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Natural convection adjacent to an inclined flat plate and in an attic space under various thermal forcing conditions

Thesis submitted by

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in November 2008

for the degree of Doctor of Philosophy

in the School of Engineering

James Cook University

This work is dedicated to
my parents, my wife, Mita
and
my baby, Adrita who was born in
during my PhD work.

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Acknowledgements

It would not be possible for me to complete this work without the support, encouragement and help from a number of people around me during my study at JCU. It is a great pleasure for me to express my sincere gratitude to all people who have helped me to reach this stage. First of all, I would like to thank my supervisors Professor John C. Patterson and Associate Professor Chengwang Lei for suggesting the original problem, their guidance and for many valuable discussions that we have had at weekly meetings throughout my candidature.

I am also grateful to the office staff, especially, Ms Helen Simpson, Ms Maxine Goulston and Ms Alison Ambrey for their official support and assistance with conference matters.

I am pleased to thank Dr. Feng Xu, who recently graduated from our research group. When I joined this group as a PhD student, I got many help from him about using Fluent and others. Thanks to Dr Tomasz Bednarz for his cordial help regarding some UDF writings for the simulations. Thanks to my office mates, Ms Yadan Mao and Mr. David Henderson. They gave me considerable assistance in some aspects when I really needed.

I am also pleased to thank the School of Engineering, James Cook University for providing me the scholarship during my study.

Finally, my sincere thanks go to my loving wife, Ms Mita Ghosh. Without her full support and consistent encouragement it would not be possible for me to finish my PhD. Also thanks to my family and my wife's family for their emotional support and patience to me. They have been waiting for the moment very patiently.

Abstract

The natural convection thermal boundary layer adjacent to an inclined flat plate and inclined walls of an attic space subject to instantaneous and ramp heating and cooling is investigated. Attention in this study has been given to fluid having a Prandtl number less than unity. A scaling analysis has been performed to describe the flow behaviour and heat transfer. Major scales quantifying the flow velocity, flow development time, heat transfer and the thermal and viscous boundary layer thicknesses at different stages of the flow development are established.

In Chapter 3, an investigation of the natural convection boundary layer adjacent to an inclined plate subject to sudden heating and a temperature boundary condition which follows a ramp function up until a specified time and then remains constant is reported. The development of the flow from start-up to a steady-state has been described based on scaling analyses and verified by numerical simulations. Different flow regimes based on the Rayleigh number are discussed with numerical results for both boundary conditions. For ramp heating, the boundary layer flow depends on the comparison of the time at which the ramp heating is completed and the time at which the boundary layer completes its growth. If the ramp time is long compared with the steady state time, the layer reaches a quasi steady mode in which the growth of the layer is governed solely by the thermal balance between convection and conduction. On the other hand, if the ramp is completed before the layer becomes steady; the subsequent growth is governed by the balance between buoyancy and inertia, as for the case of instantaneous heating.

In Chapter 4, the natural convection boundary layer adjacent to an inclined plate subject to sudden and ramp cooling boundary conditions is reported. It is found that the cold boundary layer adjacent to the plate is potentially unstable to a Rayleigh-Bénard instability if the Rayleigh number exceeds a certain critical value. A scaling relation for the onset of instability of the boundary layer is achieved. For the ramp cooling case, the onset of instability may set in at different stages of the boundary layer development. A proper identification of the time when the instability may set in is discussed. A numerical verification of the time for the onset of instability is presented in this chapter. Different flow regimes based on the stability of the boundary layer have also been discussed with numerical results.

In Chapters 5 and 6, a discussion of the fluid dynamics in the attic space is reported, focusing on its transient response to sudden changes of temperature along the two inclined walls. The transient behaviour of an attic space is relevant to our daily life. The sudden and ramp heating/cooling boundary conditions are applied on the sloping walls of the attic space. A theoretical understanding of the transient behaviour of the flow in the enclosure is performed through scaling analysis. A proper identification of the timescales, the velocity and the thickness relevant to the flow that develops inside the cavity makes it possible to predict theoretically the basic flow features that will survive once the thermal flow in the enclosure reaches a steady state. A time scale for the heating-up/cooling-down of the whole cavity together with the heat transfer scales through the inclined walls has also been obtained through scaling analysis. All scales are verified by the numerical simulations.

Further, a periodic temperature boundary condition is also considered in Chapter 7 to show the basic flow features in the attic space over diurnal cycles. The numerical results reveal that, during the daytime heating stage, the flow in the attic space is stratified; whereas at the night-time cooling stage, the flow becomes unstable. A symmetrical solution can be seen for relatively low Rayleigh numbers. However, as the Ra is gradually increased, a transition occurs at a critical value of Ra. Above this critical value, an asymmetrical solution exhibiting a pitchfork bifurcation arises at the night-time. It is also found that the calculated heat transfer rate at the night-time cooling stage is much higher than that during the daytime heating stage.

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Nomenclature

A	h/l, slope of the plate/ aspect ratio of the cavity
a, b	coefficients of the discretized equation (2.26)
$\vec{A}_e$	surface area vector enclosing the control volume
c_p	specific heat capacity at a certain pressure
L	length of the plate, length of the sloping wall of the attic
l	half length of base of the attic, length of the horizontal projection of the plate
h	height of the plate/attic
h_{eff}	$q/\Delta T$, heat transfer coefficient
$F(\phi)$	function of ϕ
F_i	body force
F_x, F_y, F_z	components of the body force (in the x-, y- and z- directions)
g	acceleration due to gravity
k	thermal conductivity
Nu	$h_{eff}h/k$, Nusselt number
P	pressure
Pr	ν/κ, Prandtl number
q	$h_{\mathrm{eff}}\Delta T$, convective heat flux through a boundary
Ra	$g\beta\Delta T h^3/(\kappa\nu)$, Rayleigh number
s_0, s_1	Series number of the control volume
T	temperature
T_A	$\Delta T/2$, amplitude of the diurnal temperature
t	time
t_s	steady state time
t_{sr}	quasi-steady time
t_p	ramp time
t_f	heating-up time for sudden heating
t_{fr}	heating-up time for ramp heating/cooling
t_{fc}	cooling-down time for sudden cooling
T_0	temperature on the bottom surface of the attic (Chapter 7)

T_c	cooling temperature
T_h	heating temperature
T_s	surface temperature condition
u, v	velocity components
u_s	steady state velocity
u_{sr}	quasi-steady velocity
$\vec{v}$	velocity vector
x, y, z	coordinates

Greek symbol

α	under-relaxation factor
β	thermal expansion coefficient
ΔT	temperature difference between hot or cold surface and the ambient
Δt	time step
$\Delta\phi$	variation of ϕ
δ_T	thickness of the thermal boundary layer
δ_{Ts}	steady state thickness of the thermal boundary layer
δ_{Tr}	thickness of the thermal boundary layer at quasi-steady time
δ_{Tq}	thickness of the thermal boundary layer at the quasi-steady stage
δ_p	thickness of the thermal boundary layer when the ramp is finished
ϕ	quantity in the general transport equation (2.18)
$\bar{\phi}_e$	average of ϕ on the edges
ϕ_{old}	value of ϕ in the previous iteration
Γ_ϕ	diffusion coefficient for ϕ in the general transport equation (2.18)
κ	thermal diffusivity
μ	dynamic viscosity
ρ	density
ν	μ/ρ, kinematic viscosity
ρ_0	density at the reference state

Subscript

e	edge of the control volume
i, j	tensor indices
n	normal to the edge
nb	number of edges enclosing the control volume

Superscript

n	time level