21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

Convection Heat Transfer from an Inclined Narrow Flat Plate with Uniform Flux Boundary Conditions

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Abstract

Natural convection from flat plates finds diverse applications in engineering and natural systems. While previous studies have considered natural convection from isothermal vertical plates in air and tilted plates in water subject to uniform flux, little attention has been given to natural convection from inclined narrow plates in air. This work reports on experiments undertaken on an inclined narrow plate with uniform flux boundary conditions. The spatial distribution of temperature along the length of the plate was measured for a range of imposed uniform flux values and inclination angles, ranging between vertical and downward-facing horizontal. The temperature profile along the plate indicates convective heat transfer rates associated with the development of the flow from a laminar to a turbulent regime. An interesting result of increased convection loss at a downward-facing inclination was observed, and is shown to be associated with the absence of sidewalls. Smoke visualisation of the flow was undertaken and the transition from laminar to turbulent flow was observed.

Introduction

Natural convection heat transfer has been the focus of numerous experimental and theoretical studies [1, 2, 13, 14]. Natural convection from the flat plate geometry is a fundamental case which finds application in a variety of engineering and natural systems as diverse as solar water heaters, cooling of electronic systems and melting of icebergs [7, 15]. Another setting where this mode of heat transfer occurs is concentrating solar power (CSP) receivers [10, 11]. These are banks of vertical tubes which are formed into cylindrical or flat shapes, often with vertical characteristic lengths of up to 25 m or more. If the surface roughness of each panel (due to tube curvature) is ignored, each segment can be characterized as a vertical flat plate. Given the large dimensions and the high temperatures at which these receivers operate, turbulent natural convection is a frequently-occurring flow regime, and if relatively low wind speeds are present in the vicinity of an external receiver, natural convection rather than forced convection may dominate [8].

Numerous studies have been undertaken on natural convection from a flat plate subjected to isothermal boundary conditions. Churchill and Chu [2] presented a theoretical investigation of data reported from experiments and proposed a correlation which could be applied to laminar and turbulent flow regimes, as well as vertical and inclined plates. Tsuji and Nagano [13] conducted experiments on a four-metre copper plate to study the turbulent boundary layer in natural convection. Velocity and temperature profiles within the boundary layer were measured in order to calculate Reynolds stress and turbulent heat fluxes. Transition from laminar to turbulent flow has also been studied by numerous authors, using different methodologies [5, 6, 16].

In comparison to studies of isothermal flat plates, uniform flux boundary conditions have received less attention [9]. Vliet [14] first reported experiment data from such a case, commenting on the influence of inclination on the onset of turbulence. Temperature distributions along vertical and inclined downward-facing plates have been reported as a function of flux, in water and air [3, 4]. It was reported that in the laminar regime, the parallel component of gravitational force could be used to correlate the Nusselt and Rayleigh numbers. In the turbulent regime, however, the magnitude of the gravitational force yields better results for the correlation [14]. That both the plate-normal and plate-parallel components of the gravitational force influence the dynamics of the flow in the turbulent regime has bearing on the impact of plate aspect ratio and the sidewalls – which can restrict the boundary layer to be two-dimensional – in determining flow behaviour.

Based on a review of the relevant literature, there is a lack of studies relating to convection heat transfer from turbulent flow along narrow plates. The interplay between the magnitude of components of the buoyant force acting normally and parallel to a heated narrow plate has not been studied in great detail. Adiabatic sidewalls that restrict the inflow of mass and air to the boundary layer along the plate could influence the heat transfer behaviour. These are motivations for a detailed study on this topic.

This study aims to experimentally investigate natural convection along an inclined narrow flat plate, in air, subject to uniform flux boundary conditions. The flat plate experimental setup is designed such that it allows for the development of turbulent flow along the plate height. The influence of sidewalls on the resulting convection loss from the plate is investigated. Moreover, smoke visualisation is used to qualitatively assess the different convection regimes along the plate.

Methods

Experimental setup

Figure 1 shows the experimental setup used in this study. An aluminium plate with dimensions of 1.8 m × 0.22 m (height × width) is assembled using 18 modular units, each consisting of a 0.1 m × 0.22 m × 0.004 m (H×W×T) aluminium plate, an Omega™ silicone rubber heater with a flux density of 1550 W/m^2, and two Superwool® insulation boards, one of 25 mm and another of 50 mm thickness. Each unit is fitted with four K-type thermocouples. As indicated in figure 1(c), thermocouples TC1 and TC2 are placed behind the aluminium plate, and embedded in blind holes which terminate 1 mm from the front surface. These two thermocouples measure the temperature at the centre and near the edge of the plate. Thermocouple TC3 is placed between the heater and 25–mm thick insulation board; thermocouple TC4 is placed between the two insulation board layers. The latter two thermocouples

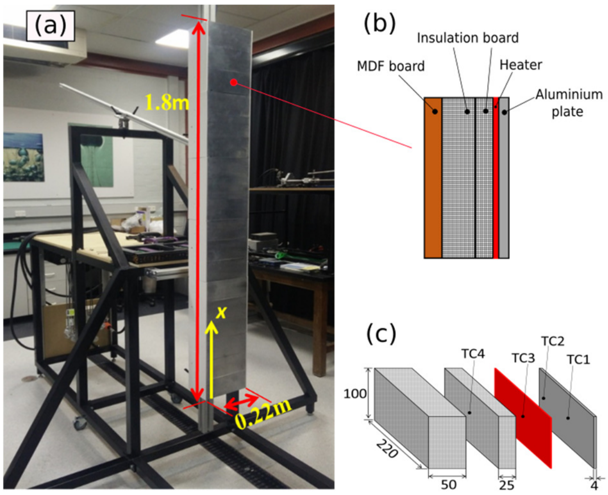

Figure 1 Experiment setup and constitutive unit: (a) Photo of experiment setup, showing the flat plate and mounting frame assembly. Yellow arrow denotes the location coordinate starting from the leading edge; (b) Side-view of one representative heating unit, showing components; (c) Exploded view of heating unit, showing thermocouple (TC) locations as well as dimensions of components. Note that dimensions are in millimetres.

allow for the estimation of conduction losses through the back of each unit.

A schematic of the control system is shown in figure 2. Power is delivered to the 18 heaters using two 12-channel light dimmer units (Redback RED3 Rackmount, LSC Lighting Systems Pty Ltd). These units provide phase-angle control of the output power. A data logger (dataTaker® DT80) is used to read signals from the 72 thermocouples used in the plate assembly. An Arduino®MEGA 2560 with a Digital Multiplex (DMX512) shield is used to communicate with the dimmer unit, via a Matlab program. A similar power control system was used in [11].

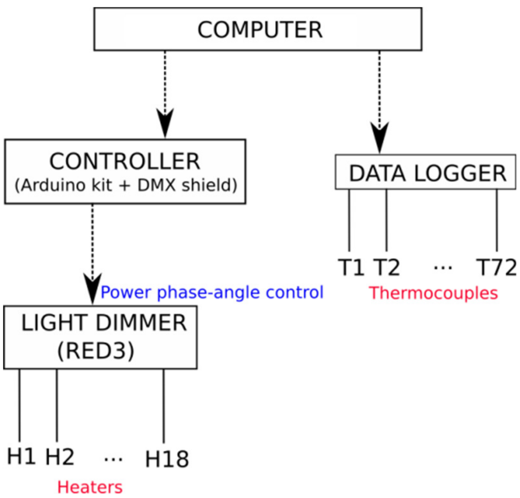

Figure 2 Schematic of the power control system used for the experiments

Experiments with uniform flux from the heaters are conducted for this study. Values of 5, 8, 9 and 10% of total power are delivered to each of the 18 heaters, via the RED3 dimmer units, where the total power corresponds to 183 W. The temperature of each section of the heated plate is monitored, and logged. Steady-state is deemed to have been reached after the rate of change of temperature of each of the 72 thermocouples is less than 1°C/h.

Smoke visualisation is carried out using a Björnax Smoke-Pen™, which allows for a qualitative inspection of the flow across the flat plate. The smoke source is placed on the vertical symmetry plane at the leading edge of the rig.

Temperature data obtained from the experiments is used to calculate the local convection heat loss from each unit of the plate. This is achieved by an energy balance of total heating power input for each section of the flat plate, the thermal radiation from the aluminium plate (thermal emittance, ε=0.10), as well as heat conduction through the insulation boards. Equation (1) shows the parameters that are obtained using experimental data as well as thermophysical properties of the material used in assembling the plate, in calculating the convection heat loss from each unit.

$$\dot{Q}_{\text{conv,local}} = P_{\text{input,unit}} - \dot{Q}_{\text{cond,local}} - \dot{Q}_{\text{rad,local}} \quad (1)$$

where $P_{\text{input,unit}}$ is the total input power for each unit, obtained from a look-up table of power percentage versus power, as measured by a power meter providing the corresponding true power values.

Results and Discussion

Effect of flux on temperature distribution

Figure 3 shows the distribution of temperature along the length of the vertical flat plate, for uniform flux experiments at steady state. When the total flux increases from 409 W/m^2 to 636 W/m^2, the development of flow from laminar to fully turbulent is more pronounced. For the lowest imposed flux, the point of transition from laminar to turbulent flow, as denoted by the onset of reduction in temperature along the plate, is higher along the plate than for the case of higher flux values. Moving upwards from the leading edge, the temperatures at all flux levels increase roughly linearly, consistent with the expected laminar boundary layer in this section of the plate. At the onset of transition to turbulent flow, the temperature starts to decrease due to turbulence-enhanced convection. More uniform temperatures are seen in the fully-developed turbulent zone, at x > 1.2 m. Smoke visualisation tests were undertaken during the experiment which show regions of laminar, transition and turbulent flow—refer to figure 7(b)—which is consistent with trends observed from temperature data presented here. Similar temperature distributions to those presented here have been reported in other work [3, 4, 14].

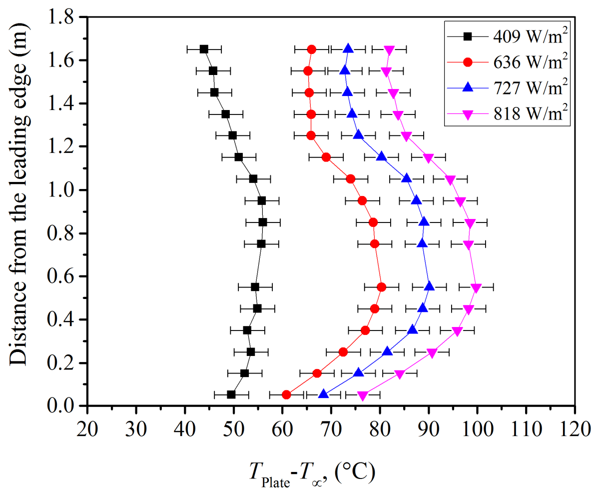

Figure 3. Temperature distribution along the length of the vertical heated plate without sidewalls, for different values of imposed uniform flux.

Effect of plate inclination on temperature distribution

Figure 4 shows the temperature distribution along the plate, for different plate inclination angles, as measured from the vertical, with the heated surface facing downwards. When plate inclination was changed from $\theta = 0°$ to $\theta = +30°$, the heat transfer rate from the plate increased, i.e. lower steady-state temperatures are obtained. The trend that was observed in the data could be attributed to the interaction between the buoyancy force components and (lack of) sidewalls for the setup.

In the vertical orientation of the flat plate, no component of the buoyancy force acting normal to the plate, exists. However, at $\theta = 30°$, such a force does exist, which acts to force the buoyant air towards the plate. Given that no sidewalls exist, this buoyant air does not rise along the surface plate, but instead moves towards the plate edges and leaves the surface of the plate from the side, thus increasing the heat transfer. As reported in [7], for narrow plates, the presence (or lack thereof) of sidewalls can influence the dynamics of the boundary layer and in some instances, increase the convection heat transfer. Given that the aspect ratio (i.e. ratio of width-to-height) for the plate used in this study is 0.12, it seems that this influence is substantial. At inclination angles of 60° and 90°, trends are consistent with those reported in the literature for wide plates—i.e. lower convection heat transfer at larger inclinations. There is a weaker component of the buoyancy force driving a systematic flow along the plate, and the lowest rate of heat transfer is observed for the horizontal plate facing downwards.

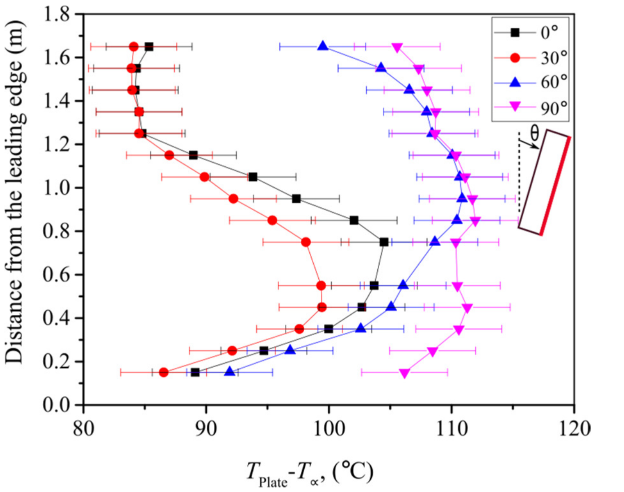

Figure 4 Temperature distribution along the length of the heated plate, without sidewalls, as a function of inclination angle. Total imposed flux is kept constant and uniform at 818 W/m^2. Inset shows the positive angle definition, with the heated plate shown in red.

Effect of sidewalls on temperature distribution

To investigate the influence of sidewalls on convective heat transfer, two medium-density fibreboard panels were fixed firmly on both sides of the heated plate, so that no gaps existed between the plate and the sidewalls. Uniform flux experiments were conducted, with the plate inclined at $\theta = -10°$, 0° and +10°. Figure 5 shows the results obtained from these experiments. Results from the downward-facing inclined plate ($\theta = +10°$) show a reduced heat transfer rate, and thus increased steady-state temperatures along the height of the plate, contrary to the trend observed in figure 4, for the change in inclination from $\theta = 0°$ to $\theta = +30°$. It is noteworthy that for the case of $\theta = +10°$, the point of transition from laminar to turbulent flow, as evidenced by the reduction in temperature, occurs at a higher location than that for a +30° inclined plate, without sidewalls. Thus, the notable impact that the sidewalls have in restricting lateral flows from interacting with the heated surface of the plate, allowing for an increased boundary layer thickness and delaying the onset of transition to turbulence, can be inferred from the results. Furthermore, as figure 5 shows, the temperature distribution on the plate inclined at $\theta = -10°$ leads to increased heat transfer. Both the $\theta = -10°$ and $\theta = 0°$ cases are characterised by a nearly uniform temperature for $x > 1.2$ m, signifying a fully developed turbulent regime, whereas for the case of $\theta = +10°$, the turbulent regime is not yet fully developed.

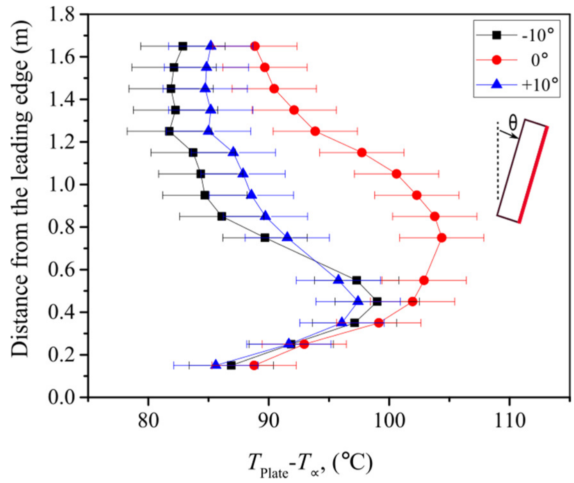

Figure 5 Temperature distribution along the length of the heated plate, with sidewalls, as a function of inclination angle. Total input flux is kept constant and uniform at 818 W/m^2. Inset shows the positive angle definition, with the heated plate shown in red.

Convective heat loss

An energy balance is used to calculate convective heat losses, as shown in equation (1). Figure 6 presents results obtained from uniform flux experiments undertaken without sidewalls. Consistent with data presented in previous figures, the rate of convection increased at an inclination of 30° in comparison with 0° and 60°. At higher values of plate inclination, and with an increase in overall plate temperature, radiation and conduction heat loss from the plate increased while convection loss decreased. To the best of our knowledge, an increase of convection heat transfer at intermediate inclination angles has not been reported for tilted flat plates without sidewalls, but it has been reported in tilted rectangular enclosures [12].

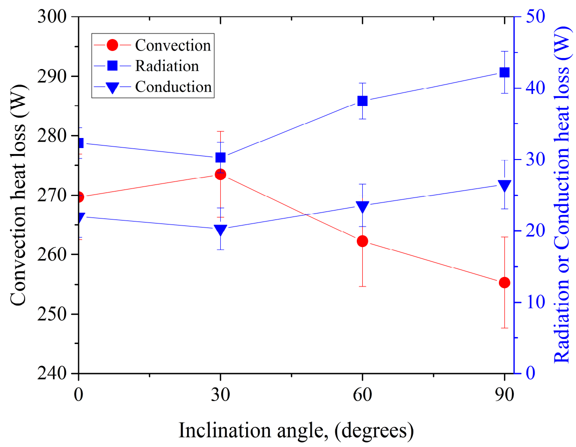

Figure 6. Heat loss from the flat plate as a function of angle, subject to uniform flux boundary condition, without sidewalls.

Using convection heat loss values and temperatures obtained from the experiments, local values of the convective heat transfer coefficient h are calculated over each plate. Figure 7

(a) shows these results for one representative experiment. A gradual decrease in h as x increases for $x < 0.6$ m is consistent with the presence of a steady-state laminar flow regime. Between distances from the leading edge of $x = 0.6$ m to $x = 0.9$ m, values of h remained relatively constant, which could be due to structured laminar vortices in the transition region [16]. In the turbulent region, the convection coefficient increased. Figures 7 (b) and (c) show two smoke visualisation photos taken during an experiment. Visualised flow patterns are consistent with trends obtained from temperature data (e.g. figure 3), as well as those seen in figure 7 (a).

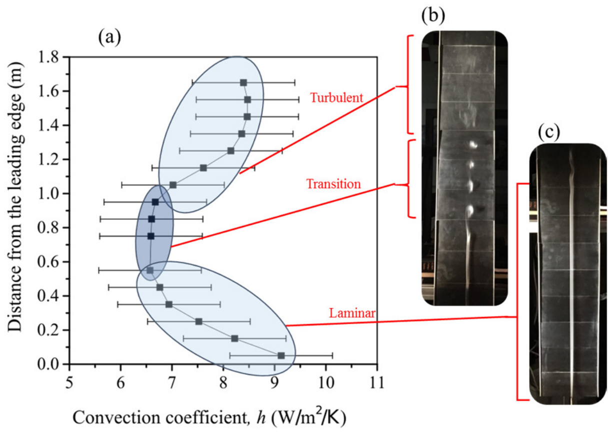

Figure 7. (a) Variation of convection coefficient along a vertical plate for 818 W/m^2 uniform flux experiment, without sidewalls, (b)-(c) Photos of smoke visualisation during experiment, qualitatively showing turbulent and laminar flow regimes, respectively.

Conclusions

An experiment was designed to determine convection heat loss from an inclined narrow flat plate, in air, subjected to uniform flux boundary conditions. The setup dimensions allowed for the development of turbulent flow, and smoke visualisation provided the location of transition to turbulence, as well as a qualitative inspection of flow behaviour.

Temperature profiles along the length of the flat plate provided an insight into the changes in convective heat transfer coefficient. An increasing boundary layer thickness in the steady laminar region was thought to be associated with the observed increase in local plate temperature, whereas in the transition zone (also laminar), a gradual reduction of temperature was measured, which is thought to be due to an increase of convective heat transfer caused by visualised structured vortices. In the fully-developed turbulent region, a relatively uniform temperature profile was observed.

A significant finding of this study was the increased heat transfer rate that was observed at an inclination of 30°, in comparison to 0° (vertical plate) and 60°. Given the narrow aspect ratio of the plate and the absence of any sidewalls, the component of buoyant force normal to the surface would result in an increased span-wise flow towards the sides of the plate, thus reducing the surface temperature. However, this effect is thought to become relatively weaker as the downward facing heated surface becomes closer to horizontal. Once sidewalls were incorporated into the setup, heat transfer trends became consistent with those stated in the literature for wide plates, i.e. quasi two-dimensional flows.

Findings from this study can contribute to our understanding of turbulent natural convection over narrow flat plates. Further investigation into the effect of boundary conditions on flow development and heat loss from narrow plates is necessary, and the current setup allows for a wider set of such parameters to be studied.

Acknowledgments

This research was funded by the Australian Renewable Energy Agency (ARENA) for the project titled: “Bladed Receivers with Active Airflow Control” (2014/RND010).

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