STUDY OF FREE CONVECTION AROUND INCLINED PLATES USING PIV

Thesis submitted in partial fulfillment for the Award of Degree

Doctor of Philosophy

By

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Ajit Kumar Jha

Ajit Kumar Jha

Dedicated to
my beloved parents

ABSTRACT

Free convection is induced by a buoyancy force on a fluid caused due to a density variation produced by a temperature difference between a solid surface and the bulk fluid. It is a reliable and cost-effective approach of transferring heat because no external devices are required to cause fluid motion. Free convection flows over flat surfaces occur in various applications, like the cooling of electronic components, the heating of spaces, the solidification process in casting, and the heat dissipation of exposed surface of electric transformers. The mechanics and importance of free convection, and objective of the thesis are discussed in chapter 1.

Due to a wide range of industrial and practical applications, free convection has been the subject of study for the past few decades. The literature review on the topic of free convection over a heated flat plate are discussed in chapter 2. Analytical solution of velocity and thermal boundary layers over a vertical plate is well known. A large number of experiments have also been conducted to study the phenomena in greater details for various geometries and boundary conditions. However, most of the experimental studies have focussed on surface temperature measurement and limited studies are available on the measurement of velocity field formed over a heated flat plate. Flow velocity has been previously analysed using a dye technique, particle visualization, and hot-wire anemometer (HWA). Techniques such as HWA are used for a point-wise measurement of velocity and are intrusive in nature. These intrusive methods can alter the features of the flow field, such as the magnitude of velocities and their circulation patterns. Techniques such as dye technique and particle visualization method employ visual inspection by addition of foreign material in the flow field. These visualization methods give only a qualitative result but for a complete understanding of the mechanism of the flow, quantitative results are also needed. For example, these methods are unable to find the exact location of the onset of

transition from laminar to turbulent over a heated flat plate. Quantitative flow visualization has increasingly become possible due to advancements in optical systems and digital image processing, leading to the development of techniques such as Particle Image Velocimetry (PIV). This is an optical, non-intrusive technique which can be used both for flow visualization and whole field measurement of velocity. Therefore, the PIV technique is employed in the current work to explore some essential flow physics that cannot be found using qualitative methods. The working principles of the PIV technique in great details is discussed in chapter 3.

The flow and thermal characteristics of free convection alter as the orientation of the heated surface is varied. A case in point is a solar collector whose inclinations affects its heat transfer performance. It is therefore vital to examine the impact of different inclinations on the flow pattern in free convection to effectively design thermal systems. Hence, in the present work, the objective was to study free convection behaviour over a heated flat surface whose inclination is varied from horizontal to vertical ($0° \leq \emptyset \leq 90°$). The flow structure analysed in the present work develops close to the flat plate measuring 150 mm long, 100 mm wide and 0.5 mm thick which was immersed in water and subjected to a uniform heat flux (q_w''). The flat plate assembly was kept in a large water tank to prevent obstruction of the flow over the flat plate from the tank wall. The maximum modified Rayleigh number based on the plate length for the case of the vertical plate was found to be 2.33×10^{10}.

Based on the inclination angle of the plate, the present work is divided into three sections which deal with: vertical ($\emptyset = 90°$), inclined ($30° \leq \emptyset \leq 60°$), and near horizontal ($0° \leq \emptyset \leq 10°$) plate inclination, respectively. The free convection boundary layer that forms over a vertical flat plate is investigated under various heating conditions and is described in chapter 4. The use of PIV for measurements within the boundary layer and/or near wall measurements poses challenges because of wall reflections, steep velocity gradients, presence of a shadow region and low seeding density. Therefore, special measures have been taken to overcome the challenges that near-wall measurements pose. For the experimental condition employed, it is found that the velocity boundary layer consists of a thin inner layer (~2 mm) and a thicker outer layer (~15 mm). The thicknesses of the inner and outer velocity boundary layers increase along the streamwise direction and decrease with the applied heat flux.

In chapter 5, a study of the free convection phenomenon over an inclined plate whose inclination varies from 30° to 60° from horizontal has been presented. It is found that the laminar to turbulent transition occurs when the inclination of the plate $\emptyset \leq 45°$ and only laminar flow appears over the plate for the range of heat flux considered when the inclination angle is more than 45°. With the help of PIV technique, the investigation of onset of velocity transition over the inclined plates has been carried out. The use of various hydrodynamic parameters such as shear stress and velocity boundary layer thickness for defining or identifying the onset of velocity transition has been discussed. The influence of heat fluxes and inclination angles on the beginning of transition has been investigated. It is found that as the heat flux increases, the transition occurs earlier in the streamwise direction and gets delayed as the angle of inclination increases. The largest distance of onset of transition $x_t =$ 136 mm, is found at $\emptyset = 45°$ and $q_w'' =$ 100 W/m^2 and the corresponding Ra_x^* is 7.27 × 10^8. The smallest value of x_t obtained for $\emptyset = 30°$ and $q_w'' =$ 5000 W/m^2 is 41 mm which corresponds to Ra_x^* of 3.09 × 10^8. In the laminar regime, the inner VBL thickness decreases with the increase in inclination angle and also with the heat flux. Also, the wall shear stress increases with the increase of plate inclination and the heat flux in the laminar regime.

In chapter 6, our attention is focused on free convection above a horizontal or slightly inclined heated plate. As the flow moves from both sides of the plate, it is observed that at a certain distance from the both ends, the two flows interact, then separate off the plate to form a plume. This distance from the leading edge, termed as the 'lift-off' point is found to be solely determined by the inclination angles and is unaffected by the heat flux.

When the flow structure is investigated for $0° \leq \emptyset \leq 10°$, three distinct flow patterns can be identified: (i) laminar flow, (ii) transition flow, and (iii) plume. The position of these three regions gets displaced over the plate with the effect of inclination angle and heat flux. It is found that the onset of transition gets delayed with increasing inclination angle and occurs earlier with an increase of heat flux. The maximum value of the location of onset of transition from leading edge per unit plate length is 0.21 and was obtained for $\emptyset = 10°$ and $q_w'' = 500$ W/m^2. On the other hand, the transition length increases with the heat flux and also with the inclination angle. The maximum value of transition length per unit plate length is 0.58 and it was obtained for $\emptyset = 10°$ and $q_w'' = 2000$ W/m^2.

The velocity profile within the VBL is plotted which indicated that the inner VBL thickness decreases in the laminar regime and increases in the transition regime. Also, similar to the case of inclined plate, the inner VBL thickness decreases with the increase in inclination angle and also with the heat flux in laminar regime.

From the analysis of buoyant plume, it was found that at a particular height from the plate, the centre line velocity increases with the heat flux and decreases with the inclination angle. It is observed that plume width first decreases (due to necking) and then increases in the vertical direction (due to horizontal diffusion). Also, an increase in heat flux and inclination angle causes an increase of plume width at a particular height from the plate.

Chapter 7 discusses the important conclusions of the thesis as well as the scope for future work.

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Abbreviation

L	length of the plate (m)
x	distance along the plate (m)
x'	x-coordinate in horizontal direction(m)
x_t	the streamwise distance from leading edge to onset of velocity transition (m)
Δx_{tr}	the length of the transition regime measured only for ascending flow (m)
x_{start}	starting point of streamwise location for identification of onset of transition (m)
x_{end}	endpoint of streamwise location for identification of onset of transition (m)
y	distance normal to the plate (m)
y'	y-coordinates in vertical direction (m)
u	velocity in the x direction (m s^{-1})
u_e	streamwise velocity at the edge of velocity boundary layer (m s^{-1})
u_{max}	maximum u-velocity at a particular x (m s^{-1})
v	velocity in the y direction (m s^{-1})
v_{max}	maximum v-velocity within the buoyant plume
R	$\sqrt{u^2 + v^2}$
k	thermal conductivity (W m^{-1} K^{-1})
g	acceleration due to gravity = 9.81 m/s^2
T	temperature of the fluid (℃)
q''_w	heat flux at the wall (W m^{-2})
T_s or T_w	surface or wall temperature of the plate (℃)

T_∞	bulk fluid temperature
ΔT	temperature difference between wall and bulk fluid (°C)
Pr	Prandtl number
h_x	local heat transfer coefficient (W m^{-2} K^{-1})
Nu_x	local Nusselt number
Gr_x^*	local modified Grashof number $= \frac{g\beta q_w'' x^4}{\vartheta^2 k}$
Ra_x^*	local modified Rayleigh number $= Gr_x^* \times Pr$
Ra_L^*	average modified Rayleigh number $= Gr_L^* \times Pr$
Ra_{cr}^*	Rayleigh number corresponds to the onset of transition
f'	non-dimensional u-velocity
f'_{max}	non-dimensional maximum u-velocity
c_{fx}	local skin friction coefficient
u_r	reference velocity (m s^{-1})
t	time after the start of heating (s)
t_s	time taken to reach steady state condition (s)
d_p	particle diameter (m)
$f_\#$	f-number
M	magnification
AD	absolute deviation
MAD	mean absolute deviation
$E(x)$	experimental curve

$y(x)$	power law fitting of the experimental curve
C	a constant value used for identification of transition
b	Plume width (m)

Greeks symbols

ϑ	kinematic viscosity (m^2 s^{-1})
β	coefficient of thermal expansion (K^{-1})
α	thermal diffusivity (m^2 s^{-1})
δ_i or δ_{vi}	inner velocity boundary layer thickness (m)
δ_{vo}	outer velocity boundary layer thickness (m)
δ or δ_v	overall or velocity boundary layer thickness (m)
μ	dynamic viscosity (N s m^{-2})
$\emptyset$	angle of flat plate with horizontal
ρ_p	particle density (Kg m^{-3})
ρ_f	fluid density (Kg m^{-3})
λ	wavelength of the incident laser light
τ_w	shear stress at the wall (N m^{-2})
$\bar{\delta}$	non-dimensional velocity boundary layer thickness
θ	non-dimensional temperature in the boundary layer
$\theta(0)$	non-dimensional temperature at the wall
η	similarity variable = $\frac{y}{x}\left(\frac{Gr_x}{5}\right)^{1/5}$

Subscripts

vi	inner velocity
vo	outer velocity
v	velocity
t	transition
w	wall
x	local
L	average
cr	critical
r	reference
max	maximum
∞	bulk
e	edge of velocity boundary layer