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Transient intrusion flow in a section-triangular attic

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ABSTRACT

Natural convection in an attic between the roof and the ceiling plays a role in the thermal performance of buildings. The intrusion flow on the ceiling originated from the cooling inclined roof due to buoyancy, which often appears during winter- or night-time and determines heat transfer through the ceiling, is studied using scaling analysis and numerical simulation. Seven regimes and four scenarios of different heat transfer and dynamic of the transient intrusion flow are presented. Scaling relations of the intrusion flow of different regimes and critical times of the transition between those regimes dependent on Rayleigh number (Ra), Prandtl number (Pr) and aspect ratio (A) are obtained. Based on numerical simulation, the selected velocity scales are validated. Furthermore, the development of natural convection flows and heat transfer in the section-triangular attic are characterized.

1. Introduction

Natural convection in an attic between the roof and the ceiling of a building considerably determines the thermal comfort of occupants in. Heat transfer and dynamic in the attic are usually complex due to a variety of thermal boundary conditions, which could be generated by multi-layered material of the envelope with non-linear properties, geometries, geographical locations or weather patterns. Accordingly, a number of studies on this issue have been carried out over the last three decades devoting to minimize the energy cost of cooling and heating [1].

Since most of the cross-sections of attics are triangular, heat transfer and flows in an attic with a triangular cross-section (also referred to as a triangular cavity for a two-dimensional problem) have drawn more attention in the previous studies (see [1]). Usually, the two basic sets of thermal boundary conditions are considered, which are cold-top and hot-bottom corresponding to winter-time or night-time, and hot-top and cold-bottom corresponding to summer-time or day-time [2,3]. Flows and heat transfer for the former scenario have been more investigated due to its complexity involving e.g. possible thermal instability. Flack [4] investigated natural convection in the air-filled cavity heated below experimentally and reported the critical Grashof numbers for determining the transition from laminar flow to turbulent flow. Later, Poulikakos and Bejan [5] revisited this issue and obtained the relation between the Nusselt number and Rayleigh number ($Nu = 0.345Ra^{0.3}$ for $Ra = 10^6$–10^9). In fact, many of the earlier studies (e.g. [6]) assume that flows in the triangular cavity are symmetrical. However, the study [7] has demonstrated that a pitchfork bifurcation from symmetrical to asymmetrical flow in the cavity may happen as the Rayleigh number increases. Ridouane et al. [8] analyzed the transition from a symmetrical and an asymmetrical flow and presented the critical value for the appearance of the bifurcation. Chaotic or even turbulent flows in the triangular cavity for larger Rayleigh numbers have also been investigated [9]. Further, the influences of the base angle of the inclined wall [10,11] and the shape of the hot base wall [12] have been examined.

Recently, more studies [13–20] focused on transient flows in the triangular cavity. Lei et al. [13,14] observed transient flows in the water-filled cavity using shadowgraph technique. They classified transient flows into different stages including initial stage, transitional stage and quasi-steady stage. Transient flows in the triangular cavity with different thermal boundary conditions have been considered widely in the last decade [21–28]. In particular, transient boundary layer flows near the inclined top wall of different thermal conditions have been investigated in e.g. [16–18] using scaling analysis proposed in [29].

Apart from transient boundary layer flows near the inclined top wall, the experiment in [13] shown that when the suddenly cooling condition is imposed on the top wall of the triangular cavity, the boundary layer flow near the inclined top wall forms and is discharged because of the existence of the bottom wall, which may in turn result in a horizontal intrusion flow on the bottom wall. The intrusion flow plays a role in heat transfer and dynamic in the attic due to its determining heat transfer through the ceiling. Previous studies related to the transient intrusion flow are often about natural convection flows in a

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Nomenclature

a	exponent of time
A	aspect ratio
g	gravity acceleration
h	height of the attic
Nu	Nusselt number
p	pressure
P	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh number
S_{cv}	dimensionless distance for which the front of the bottom intrusion flow (BIF) travels under unsteady viscous dominance (BS1)
S_{vs}	dimensionless distance for which the BIF's front travels under unsteady inertial dominance (BS2)
S_{sg}	dimensionless distance for which the BIF's front travels under steady inertial dominance (BS3)
t	time
t_c	time when the distinct BIF forms
t_v	time of the transition between BS1 and BS2
t_s	time of the transition between BS2 and BS3
t_g	time of the transition between BS3 and steady viscous dominance (BS4)
t_1	time of the transition between conduction and convection dominance under BS1
t_2	time of the transition between conduction and convection dominance under BS2
t_3	time of the transition between conduction and convection dominance under BS3
t_4	time of the transition between conduction and convection dominance under BS4
T	temperature
T_0	initial temperature
ΔT	temperature difference between the top and bottom walls
u	velocity component in x-direction
u_I	velocity of the BIF
u_{cv}	velocity of the BIF under BS1
u_{vs}	velocity of the BIF under BS2
u_{sg}	velocity of the BIF under BS3
u_{gv}	velocity of the BIF under BS4
U	dimensionless velocity of component u
v	velocity component in y-direction
v_T	velocity of the inclined boundary layer flow (IBLF) at unsteady state
v_{Ts}	velocity of the IBLF at steady state
V	dimensionless velocity of component v
w	half width of the attic
x, y	dimensional coordinates
X, Y	dimensionless coordinates

Greek symbols

α	angle between the bottom and inclined top walls
β	coefficient of thermal expansion
δ_T	thickness of the IBLF in the unsteady stage
δ_{Ts}	thickness of the IBLF in the steady stage
δ_I	thickness of the BIF
Θ	dimensionless temperature
κ	thermal diffusivity
ν	kinematic viscosity
ρ	fluid density
τ	dimensionless time

differentially heated cavity [29–32]; that is, the intrusion flow originates from the boundary layer flow near the vertical thermal wall and travels on the insulated horizontal wall.

However, heat transfer and dynamic of the intrusion flow originated from the inclined thermal boundary layer flow are still unclear yet. Apparently, the intrusion flow on a heated wall is potentially unstable due to the effect of Rayleigh-Bénard instability and in turn becomes more complex. Moreover, the driving force of the intrusion flow differs from that induced by vertical thermal walls in [30–32]. The similarity solutions of the intrusion flow with uniform velocity on a heated wall (e.g., [33,34]) shown that the local Nusselt number characterizing the heat transfer of the bottom wall mainly depends on the local Reynolds number. Therefore, it is of practical significance to analyze the behaviors of the intrusion flow under different heat transfer and dynamic, and in turn obtain the corresponding scaling relations, which motivates this study.

In this paper, the possible flow regimes are examined and the scaling relations of transient flows in the triangular cavity are obtained using scaling analysis in Section 2; Section 3 presents the numerical procedure; the intrusion flow is characterized and the selected velocity scales are validated in Section 4; Section 5 presents the conclusions.

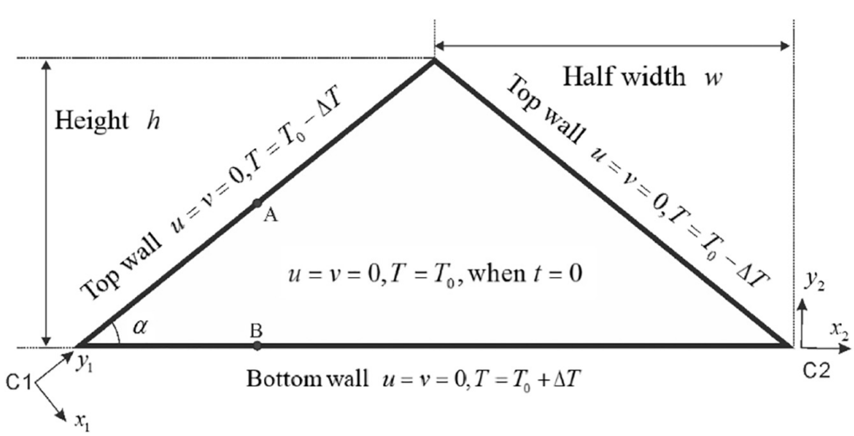

Fig. 1. The air-filled triangular cavity notion and the initial and boundary conditions.

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