [1–7] is difficult. As a consequence, the numerical and laboratory studies [8–15] have been increasingly adopted to obtain insight into thermodynamics of fog. One diurnal period of the thermally driven circulation over a valley under calm geostrophic wind conditions has been studied using large-eddy simulations in Ref. [8]. Complex vertical distributions of temperature, humidity and aerosols on horizontal terrain have also shown by a water pool experiment [9]. Further, the flow behavior of radiation fog in idealized cases and its sensitivity to geotropic wind speed and initial humidity have been investigated [10]. The simulations have showed an irregularity in wind flow and tracer circulation between the valley side walls according to the location of the slope with respect to the sun. Princevac & Fernando [15] have considered a valley as a triangular-shaped cavity. The authors found that the stratification of the fluid in the cavity can be completely destroyed by the thermal flow from the fluid on the inclined wall, which is relevant to the appearance and disappearance of fog.

In fact, natural convection flows in a rectangular cavity are well established in the literature [16,17]. However, the rectangular cavity is not an adequate model for many geophysical situations where the sloping boundaries have significant effect on natural convection flows. Accordingly, natural convection flows in a triangular shaped cavity have received attention recently [18]. The dynamics of natural convection flows in an attic shaped cavity with different thermal boundaries and scaling relations have been discussed. A qualitative analysis of the convection flows in the cavity together with the heat transfer was measured [19,20]. Additionally, several authors [21–25] assessed the instability and bifurcation of solutions of natural convection flows in the cavity based on various Rayleigh numbers. Recently, transient

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Nomenclature

A	aspect ratio (H/L)
f	non-dimensional frequency
f_p	non-dimensional peak frequency
g	gravitational acceleration (m/s^2)
H, L	height and half length of the cavity (m)
k	thermal conductivity (W/(m·K))
l	length of the inclined wall (m)
ln	non-dimensional length of the inclined wall (l/H)
n	non-dimensional coordinate perpendicular to the inclined wall
Nu	Nusselt number
P	pressure (N/m^2)
p	non-dimensional pressure
Pr	Prandtl number, ν/κ
Q	flow rate, $U_s\delta_{T_s}(m^2/s)$
Q_n	non-dimensional flow rate
Q_{n_max}	maximum of the non-dimensional flow rate
Ra	Rayleigh number, $g\beta(T_h - T_c)H^3/\nu\kappa$
S	surface area, $HL(m^2)$
SD	standard deviation of the temperature
SD_{ini}	initial value of SD
SD_n	standard deviation normalized by the initial value, $\frac{SD}{SD_{ini}}$
s	non-dimensional coordinate along the inclined wall
T	dimensional temperature (K)
T_w	dimensional temperature of the inclined wall (K)
T_c, T_h	temperatures of the stratified fluid at $Y = 0$ and H (K)
t	time (s)
t_s	time scale at which the thermal boundary layer becomes steady (s)
ΔT	temperature difference, $(T_h - T_c)$
U, V	velocity components (m/s)
U_s	velocity scale along the inclined wall at a steady state
U_T	velocity scale along the inclined wall
u, v	non-dimensional velocity components in x- and y-directions
X, Y	horizontal and vertical coordinates
x, y	non-dimensional horizontal and vertical coordinates
ϕ	angle of the cavity
β	coefficient of thermal expansion (1/K)
κ	thermal diffusivity (m^2/s)
δ_T	thickness of the thermal boundary layer (m)
δ_{T_s}	thickness of the thermal boundary layer at a steady state (m)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
θ	non-dimensional temperature
θ_w	non-dimensional temperature of the inclined walls
τ	non-dimensional time
$\Delta\tau$	non-dimensional time step

natural convection flows in the attic shaped cavity have also been visualized in Ref. [26]. The development of transient natural convection flows following heating the bottom and cooling the top is classified into three stages: an initial stage, a transitional stage, and a steady or quasi-steady stage. The fluid is cooled and moves along the inclined wall and reaches the bottom corner; then it moves toward the center of the cavity on the bottom. As a result, a pair of circulations forms in the cavity. It has been revealed that the thermal boundary layer varies with different Rayleigh numbers, and the thickness is larger for smaller Rayleigh numbers. Further, the heat transfer through the attic cavity has also been investigated [27–31]; these studies have considered sudden (instantaneous) and ramp heating or cooling boundary conditions.

Apart from the attic shaped triangular cavity, the dynamics and heat transfer of natural convection flows in a wedge shaped triangular cavity (modeling reservoir sidearm, seashores and different shallow-water bodies with an inclined bottom surface) were investigated in Refs. [32–37]. The development of natural convection flows from an isothermal and stationary state passes through three distinct stages [32–34]. In the initial stage conduction is dominant; in the transitional stage natural convection flows appear owing to the existence of Rayleigh-Bénard instability, which is described by rising plumes on the incline wall. Finally, in the quasi-steady stage, natural convection flows are described by instability of decreasing intensity. The mode of heat transfer and the flow status dependent on the horizontal position of the wedge cavity for different Rayleigh numbers have been discussed [35–37]. There are three possible flow regimes in the shallow littoral region. For small Rayleigh numbers, conduction dominates the heat transfer in the entire domain. For medium Rayleigh numbers, the heat transfer is dominated by conduction in the near shore and steady natural convection flows become dominant with the increase of the distance from the shore. For large Rayleigh numbers, conduction dominates the heat transfer in the near shore and the transition to unsteady natural convection flows occurs near the deep region.

Natural convection flows in an attic or a wedge shaped triangular cavity, although considerably investigated, cannot accurately describe flows in a valley. Accordingly, Princevac and Fernando [15] have carried out an experiment in a valley shaped tank filled with stratified water in order to understand the mechanisms responsible for morning breakup of the steady layer in the valley. Two flow configurations are taken into account. Firstly, if the heat flux is strong in comparison with the stratification, the upslope advection flow is dominant and reaches the top and then horizontally moves to the center of the tank. Secondly, if the stratification is stronger than the heat flux, the boundary layer flow moves upward in the lower-half but downward in the upper-half along the inclined wall. Then, the devastation of the steady core stratification occurs owing to a prevalent horizontal intrusion and its entrainment of the core fluid into the bottom layer. Although the destruction of the cold pool has been observed in the experiment, the dynamics of the stratification breakup of the fluid in the cavity is indistinct; moreover, further quantitative analysis of the heat transfer is required. This study aims to address these gaps.

In the present study, the development of natural convection flows in a valley shaped cavity with linearly stratified fluid is investigated using numerical simulation. We have compared our numerical results with the second flow configuration of the experiment by Princevac and Fernando [15]. Additionally, the time scale describing the breakup of the stratification is obtained using a simple scaling and verified by number results.

The governing equations and numerical methods are described and the model is validated with the experiment by Princevac and Fernando [15] in Section 2. The development of natural convection flows in the cavity for different stages is distinctively characterized in Section 3. The heat and mass transfer through the cavity are calculated and discussed in Section 4. Finally, the conclusions are presented in Section 5.

2. Numerical procedures

Natural convection flows into a valley shaped triangular cavity with stratified water are investigated using two dimensional numerical simulation. The physical model with boundary conditions is illustrated in Fig. 1. The height, horizontal length and the length of the inclined wall of the cavity is H, $2L$ and l, respectively. To compare the results with the experimental results [15], we have also considered the similar dimensions of the cavity including the aspect ratio of $A = 0.36$. The miniscule