

1 Introduction

1.1 Free convection

Thermal energy and mass transport across a solid-fluid interface is a practical engineering problem. In the absence of fluid motion, the thermal energy and mass transfer occurs by diffusion caused by temperature and concentration gradients, respectively. If the fluid is in motion, then along with diffusion, energy and mass are also transferred by the moving fluid. This phenomenon of thermal energy and mass transport by diffusion and bulk fluid motion is called convection. Commonly, such a thermal energy transport is called convective heat transfer while the mass transport is termed as convective mass transfer. In many situations, such as cooling of a turbine blade by fluid injection, convection of both heat and mass occurs simultaneously. It may be added that fluid motion may also be induced by gradients in surface tension at an interface, leading to mass transfer. Such type of convective mass transfer is called the Marangoni effect. We shall focus specifically on convective heat transfer in this work.

Of the three modes of heat transfer- diffusion, radiation and convection, the last one involves transfer of thermal energy between a solid wall and a fluid moving over it, when both are at different temperatures. If the motion of the fluid is caused by an external forcing device such as a pump or a fan, the mode is called forced convection. On the other hand, if the fluid motion is caused by an external body force acting on density gradients induced by the transport process, the phenomena is called free convection. In situations where the effects of free and forced convection are comparable, we encounter a more complex phenomena called mixed convection. Ratio of non-dimensional numbers like Reynolds number and Grashof number are used to determine whether the convection process is free, forced or mixed.

In free convection over heated surfaces, which is the subject of study of this thesis, the density gradient is caused due to a temperature gradient and the external body force is the gravitational field. The action of gravity on the fluid mass with density gradients results in a net buoyancy force on the fluid, which induces fluid motion. Such flows are therefore also called buoyancy-driven flows. In these flows, the fluid is treated as incompressible except in the buoyancy term in the momentum balance equation. As a result, the momentum equation, containing the temperature terms becomes coupled with the energy equation. Both these equations become coupled and have to be solved simultaneously to find the velocity and temperature fields. The quantity of interest to be determined in convection heat transfer problems is the heat transfer coefficient (h) which is defined by the expression

$$q_w'' = h(T_w - T_\infty) \quad (1.1)$$

where q_w'' is the heat flux at the solid-liquid interface, and T_w and T_∞ are the wall and bulk fluid temperature, respectively. The heat transfer coefficient is fluid mechanic property of the system and depends on a number of factors like flow velocity, type of flow, geometry of flow and thermodynamic properties of the fluid.

1.2 Classification of free convection

Depending on the geometry and flow pattern, free convection can be classified into two categories: (i) External and (ii) Internal free convection

In external free convection, the flow boundary layers develop freely, without being constrained by adjacent solid walls. Flow over a heated plate placed in a quiescent medium is an example of such a flow.

In internal free convection flow, the flow field is enclosed by solid boundaries which interrupt the free development of boundary layers. The air flow inside a double-pane window is an example of such a system. There are two classes of internal free convection

problems, depending on the type of thermal boundary condition used. The first is cavities with heated or cooled sidewalls. The above example falls in this category. The second class is cavities, heated or cooled from below. The heat transfer inside a flat-roof attic space is an example. Classically, the name given to such flows is Benard convection. The present work, external free convection is analyzed.

1.3 Application of free convection

Free convection is a cost-effective and reliable method of heat transfer [1–3]. The mechanism of external free convection has a vast range of practical applications. It is most frequently used to cool electronics equipment's, such as electronic baseboards and power transistors, so that a safe operating temperature is maintained. The temperature in heavy electrical transmission lines is maintained by convective heat loss. The heat dissipated from refrigerator condenser coils to the environment is by free convection. Apart from these popularly used applications, free convection is significant in the design of nuclear reactors, food processing, meteorological investigations, and so on. Figure 1.1 shows the various applications of external free convection.

1.4 Factors affecting external free convection

In convective heat transfer, the presence of a velocity and thermal boundary layer, necessitates finding out the wall shear stress and the heat transfer coefficient. These are usually expresses in non-dimensional form in terms of local skin friction coefficient and the Nusselt number respectively. The following factors affect these two non-dimensional quantities.

(a) Wall boundary condition: The no-slip boundary condition is the standard wall boundary condition for velocity. The boundary conditions of constant wall temperature and constant heat flux are the most common wall conditions from an engineering perspective.

When a phase change process, like boiling or condensation, occurs at the surface, the constant surface temperature condition is realized. Constant surface heat flux is achieved when the surface is uniformly heated by radiation or electric resistance. It is found that the heat transfer in external flow in the case of uniform wall heat flux is greater than the constant wall temperature case for the same Rayleigh number.



Figure 1.1: Various applications of free convection

(b) Surface orientation: Free convection flow characteristics depend on the wall orientation. The flow phenomenon over a horizontal and a slightly inclined plate is completely different from that over a vertical plate. Figure 1.2 shows the flow over an inclined flat plate with four different heating conditions. For a heated surface facing upward and a cooled surface facing downward, figures 1.2(a) and 1.2 (d) respectively, the velocity

boundary layer thickens towards the trailing edge. However, in other cases where heated wall is facing downward (figure 1.2(b)) and a cooled wall facing upward (figure 1.2(c)), the opposite effect is felt [4]. As the inclination angle from the vertical increases, the tendency of flow separation from the wall increases. This is evident from figure 1.2.

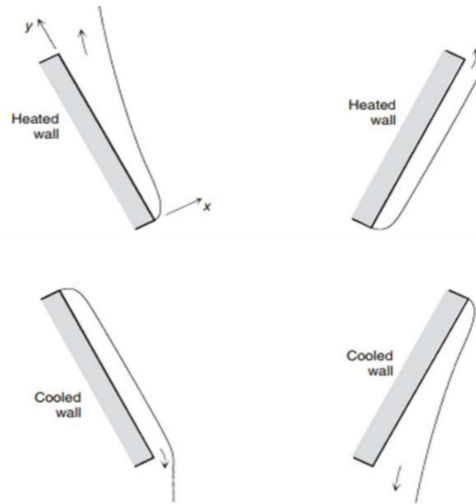


Figure 1.2: Free convection flow over an inclined plate for different heating condition [4]

Figure 1.3 shows the flow over a horizontal flat plate with four different heating conditions. The flow transforms from a boundary layer into a vertical plume for both the horizontal top-heated upward-facing surface and a downward-facing cooled bottom surface. In other cases, the boundary layer covers the entire surface, and the flow spills over the edges, as shown in figure 1.3. As evident from these flow patterns, the wall shear stress and the heat transfer coefficient drastically vary, depending on the flow orientation.

(c) Thermo-physical properties of the ambient fluid: In free convection phenomena, the flow and thermal characteristics depend on the thermo-physical properties of the fluid like its coefficient of thermal expansion, thermal conductivity and viscosity. The reason is that the fluid motion is caused due to a density difference produced by temperature gradients in the flow field. In fact, larger is the temperature difference of a fluid particle from the ambient fluid temperature, larger is the buoyancy force acting on it. For the simplification

of free convection problems, the Boussinesq approximation is generally used. It assumes that the compressibility effects are small and the density changes are caused by temperature changes alone. Then the density can be assumed as a constant term in both the continuity and momentum equations, except in the gravity term. Properties of the fluid such as viscosity, thermal conductivity and specific heat are also assumed constant in this approximation. Moreover, the temperature differences in the fluid are assumed to be small (~ 10 K). Sparrow and Gregg [5] obtained a numerical solution for several hypothetical fluid property variations. They provided a correlation of the reference temperature with the surface and bulk fluids temperature for calculating a property. However, in literature, mostly the mean film temperature is used as a reference temperature to calculate the fluid properties.

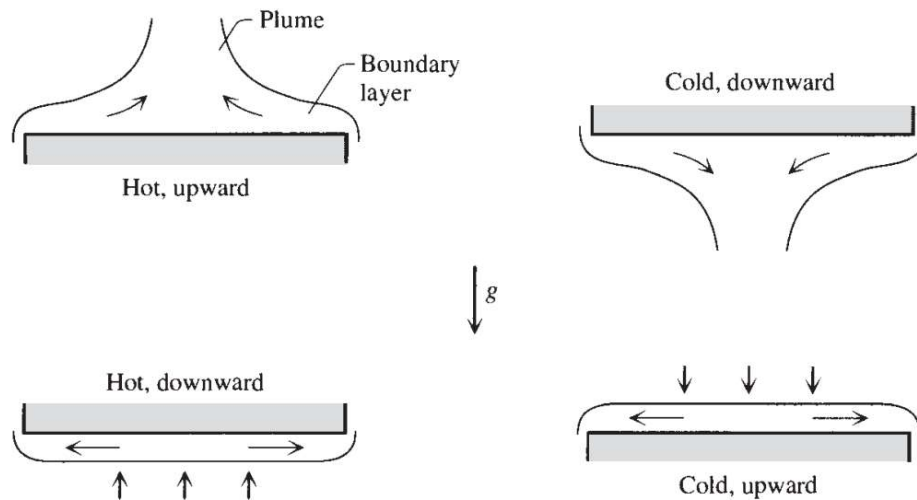


Figure 1.3: Free convection flow over a horizontal plate at different heating conditions [4]

(d) Flow regimes: Based on the flow characteristics, the flow regimes over a surface can be divided into three categories: laminar, transitional and turbulent flow. In figure 1.4, the different flow regimes over a heated vertical flat plate in free convection are shown. The fluid in the laminar boundary layer has negligible or no random motion. The flow starts to

deviate from the laminar regime due to disturbances from either an internal or an external source. The disturbances at the beginning of the transition may at first develop into relatively insignificant manifestations in the flow field. These lead to increased convection, which feeds the instability mechanism further and eventually results in a complete vortex-shedding event. As a result, disturbances are intensified in turbulent regimes, and the rate of growth and physical size of these disturbances depend on the energy available to drive them. The transition in a free convection boundary layer depends on the relative magnitude of the viscous and buoyancy forces in the fluid. The Rayleigh number is used to denote the ratio of the buoyancy force to the viscous force. For a vertical plate, with constant wall temperature boundary condition, the critical Rayleigh number is around 10^9 . Rayleigh number plays the same role in determining transition in free convection as Reynolds number does in forced convection.

(e) Characteristics length: The behavior of the flow structure over a surface is influenced by the length of the surface, as depicted in Figure 1.5. This figure shows that multiple plumes are formed when the flat plate has an infinite length. This is due to the additional upward motion, which breaks up the boundary layer and forms a plume. A net upward force is generated in case of a hot surface is in a cooler environment, causing the heated fluid to rise. As a result of changes in the flow structure, there are corresponding alterations in the heat transfer coefficient and wall shear stress.

1.5 Motivation and objectives

As discussed earlier, the mechanism of free convection has a vast range of practical applications. The phenomenon of free convection above a heated vertical flat plate has been extensively studied and analytical solution of the velocity and thermal laminar boundary layers are available. It may be added that the analytical solution is available for Prandtl

number of 1.0 and its multiples of 10. The analytical solution has been used in the present work to validate the accuracy of the experimentally determined velocity field by PIV.

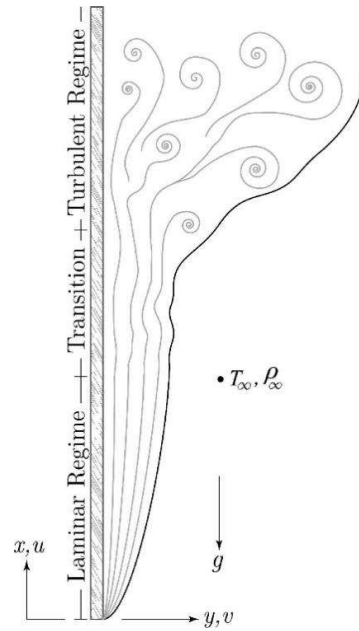


Figure 1.4: Various flow regimes over a vertical flat plate [6]

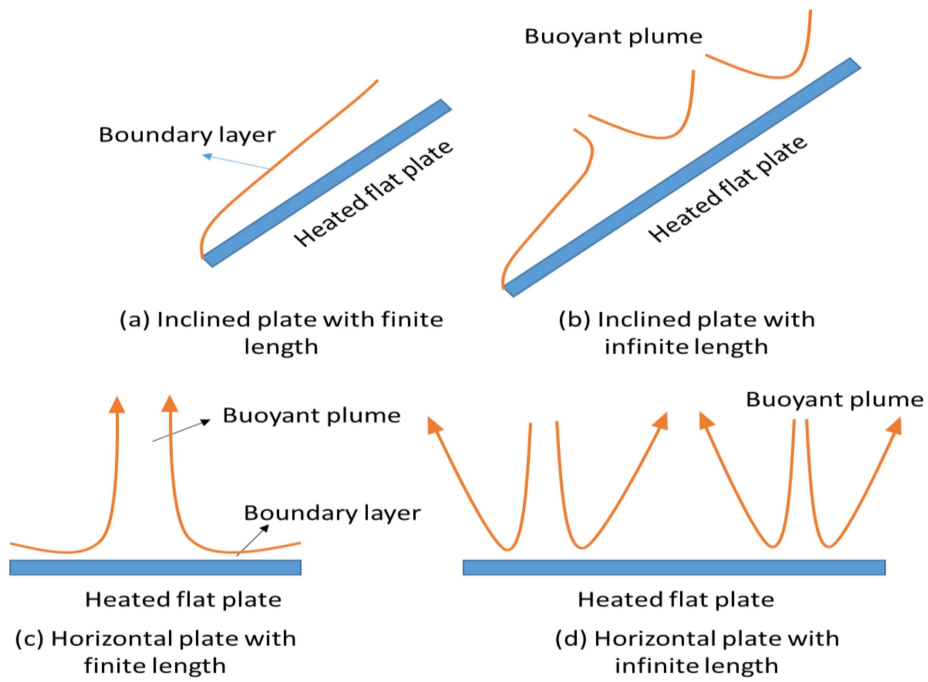


Figure 1.5: Effect of plate length on flow structure

For geometries other than the vertical plate, analytical solutions are limited. The reason is that the laminar boundary layers (hydrodynamic and thermal) either become turbulent or get detached from the surface. Therefore, an experimental approach becomes necessary for complicated flow scenarios. Most of the previous experimental studies on free convection boundary layer (FCBL) have focused mainly on temperature measurement while limited results are available for velocity measurement. Previously, the experimental approaches used to evaluate velocity in free convection were either qualitative in nature or quantitative point-wise measurements. Qualitative visualization is achieved using dye, visualization of solid particles or hydrogen bubbles. On the other hand, hot-wire anemometer (HWA) and laser Doppler velocimetry (LDV) are examples of quantitative flow measurement techniques. HWA and LDV are probe-type techniques that are utilized for point-wise velocity measurement and are intrusive in nature. Hot Wire Anemometry (HWA) was used by Cheesewright et al. [7] and Tsuji et al. [8] to quantify velocity in a turbulent FCBL. The heat transfer rate from the heated sensing elements to the fluid is the basis for measuring velocity by the HWA technique. On the other hand, LDA measures the light scattered by small particles (Doppler shift) and correlates it with particle velocity. Due to technological advancements, measurements using these methods are usually reliable nowadays, and their frequency response is adequate for detecting rapid changes in flow. However, because of performing single point measurement at a time, these techniques cannot provide accurate details about the whole-field flow characteristics. Furthermore, these techniques become time-consuming if measurements have to be taken over the entire flow field. Also, the invasive nature of the technique can disturb the flow field, causing the magnitude of velocity and flow pattern to differ from the actual value [9].

Visual inspection can be performed in the flow field using techniques such as the dye and the particle visualization method. These flow visualization techniques enable the

flow field to be visualized as opposed to the single point velocity measurement using single point probes. It is useful for understanding the flow mechanism and immediately obtaining information about the effect of altering some feature of the flow or its boundaries. A. Szewczyk [10] investigated the “natural transition” mechanism in FCBL using the dye method. Husar et al. [11] investigated the free convection flow field pattern adjacent to different planforms of heated surfaces, whereas Lewandowski et al. [12] visualized the flow structure above a heated surface kept in a horizontal position using a dye technique. Using the particle visualization technique, Burak et al. [13] and Fujii et al. [14] inspected the free convection velocity field on a vertical surface with a heat-flux discontinuity and over a heated plate with different inclinations, respectively. The dye and particle visualization methods produce only qualitative results; however, quantitative results are required to thoroughly understand the flow feature [15,16]. These methods, for example, cannot pinpoint the exact location of the start of transition point where the flow goes from the laminar to turbulent regime over a flat plate.

As mentioned above, the probe techniques are constrained by the number of measurement points in a flow field, whereas the flow visualization techniques are qualitative. With the development of methods like PIV, quantitative flow visualization has recently become feasible owing to advancements in optical systems and digital image processing. Taking precise measurements at numerous locations across the flow field, PIV combines the benefits of the quantitative nature of single-point probes with the whole-field nature of flow visualization. Due to this advantage in velocity measurement, the PIV technique was used to measure the velocity field in the present work. A complete description of the PIV technique is provided in chapter 3.

As per the available literature, the emphasis in the past has been mostly directed towards studying heat transfer through a flat plate in a free convection environment. As

mentioned earlier, the flow characteristics vary with the inclination angle and heating conditions. Hence, it is essential to investigate the flow behavior at various inclinations of the plate under different heating conditions to obtain an understanding of the associated flow physics in regions close and away from the plate. Techniques to determine the point of transition have been developed. The detached flow structures in the form of plumes have also been investigated. Correlation with earlier results of temperature measurements has also been carried out using thermocouples embedded in the plate. It is expected that the results obtained could be helpful in enhancing our knowledge of free convection. The objectives of this thesis are defined as-

- Development of free convection facility for heated flat plate whose inclination angle varies from horizontal to vertical.
- Employed the PIV technique to accurately measure the velocity field over a heated flat plate in free convection.
- Study of free convection fluid flow characteristics at various inclination angles varied from horizontal to vertical.
- Investigation of the characteristics of free convection fluid flow under various heating conditions.

1.6 Thesis outline

This work aims to analyze the flow characteristics around a flat plate in free convection environment. An experimental facility is developed and employed for measuring the free convection velocity field using PIV technique and surface temperature of the flat plate using thermocouples. The experiment was done for various plate inclinations and heat flux conditions. This thesis is divided into following seven chapters:

Chapter 1, The present chapter contains the background, motivation and objective of the research and outline of the thesis.

Chapter 2, **Literature Review**, covers literature review on the free convection flow over a vertical, inclined and horizontal flat plate.

Chapter 3, **Particle Image Velocimetry**, provides detailed information about the use of particle image velocimetry (PIV) technique for velocity measurement.

Chapter 4, **Flow over a Vertical Heated Flat Plate**, describes the qualitative and quantitative analysis of flow above a vertical flat plate. The PIV challenges for the measurement of velocity near the wall has been discussed. The various hydrodynamic parameters like boundary layer thickness, shear stress and thermal parameters like Nusselt number have been presented in this chapter.

Chapter 5, **Flow over an Inclined Heated Flat Plate**, provides information about the flow physics when the plate is inclined to the horizontal. The start of transition regime, variation of shear stress, boundary layer thickness for the plate inclination varying from 30° to 60° from horizontal have been presented.

Chapter 6, **Flow over a Heated Horizontal and Slightly Inclined Flat Plate**, reports the flow physics when the plate is oriented horizontally and slightly inclined less than and equal to 10° to horizontal. The important parameters like lift-off point, buoyant plume, shear stress have been presented.

Chapter 7, **Conclusion and Scope for Future Work**, summarizes the key finding of the present research work and suggested areas where future work may be carried out.