THE COOLING EFFECT OF AIR ON FLAT PLATE SOLAR ENERGY COLLECTORS

BY

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DECLARATION

I declare that this thesis is my original work and has not been previously presented for a degree award of Maseno University or any other University. All sources of information have been supported by relevant references.

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DEDICATION

I dedicate this thesis to my supportive wife Sabrina and her sister Olivia. May this noble work inspire you to have goals in life and aspire to achieve them for the benefits of humanity.

ABSTRACT

Use of solar energy devices requires that they be exposed to receive maximum solar radiation. Unfortunately, the intensity of solar radiation incident on these devices varies throughout the day with the position of the sun in the sky hence making these devices to under-perform. Moreover, high temperature associated with the heating effect of the much needed solar radiation also destroys solar PV cells whose optimal operation temperature is 25^oC. This is contrary to solar thermal energy collectors whose performance improves with increased temperature. To improve the performance of flat plate solar PV and thermal energy collectors, it is important to determine their optimal angle of orientation with respect to solar radiation and wind. To address these challenges, it was important to achieve the study objectives which were to investigate cooling effect of air with a view to improving the performance of flat plate solar energy collectors, determine the dependence of wind-related heat transfer coefficient (h_w) on angle of incidence of wind onto the flat plate solar energy collectors and to develop the currently lacking single expression of (h_w) for the full possible range of angles of incidence of wind onto the flat plate solar energy collectors from 0^o to 90^o. To achieve these study objectives, it was important to understand the effect of air velocity (u), angle of incidence of wind (θ_i) and temperature variation on the performance of these devices. To study the effect of these variables on the performance of flat plate solar energy devices, a laboratory experiment was set up having a flat plate inside a wind tunnel to collect data on cooling effect of air at different angles of inclination of the plate (θ_p). Velocity and temperature at different angles of orientation of the plate were measured using thermo-anemometer and digital data logger respectively. Data collected under steady state condition were used to determine wind-related heat transfer coefficient (h_w). The dimensionless numbers associated with this study were Nusselt (Nu), Reynolds (Re) and Prandtl (Pr). These are correlated by $Nu = \gamma\ (RePr)^{n}$ which links (h_w) with θ_p, θ_i and u. To show variation of (h_w) with (u) and (θ_i), graphs of (h_w) against (u) and (θ_i) were plotted by OriginPro. The values of (h_w) under different conditions were used to determine suitable orientation of flat plate solar energy devices with reference to wind and solar radiation, for their optimum performance. The study found that in a relatively low air velocity, the value of (h_w) was insensitive to incident angles of wind onto plate. However, as air velocity increased, the variation of (θ_i) with (θ_p) strongly influenced the plate's steady state temperature which in turn influenced the magnitude of (h_w). The incident angles of wind yielding low and high values of (h_w) were found suitable for optimum operation of solar thermal and PV energy collectors respectively. The study recommends that the optimal tilt angles of solar PV panels and solar thermal panels would be 0^o and 45^o respectively relative to wind. The results of this study will serve as reference for researchers, solar thermal and PV panels' installers.

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LIST OF ABBREVIATIONS, SYMBOLS AND SYMBOLS

A	:	Area of the heated surface exposed to convection (m^2)
$\boldsymbol{\delta}$	:	Thickness of the insulator (m)
I	:	Electrical current (A)
μ	:	Dynamic viscosity (Pa.s)
h	:	Convection heat transfer coefficient (W/m^2 K)
g	:	Gravitational acceleration (m/s^2)
β	:	Thermal expansion coefficient (K^{-1})
T	:	Temperature (K) or (^{o}C)
u	:	Air velocity (m/s)
V	:	Electrical voltage (volts)
ε	:	Emissivity
σ	:	Stefan-Boltzmann constant $5.669 x 10^{-8}$ (W/m^2K^4)
L	:	Characteristic flow length, plate length (m)
Q	:	Quantity of heat lost per second (W)
k	:	Thermal conductivity of the fluid (air) (W/mK)
ν	:	Kinematic viscosity (m^2/s)
$\boldsymbol{\gamma}$	:	A function depending on the plate tilt angle/incident angle of wind on the plate
$\boldsymbol{\psi}$	:	A constant that moderates the damping effect of γ on f (u) and air properties (t_n)
ΔT	:	temperature difference between the plate wall and ambient air
Re	:	Reynolds number
Pr	:	Prandtl number
Gr	:	Grashof number
Nu	:	Nusselt number
$\boldsymbol{T_p}$	:	Plate wall temperature
$\mathbf{T_a}$	:	Ambient air temperatures
$\mathbf{T_o}$	:	Surrounding surface temperature of the plate
$\boldsymbol{T_{ii}}$	:	Insulator inner temperature
$\mathbf{T_{ie}}$	:	Insulator external surface temperature
$\boldsymbol{R_r}$	:	Radiation thermal resistance
$\boldsymbol{R_h}$	:	Convective thermal resistance
$\boldsymbol{R_k}$	:	Conductive thermal resistance
$\boldsymbol{k_i}$	:	Thermal conductivity of the insulator

$\boldsymbol{\varepsilon}_p$	:	Plate emissivity
$\boldsymbol{\varepsilon}_o$	:	Emissivity of the surrounding air above the heated plate
Q_{h_w}	:	Wind-related (forced) convection heat loss
Q_{h_o}	:	Free convection heat loss
Q_r	:	Radiation heat loss
Q_k	:	Conduction heat loss
q_t	:	Electrical heat flux
θ_p	:	Plate tilt angle relative to horizontal air-flow
θ_i	:	Incident angle of horizontal air-flow onto the collector
t_n	:	Temperature dependent air properties
A_p	:	Plate surface area exposed to convection
A_i	:	Surface area of the insulator in contact with the wall of heated plate
γ_{max}	:	A function of incident angle of wind onto the plate for the curve of h_w when $\theta_i = 90^o$
γ_{min}	:	A function of incident angle of wind onto the plate for the curve of h_w when $\theta_i = 0^o$
h_w	:	Wind-related convection heat transfer coefficient
$h_{w(max)}$	:	Wind-related convection heat transfer coefficient for curve of h_w when $\theta_i = 90^o$
$h_{w(min)}$	:	Wind-related convection heat transfer coefficient for curve of h_w when $\theta_i = 0^o$
h_o	:	Heat transfer coefficient in still air
$\sum[\gamma t_n f(u)]_{max}$	:	The difference between $h_{(w)\,max}$ and h_o for the curve of h_w when $\theta_i = 90^o$

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CHAPTER ONE
INTRODUCTION

1.1 Background of the Study

Wind is a moving air resulting from convection currents. Convection is the transport of mass of fluids as a result of density gradient and/or pressure gradient. In the process, energy is transferred and this can happen in all forms of convection namely natural convection and forced convection. Forced convection is a mechanism, or type of transport in which fluid motion is generated by an external source like a pump, fan, suction device etc. Natural convection results from temperature difference between hot body and the surrounding fluid which gives rise to fluid density gradient. The movement of mass and heat in free convection depends on the density difference which is driven by buoyancy forces of the flow in the presence of the gravitational force field. The rate of convection heat transfer is directly proportional to the temperature difference between the surrounding fluid and the heated surfaces like that of solar energy conversion devices. Convection heat transfer therefore, depends on temperature which is one of the important factors affecting the efficiency of solar energy converters such as solar photovoltaic panels and solar thermal energy collectors. Solar PV cells operate optimally at relatively low temperatures as opposed to solar thermal heaters which require high temperatures to optimize their energy conversion efficiency.

The study of the effects of air in motion (wind) on solar energy collectors along the equator is of great interest since sunlight intensity is very high and this affects the performance of both solar thermal and PV energy collectors. Variation in operating temperature with sunlight intensity influences the current and voltage of the PV cells. For instance, an increase in temperature causes a linear decrease in the efficiency of solar PV panel power output and vice versa according to Skoplaki and Palivos (2009) and Cindy and Demand (2010). For crystalline solar cells, the reduction in conversion efficiency is approximately 0.4% to 0.5% for every degree rise in temperature (Notton et *al.,* 2005). Moreover, the efficiency of wafer–based crystalline as well as thin film solar cells reduces with increase in panel temperature (Katkar *et al.,* 2011). Therefore, reducing the operating temperature of the photovoltaic panels is very important for the panels to work efficiently and protect the cells from irreversible damage. A low-cost cooling system for PV cells is thus needed and that is passive cooling via wind. In an attempt to exploit renewable energy technologies with a view to reducing environmental pollution and global warming, several studies on cooling effect of air on flat plate solar energy collectors have been conducted to optimize their performance. The studies on optimization of solar energy collector tilt angles relative to air-flow have been conducted by Sparrow et *al*. (1979), Duffie and Beckmann (1980), Othieno (1985) as well as Tiwari and Malhotra (2013). Solar energy collector tilt angles significantly influence the steady-state temperature of solar collector plate which in turn influences wind-related heat transfer coefficient and ultimately the collector's cooling rate. Despite all these previous studies, there are still unsolved problems that the current study undertakes to address upon investigation in order to fully exploit solar energy technologies. Even though mode of heat transfer by convection is complex due to the many parameters involved in its study, several correlations of wind-related heat transfer coefficient have been developed to help in convection heat transfer analysis. However, these correlations of wind-related heat transfer coefficient have either under-estimated or over-estimated convection energy losses from the flat plate solar energy conversion devices which are exposed to wind at different angles of incidence.

Furthermore, the dependence of wind-related heat transfer on incident angles of wind on to the collector at high air velocity has not been fully explored. It is therefore, assumed that at both low and high air velocities, heat transfer correlation follows a linear trend which is not the case. This assumption is only true at relatively low air velocity ranging from 0 m/s to 2m/s for the full possible range of incident angles of wind ($0^o \leq \theta_i \leq 90^o$). In fact, the reduction effects of the converted kinetic energy of high velocity air molecules to thermal energy and that of viscous heat dissipation at high wind speed on heat transfer coefficient has been ignored. It has been assumed that wind-related heat transfer coefficient is linear function of wind which according to this study is wrong. Consequently, this has led to over-estimation of convection heat transfer values. To make matters worse, all the correlation functions of wind-related heat transfer coefficient revealed in the literature have been just for a particular incident angle of wind on to the plate at a given air velocity. However, no single expression of wind-related heat transfer coefficient that encompasses the full possible range of incident angles of wind ($0^o \leq \theta_i \leq 90^o$) has been developed up to date. It is therefore clearly evident that many of these problems are yet to be satisfactorily solved and hence this calls for further investigation.

1.2 Theory on Wind-Related Convection Heat Transfer

In wind-induced convection, the rate of heat flow (Q_{h_w}) is directly proportional to area of the heated surface of the plate (A_P) and temperature difference (ΔT) between the heated surface of the plate and ambient air. Therefore,

$$Q_{h_w} = h_w A_P \Delta T \qquad \ldots\ldots\ldots\ldots\ldots 1.20$$

The quantity (h_w) represents wind-related heat transfer coefficient. It is a measure of the magnitude of wind-induced heat transfer rate from the heated surfaces. This quantity (h_w) depends on many parameters for instance the properties of the fluid such as density ($\boldsymbol{\rho}$), specific heat capacity (c_p), thermal conductivity (k), kinematic viscosity ($\boldsymbol{\nu}$), thermal diffusivity and dynamic viscosity ($\boldsymbol{\mu}$). Moreover, wind-related heat transfer coefficient depends on the dimension of the plate (L), incident angle of wind onto the plate ($\boldsymbol{\theta}_i$), plate inclination angle ($\boldsymbol{\theta}_p$), fluid (i.e. air) velocity (u) and the temperature difference between heated surface and ambient air ($\boldsymbol{\Delta}$T). The study of convection as a mode of heat transfer is therefore, very complex due to the many parameters involved. Fortunately, these parameters when grouped form special relationships or associations called dimensionless numbers which help simplify the study of convection heat transfer problems. There are several dimensionless numbers but the mostly relevant for this work are Reynolds number (Re), Prandtl number (Pr), and Nusselt number (Nu). The Grashof number (Gr) is only relevant in free convection where buoyancy forces significantly determine the magnitude of heat transfer coefficient in still air.

1.3 Dimensionless Numbers

1.3.1 Reynolds Number

Reynolds number (Re) is defined as the ratio of two forces that influence the behavior of the fluid (i.e. air) in the boundary layer. These two forces are inertial and viscous forces.

$$\mathrm{Re} = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{\mathrm{uL}}{\nu} \qquad \ldots\ldots\ldots\ldots\ldots 1.21$$

The variables u, $\boldsymbol{\nu}$ and L represent fluid velocity, fluid kinematic viscosity and characteristic flow length respectively. Reynolds number influences the thickness of the boundary layer of the flow and the flow transition from laminar to turbulent. When the Reynolds number is large, the inertial forces dominate viscous forces hence fluid becomes turbulent and more efficient in carrying away heat. However, when Reynolds number is small, the viscous forces dominate inertial forces hence the fluid boundary layer thickness increases and finally becomes undisturbed. As long as the viscous forces dominate the inertial forces, these disturbances are under control. The value of Reynolds number beyond which the flow is no longer considered laminar is called the critical Reynolds number. For the fluid flow over a flat plate, the critical Reynolds number is about 10^5.

1.3.2 Prandtl Number

Prandtl number (Pr) is defined as the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity. That is, Prandtl number is given as:

$$\mathrm{Pr} = \frac{\text{Momentum diffusivity}}{\text{Thermal diffusivity}} = \frac{\nu}{\alpha} = \frac{\mu c_p}{k} \qquad \text{... ... ... 1.22}$$

The variables $\boldsymbol{\mu}$, k and c_p represent dynamic viscosity, fluid thermal conductivity and fluid specific heat capacity at constant pressure respectively. Prandtl number is a characteristic of the fluid only since it is a grouping of the properties of the fluid. In heat transfer problems, Prandtl number controls the relative thickness of the momentum and thermal boundary layers. When Pr is small, it means that the heat diffuses quickly as compared to momentum. For most gases over a wide range of temperature and pressure, Prandtl number is approximately constant.

1.3.3 Grashof Number

This dimensionless number is associated with natural convection. It is analogous to Reynolds number in forced convection. Grashof number (Gr) is defined as the ratio of buoyancy forces to viscous forces acting on a fluid.

$$\mathrm{Gr} = \frac{\text{Buoyany forces}}{\text{Viscous forces}} = \frac{L^3 g\beta\Delta T}{\nu^2} \qquad \text{... ... ... 1.23}$$

The parameters L, g, β and ΔT, represent characteristic flow length, fluid viscosity, gravity, fluid (air) thermal expansion coefficient and temperature difference between the heated surface and that of ambient air respectively. When viscous forces are greater than buoyancy forces, the flow becomes turbulent and more efficient in carrying away heat. Low values of Grashof number implies low rate of convection heat loss from heated surface since viscous forces dominate buoyancy forces. Grashof number is only significant in still air in which natural convection occurs.

1.3.4 Nusselt Number

Nusselt number is a measure of the magnitude of convection heat transfer rate from the heated surfaces. Higher values of Nusselt number means that the convection heat transfer rate is high. In forced convection, Nusselt number is expressed in terms of wind-related heat transfer coefficient (h_w), characteristic flow length (L) and fluid thermal conductivity (k). Moreover, Nusselt number (Nu) is actually the ratio of convection heat to conducted heat.

$$\mathrm{Nu} = \frac{\text{Convected heat}}{\text{Conducted heat}} = \frac{h_w A_P \Delta T}{k A_P \Delta T / L} = \frac{h_w L}{k} \qquad \ldots\ldots\ldots\ldots\ldots 1.24$$

In natural convection, Nusselt number is a product of Grashof (Gr) and Prandtl (Pr) numbers.

$$\mathrm{Nu} = \gamma(\mathrm{GrPr})^n \qquad \ldots\ldots\ldots\ldots\ldots 1.25$$

However, in forced convection, Nusselt number is a product of Prandtl and Reynolds numbers.

$$\mathrm{Nu} = \gamma(\mathrm{RePr})^n \qquad \ldots\ldots\ldots\ldots\ldots 1.26$$

The constants γ and n in the equations 1.25, 1.26 and 1.27 depend on the flow type and parameters affecting wind-related heat transfer coefficient such as incident angle of wind onto the flat plate and plate geometry. When equation 1.24 and 1.26 are compared, wind-related heat transfer coefficient (h_w) becomes:

$$h_w = \frac{k}{L}\gamma(\mathrm{RePr})^n \qquad \ldots\ldots\ldots\ldots\ldots 1.27$$

1.4 Heat Transfer Modes from the Insulated Flat Plate

There are three modes of heat transfer namely convection, radiation and conduction. These modes of heat transfer are very important since they constitute the steady state energy balance equation which is used to evaluate convection heat transfer coefficient. In order to study convection heat transfer process using a properly insulated steel plate which is electrically heated to steady state, it is important to understand heat transfer by conduction and radiation explicitly. Treating conduction as one directional in the analysis, conduction heat loss through the insulator can be expressed as:

$$Q_k = k_i A_i \frac{T_{ii} - T_{ie}}{\delta} \quad \ldots\ldots\ldots\ldots\ldots 1.28$$

T_{ii}, T_{ie}, $\boldsymbol{\delta}$, k_i and A_i in the above equation represent the insulator internal temperature, insulator external temperature, thickness of an insulator, thermal conductivity of an insulator and area of the insulator in contact with heated steel plate respectively. Radiation heat loss from the solar energy collector plate is given by:

$$Q_r = \sigma A_p \frac{T_p^4 - T_o^4}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_o} - 1} \quad \ldots\ldots\ldots\ldots\ldots 1.29$$

T_p, T_o, $\boldsymbol{\varepsilon}_p$, $\boldsymbol{\varepsilon}_o$, A_p and σ represent the plate temperature, temperature of air above the heated plate, plate emissivity, emissivity of air above the heated plate, plate surface area exposed to both free and forced convection and Stefan-Boltzmann constant which is 5.669 x 10^{-8}W/m^{2}K^4 respectively. Forced convection/wind-induced heat loss from the top cover of solar energy devices is given by:

$$Q_{h_w} = h_w A_p (T_p - T_a) \quad \ldots\ldots\ldots..1.30$$

Moreover, free convection heat loss from the top cover of solar energy devices is given by:

$$Q_{h_o} = h_o A_p (T_p - T_a) \quad \ldots\ldots\ldots..1.31$$

In equation 1.30 and 1.31, the parameters h_w, h_o, A_P, T_p and T_a represent wind-related heat transfer coefficient, free convection heat transfer coefficient, plate surface area, plate wall temperature and ambient air temperature respectively.

1.5 Wind-Related Heat Transfer Coefficient

Wind-related heat transfer coefficient (h_w) is a measure of the rate of heat loss from the heated surfaces due to cooling effect of wind. When determining wind-related heat transfer coefficient, it is important to note that Reynolds number is varied by changing air velocity while incident angles of wind varied by changing the plate tilt angles relative to wind. By taking Prandtl number (Pr) and air properties such as conductivity (k), viscosity($\boldsymbol{\nu}$) and diffusivity (α) to be that of ambient air temperature range covered while basing the Nusselt (Nu) and Reynolds (Re) numbers on the plate length (L), wind-related heat transfer coefficient (h_w) becomes a strong function of air velocity (u) and incident angle of wind onto the plate ($\boldsymbol{\theta}_i$). In a moving air (h_w) is given by the equation below.

$$h_w = \frac{k\gamma}{L}(RePr)^n = \frac{k\gamma}{L}\left(\frac{uL}{\nu} \times \frac{\nu}{\alpha}\right)^n = (kL^{n-1}\alpha^{-n})\gamma u^n = t_n\gamma u^n = t_n f(\theta_i, u) \qquad \ldots\ldots 1.32$$

In equation 1.32, it is shown that wind-related heat transfer coefficient (h_w) is a polynomial equation of order (n). The equation 1.32 further shows that both n and h_w depend on the flow type (i.e. laminar or turbulent), incident angles of wind onto the plate ($\boldsymbol{\theta}_i$), air velocity (u), plate length (L), thermal air properties such as conductivity (k), viscosity($\boldsymbol{\nu}$) and diffusivity (α). Furthermore, the constant (t_n) in equation 1.32 is a grouping of the air properties at ambient air temperature range covered {i.e. $t_n = f(L, k, \alpha)\} = kL^{n-1}\alpha^{-n}$. The quantity γ is a function of angle of incidence of wind ($\boldsymbol{\theta}_i$) onto the plate {i.e. γ=f (θ_i)}. The value of γ varies with the angles of incidence of wind onto the plate. However, in a particular equation of the curve of (h_w) at say, $\boldsymbol{\theta}_i = \boldsymbol{\theta}^o$, γ = f (θ_i) is constant. In still air, thermal energy losses occur from the top cover of flat plate solar energy devices via free convection whose heat transfer coefficient is given by (h_o). In a natural environment, solar energy collector plates are exposed to cooling by free convection in still air and forced/wind-induced convection. To factor in thermal energy losses from the top cover of solar energy collector plate in still air via free convection, equation 1.32 would take this form:

$$h_w = h_o + \gamma t_n u^n \qquad \ldots\ldots\ldots\ldots 1.33$$

For a particular equation of the curve of (h_w) at $\boldsymbol{\theta}_i = \boldsymbol{\theta}^o$ when u > 0 m/s, both γ and t_n are constants and their product ($t_n\gamma$) is also a constant represented by (λ).) In equation 1.33 and 1.34, h_o represents convection heat transfer coefficient in still air. Since $t_n\gamma = \lambda$, equation 1.33 becomes:

$$h_w = h_o + \lambda u^n \qquad \ldots\ldots\ldots\ldots 1.34$$

To evaluate wind-related heat transfer coefficient (h_w), the steady state energy balance equation is applied on electrically heated square steel plate of side L= 0.125m. It is assumed that heat loss from the insulated plate occurs majorly through convection which is determinable by convection heat loss coefficient. Furthermore, conduction heat loss from the insulated plate is treated as one direction in the analysis as shown in Figure 3.2. Given that plate wall area (A_p) = $0.125^2 m^2$, electrical voltage (V) = 3.295V and electrical current (I) = 0.25A, the electrical energy absorbed by plate of wall area 0.125^2 m^2 per unit time becomes $VI = 3.295V \times 0.25A = 0.82375W$. Electrical energy absorbed by the plate wall of a unit area per unit time would therefore, become:

$$0.125^2 \mathrm{m}^2 = 0.82375\mathrm{W}$$

$$\therefore 1\mathrm{m}^2 = \frac{1\mathrm{m}^2 \times 0.82375\mathrm{W}}{0.125^2\mathrm{m}^2} = 52.72\mathrm{W} \qquad \ldots\ldots\ldots\ldots 1.35$$

The Total heat lost by plate of wall area 0.125^2 m^2 per unit time through conduction (Q_k) and radiation (Q_r) is given by ($Q_k + Q_r$). Therefore, for a given plate wall of a unit area, conduction and radiation heat losses per unit time would become:

$$0.125^2 \mathrm{m}^2 = (\mathrm{Q_k} + \mathrm{Q_r})\mathrm{W}$$

$$\therefore 1\mathrm{m}^2 = \frac{1\mathrm{m}^2(\mathrm{Q_k} + \mathrm{Q_r})\mathrm{W}}{0.125^2\mathrm{m}^2} = 64(\mathrm{Q_k} + \mathrm{Q_r})\mathrm{W} \qquad \ldots\ldots\ldots\ldots 1.36$$

Heat lost by plate wall of area 0.125^2 m^2 per unit time through convection (Q_{h_w}) is given by $h_w A_p\left(T_p - T_a\right) = 0.125^2 h_w\left(T_p - T_a\right)$. Therefore, for a plate wall of a unit area, convection heat loss per unit time would become:

$$0.125^2 \mathrm{m}^2 = 0.125^2 \mathrm{h_w}\left(\mathrm{T_p} - \mathrm{T_a}\right)\mathrm{W}$$

$$\therefore 1\mathrm{m}^2 = \frac{1\mathrm{m}^2\{0.125^2 \mathrm{h_w}\left(\mathrm{T_p} - \mathrm{T_a}\right)\}\mathrm{W}}{0.125^2\mathrm{m}^2} = \mathrm{h_w}\left(\mathrm{T_p} - \mathrm{T_a}\right)\mathrm{W} \qquad \ldots\ldots\ldots 1.37$$

In steady state condition, the electrical energy absorbed by plate wall of a unit area per unit time is equal to the sum of heat losses from the plate wall of a unit area per unit time through conduction, radiation and convection. Putting together equation 1.35, 1.36 and 1.37, the steady state energy balance equation 1.38 is obtained and wind-related heat transfer coefficient (h_w) is determined.

$$52.72\mathrm{W} = 64(\mathrm{Q_k} + \mathrm{Q_r})\mathrm{W} + \mathrm{h_w}\left(\mathrm{T_p} - \mathrm{T_p}\right)\mathrm{W}$$

$$\therefore \mathrm{h_w} = \frac{52.72 - 64(\mathrm{Q_k} + \mathrm{Q_r})}{\mathrm{T_p} - \mathrm{T_a}} \qquad \ldots\ldots\ldots 1.38$$

The parameters T_p and T_a in equation 1.37 and 1.38 represent temperatures of plate wall and ambient air respectively.

1.6 Problem Statement

For many years, man has used conventional energy sources to power homes and industries. Global warming and environmental pollution have resulted from the emitted greenhouse gases thereby endangering the lives of plants and animals. One of the green energy technologies to be relied on is solar energy (both PV cells and thermal energy collectors). However, the performance of these devices is much affected by the conditions of the surrounding in which they are operating such as the cooling effect of air which lowers thermal energy output of solar thermal energy collectors and heating effect of solar radiation which lowers the performance of solar PV energy collectors. The optimal temperature of solar panels is 25^{o}C. Beyond this temperature, panel heating occurs leading to a decline in power generation efficiency. Variation in operating temperature with sunlight intensity influences the output current and voltage of the solar PV cells. An increase in temperature of the solar PV panel leads to an exponential increase in output current and a linear decrease in output voltage as suggested by Notton et al. (2005), Cindy and Demand (2010) and Katkar et *al*. (2011). Solar PV cell performance decreases with increasing temperature owing to increased internal carrier recombination rates caused by increased carrier concentrations. Photovoltaic conversion process/ability to draw energy from the sun declines. The cooling effect of air on solar PV panel increases their performance since it leads to improved photovoltaic conversion process.

Another problem faced by solar energy devices is the variation of solar radiation throughout the day with the changing position of the sun relative to solar energy collector. This affects the amount of solar radiation incident on these plates yet for their optimal operation, maximum solar radiation is needed. To overcome these challenges, there is need to determine optimum angle of orientation of solar energy devices in order for solar PV panels to absorb maximum solar radiation and at the same time experience much cooling effect of air to improve their performance. Likewise, there is need for solar thermal energy collectors to absorb maximum solar radiation but experience minimum cooling effect of air to improve their performance. Optimum angle of orientation is therefore, important and can be determined through studying and understanding the effects of air velocity, incident angle of air-flow relative to collector plate and temperature variation with solar radiation intensity on the performance of flat plate solar energy collectors. Finally, unified expression of h_w for the full possible range of incident angles of wind onto the plate from 0^{o} to 90^{o} is still lacking in the available literature and therefore, was to be determined by the current study.

1.7 Objectives of the Study

1.7.1 Main Objective

i. To investigate the cooling effect of air with a view to improving the performance of flat plate solar energy collectors.

1.7.2 Specific Objectives

i. To determine the dependence of wind-related heat transfer coefficient (h_w) on angle of incidence of wind (θ_i) onto the flat plate solar energy collectors.

ii. To develop a single expression of wind-related heat transfer coefficient (h_w) for the full possible range of angles of incidence of wind (θ_i) onto the flat plate solar energy collectors from 0^o to 90^o.

1.8 Significance and Justification of the Study

The cooling effect of air is of great significance in science and engineering applications as well as in a wide variety of natural circumstances such as passive solar heating as in energy conservation buildings, cooling of commercial high voltage electrical transformers, cooling of electronic devices such as chips and transistors by finned heat sinks, passive cooling of reactor core in nuclear power plants, dry cooling towers, ground thermo-siphons, heat exchangers, heating houses by electrical baseboard heaters and cooling of photovoltaic solar panels. Furthermore, in order to increase the lifespan and at the same time improve the performance of solar PV panels, cooling effect of air on them is highly needed. Conversely, solar thermal air driers and water heaters would work optimally at relatively high temperatures and hence do not need the cooling effect of air which lowers their performance in terms of thermal energy losses. The determined values of (h_w) under different conditions would lead to suggesting an arrangement for optimum performance of flat plate solar energy devices and formulating an equation for determining optimum performance of these devices. Consequently, the policy makers on renewable energy upon adopting the results of this study shall fully exploit solar energy technologies to sustain the economic growth and developments, reduce environmental pollution and global warming caused by conventional fuels. For instance, an extension of this study in passive solar design in green energy conservation buildings shall effectively reduce a building's energy demands for lighting, winter heating and summer cooling. No additional investments in mechanical and electrical devices such as pumps and electrical fans for forced cooling in summer seasons will be needed. Consequently, this shall reduce heating, cooling bills of homes and emission of greenhouse gases which cause global warming. Furthermore, insecurity in market places and streets would be reduced by a well installed solar powered flood lights.

1.9 Limitations, Remedies and Study Assumptions

1.9.1 Limitations of the Study

In the course of maintaining steady power supply through frequent adjustment of the voltage and current by using a variac, input power loss occurred. Consequently, this caused some error in the determined convection heat transfer coefficient. The uncertainties in temperature readings caused some error in the determined convection heat transfer coefficient. Conductive heat loss through insulation and radiation heat loss from the plate surface account for some input power loss and hence this resulted into minimum error in determining the convection heat transfer coefficient.

1.9.2 Minimization of Error

Errors in power supply and temperature readings were found to be ± $0.5W/m^2K$ and ± 0.1^oC respectively. Error in power supply was minimized through frequent adjustment of the voltage and current by using a variac in order to maintain steady power supply. Error in temperature readings was minimized by ensuring uniform temperature distribution on the plate by careful embedment of the heater at the back of insulated plate using thermal contact cement. Thermocouples were evenly spaced and firmly fixed on the insulator and the steel plate to ensure full exposure to wind and reduce error margin in temperature reading. All the experimental data were collected and recorded when the plate was at steady-state condition. Radiation and conduction heat losses from the heated plate were reduced using shiny aluminum foil and a 0.05m thick Styrofoam insulator respectively.

1.9.3 The Assumptions

Heat loss from the energy absorber plate occurred majorly by means of convection which could be determined by a convective heat loss coefficient. Conduction heat losses from the plate at steady-state condition, was treated as one directional in the analysis. Prandtl number and air properties such as thermal conductivity (k), thermal diffusivity (α) and viscosity ($\boldsymbol{\nu}$) were taken as that of ambient air temperature range covered at one atmosphere pressure while the Nusselt and Reynolds numbers were based on plate length (L). In steady state condition, the amount electrical energy absorbed by the plate wall of a unit area per unit time was equal to the amount of heat lost from the absorber plate of a unit wall area per unit time through conduction, radiation and convection.

CHAPTER TWO

LITERATURE REVIEW

Literature review was done to compare the reliability and sustainability of other existing methods of cooling of solar PV energy collectors with air. In this study, cooling by natural air circulation was found to be most suitable due to its reliability, sustainability, eco-friendliness.snd ability to be enhanced using fins among other methods. The existing literature on correlations/expressions of wind-related heat transfer coefficient was also reviewed to identify the knowledge gaps.

2.1 Methods of Cooling Solar PV Energy Collectors

Tonui and Tripanagnostopoulos (2008) worked on methods of cooling PV panels with different approaches like forced convection by pumps and fans, circulating water, combining PV and solar thermal collectors. To make matters worse, these stated methods of cooling PV panels are faced with many challenges for instance; the dependence on electrical fans and conventional fuels for cooling is relatively expensive. Moreover, conventional fuels are environmental pollutants, emitters of greenhouse gases and most importantly the cause of global warming. Moreover, cooling by circulating water is unsustainable since continuous supply of water and pumping mechanisms are needed. Natural air circulation is therefore, the simplest, cheapest, most effective and natural method that provides an acceptable level of cooling solar PV cells as reported by Edenburn (1980), Incropera *et al.* (2012) and Oosthuizen and Kalendar (2013). However, in previous studies, cooling by natural air circulation (wind) was never considered since its significance in science and engineering applications was probably unknown in areas like heat exchangers, cooling of electronic devices like transistors and integrated circuits (IC) using heat sink. Natural air circulation is a convection heat transfer process which is complicated by the fact that it involves fluid motion as well as heat conduction. Moreover, convection heat transfer is a complex process due to the many parameters involved in its study such as plate geometry, flow type, plate tilt angle relative to the fluid flow, temperature dependent air properties, fluid velocity, gravity, area of the surface exposed the surrounding. All these parameters must be grouped using dimensionless numbers such as the Nusselt, Reynolds, Prandtl and Grashof in order to study heat transfer process by convection. Mathematical complexity of convection heat transfer as traced to the non-linearity of the Navier-Stokes equations of motion and the coupling of flow and thermal fields might have discouraged many researchers in pursuing this field of study.

2.2 Convection Heat Transfer Enhancement Methods

To enhance heat extraction by convection, some heated surfaces have been fitted with fins. Fins increase surface area of heat transfer by providing good thermal conduction between the PV cells thereby spreading heat and dissipating it passively via convection according to Araki *et al.* (2002), Incropera *et al.* (2012) and Oosthuizen and Kalendar (2013). An increase in fin density increases collector heat removal factor as reported by Chand and Sharma (2012). Moreover, modification of fins by use of dents of different patterns and forms has further increased collector heat removal factor according to Al-Essa and Al-Hussien (2004), Alzway and Paul (2014), Elshefai (2010), Mohamed et *al.* (2012), Sahin and Demir (2008) and Zan Wu *et al.* (2012). Besides modifying heat transfer surfaces, an inclination of heat transfer surfaces has proved to be very simple and effective way of further enhancing collector heat removal factor from heated plates as reported by Rathby and Hollands (1984), Eramia et *al.* (2014) and Bejan (2004), yet this has never been fully exploited. Therefore, a modified inclined heat transfer surface relative to natural horizontal air-flow would prove to be very efficient in collector heat dissipation as suggested by Tiwari and Malhotra (2013). A study conducted by Rahman and Sharif (2013) revealed that wind-induced transfer rate on an inclined plate was very sensitive to the change in collector tilt angle as air velocity increased. They established that wind-related heat transfer rate strongly depended on plate tilt angle relative to wind. Moreover, the available literature has revealed that an increase in the velocity of air further enhanced heat extraction rate from tilted heated surfaces relative to horizontal air-flow (Holman, 1997; Othieno, 1985; Wang, 1982). With regard to this, optimization of solar energy collector tilt angles relative to wind and solar radiation is a sure way of achieving maximum performance of flat plate solar PV and thermal energy collectors.

2.3 Wind-Related Heat Transfer Coefficient and its Expressions

The dependence of wind-related heat transfer coefficient (h_w) on air velocity and incident angle of wind onto flat plate had been investigated by Othieno (1985), Test et *al.* (1981), Sparrow et *al* (1979), Mass *et al.* (1979), Watmuff et al. (1977), Sparrow and Tien (1977), Ramsey and Charmchi (1977), Churchill and Chu (1975), Duffie and Beckmann (1974) and Mc Adam (1954). However, the available literature still reveals some gaps on the proposed expressions of wind-related heat transfer coefficient especially on the dependence of wind-related heat transfer coefficient (h_w) on solar energy collector tilt angles (θ_p)/incident angles of wind onto the surface of flat plate solar energy collector. Comparative analysis of the available literature on expressions of wind-related heat transfer coefficient (h_w) literally shows that the suggested expressions still have some knowledge gaps that ought to be addressed. For instance, equations of wind-related heat transfer coefficient reported by Sparrow and Tien (1977), Sparrow et *al* (1979), Duffie and Beckmann (1980) assumed a zero convection heat transfer coefficient in still air. But as stated, this is not true since solar energy collectors will lose heat from their top covers by natural convection under such conditions according to work of Othieno (1985).

Furthermore, some expressions of (h_w) reported by Sparrow and Tien (1977) and Sparrow *et al.* (1979) were obtained with unreasonably low Reynolds numbers not exceeding 10^5. Within this range of Reynolds numbers, the velocity of air would be less than 2 m/s hence the dependence of (h_w) on plate tilt angle relative to wind could not be observed or rather distinguished. Consequently, it was wrongly assumed that even at higher wind speed than 2 m/s, wind-related heat transfer coefficient does not depend on the collector tilt angle. The equations of wind-related transfer coefficient (h_w) reported by Test et *al.* (1981),Watmuff et al. (1977) and Mc Adam (1954) did not specify the dependence of (h_w) on (θ_i) and therefore proposed that (h_w) was a linear function of air velocity. The dependence of h_w on plate tilt angle (θ_P) relative to wind or rather incident angle of wind (θ_P) onto the plate is significant and should be considered whenever accurate data are necessary. Mc Adam (1954) expressed wind-related heat transfer coefficient (h_w) for a vertical plate relative to wind in the form below:

$$h_w = 5.7 + 3.8u \qquad \ldots\ldots\ldots\ldots\ldots 2.1$$

Similarly, Watmuff *et al.* (1977) proposed a linear expression of wind-related heat transfer coefficient (h_w) in terms of air velocity (u) m/s for plate tilted at 30^o relative to wind (i.e. $\theta_i = 60^o$) of the form:

$$h_w = 2.8 + 3.0u \qquad \ldots\ldots\ldots\ldots\ldots 2.2$$

Nevertheless, (Test et *al.,* 1981) also suggested linear expression of (h_w) in terms of air velocity (u) m/s for a plate tilted at 40^o (i.e. $\theta_i = 50^o$) relative to horizontal air-flow in this form:

$$h_w = 8.55 + 2.56u \qquad \ldots\ldots\ldots\ldots\ldots\ldots 2.3$$

Quite surprisingly, Othieno (1985), Wang (1982), Green et *al*. (1981**),** Duffie and Beckmann(1980), Sparrow and Tien (1977) and Sparrow et *al.* (1979) had cautiously doubted the linear relationship between wind-related heat transfer coefficient (h_w) and air velocity and therefore, proposed nonlinear expressions of h_w for various tilt angles (θ_p) of the flat plate solar energy collector relative to wind. For instance, Othieno (1985) in his proposed general expression of h_w in equation 2.4 noticed that the curves of heat transfer coefficient (h_w) are nonlinear when plate tilt angle (θ_p) is above 40^o relative to wind of velocity $u \geq 10$ m/s. Nevertheless, the value of n in Re^n began to change in his proposed equation (2.4) where the constants c and n in his general expression of h_w depended on the plate tilt angle relative to wind. The constants k and L in equation 2.4 represented thermal conductivity of air and characteristic flow length respectively while Re represented the Reynolds number.

$$h_w = \frac{k}{L}(75 + cRe^n) \qquad \text{... ... ... 2.4}$$

The assumption that wind-related heat transfer coefficient is insignificant of the plate tilt angles both at relatively low and relatively high wind speeds overwhelmingly led to discrepancies on the computed values of (h_w). For example, expression of (h_w) reported by Duffie and Beckmann (1980) gave high values of (h_w) when air velocity above 2m/s was incident on a horizontal plate. Moreover, the expression of h_w reported by Watmuff et al. (1977) also gave high values of (h_w) when air whose with speed above 12m/s flew over a plate tilted at 30^o relative to wind ($\theta_i = 60^o$). Furthermore, the general trend of the equations of (h_w) was never known at very high air velocity since most of the investigations were done at relatively low air velocity as reported in the work of Sparrow and Tien (1977) and Duffie and Beckmann (1980). Most importantly, at an air speed greater than 10 m/s, Othieno (1985) noticed a change in the value of the constant, n, in Re^n in his proposed general expression of (h_w) in equation 2.4 when $\theta_P \geq 40^o$. Unfortunately, Othieno (1985) performed his investigations within air velocity ranging from 0 m/s to 10 m/s and hence failed to find the cause of change in the value of the constant, n, in Re^n when $u > 10$ m/s, his proposed equation 2.4 when $\theta_P \geq 40^o$. Othieno (1985) rather proposed an extrapolation of curves of heat transfer coefficient (h_w) as a way of estimating magnitudes of heat transfer coefficient at high air velocity especially beyond 10 m/s. However, this led to overestimated values of (h_w) especially at high air velocity as revealed in some of his reported equations for incident angles of wind such as 70^o to 90^o as shown in Table 5.2. In respect to this, one would wonder whether the curves of wind-related heat transfer coefficient diverge or converge when $u > 10$ m/s.

Moreover, the available literature has not revealed whether peak values of (h_w) exist at a certain air velocity for every solar energy collector tilt angles relative to the wind or not, yet the trend of the correlations of (h_w) is vital in explaining the unusual behavior of Nusselt number in which (h_w) decreases with increasing Reynolds number as reported by Tune et al. (2000). Most importantly, comparative analysis of the previous literature has established that the already existing expressions of (h_w) are only meant for the specific collector tilt angles relative to the horizontal air-flow according to Othieno (1985), Wang (1982), Grainger (1982), Sparrow and Tien (1977), Ramsey and Charmchi (1977) and Mass *et al. (*1979). However, a single expression of wind-related heat transfer coefficient (h_w) which specifies the dependence of (h_w) on the incident angles of wind (θ_i) by use of quantity which varies with (θ_i) or plate tilt angles relative to wind has not been developed. Furthermore, a single expression of wind-related heat transfer coefficient (h_w) which encompasses the full possible range of incident angles of wind ($0^o \leq \theta_i \leq 90^o$) is lacking in the already available literature. Nevertheless, with all these discrepancies noted in the available literature, the correlations of (h_w) have been used in solar energy technology without satisfactory justification. In order to address the identified gaps in the available literature, the study objectives were experimentally investigated in Maseno University Physics laboratory.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Physical Model Description

Chapter three focuses on the description of the physical model and research methodology used to achieve the study objectives. To start with, the data collection method for the experimentally designed study was through direct measurement using suitable equipment described in this chapter. The current study applied a steady state energy balance equation to evaluate convective heat transfer coefficient in terms of constant electrical heat flux, radiation, conduction and convection heat transfers per unit area of the plate. Furthermore, dimensionless numbers such as Nusselt, Reynolds and Prandtl numbers were applied to study convection heat transfer. The study was conducted using square steel plate which was painted black to enhance heat absorption and emission ability. To ensure good thermal contact and uniform heating of the plate, the electrical heater was glued on the back of the flat plate using good thermal contact cement while the back side of the heater was placed on the polished surface of aluminum foil in order to reduce radiation heat loss. The assembly of the steel plate, heater, and aluminum foil was effectively insulated at the back and sides by a 0.05m thick Styrofoam insulator of low thermal conductivity of 0.029W/mK to reduce conductive heat energy losses to an insignificant level.

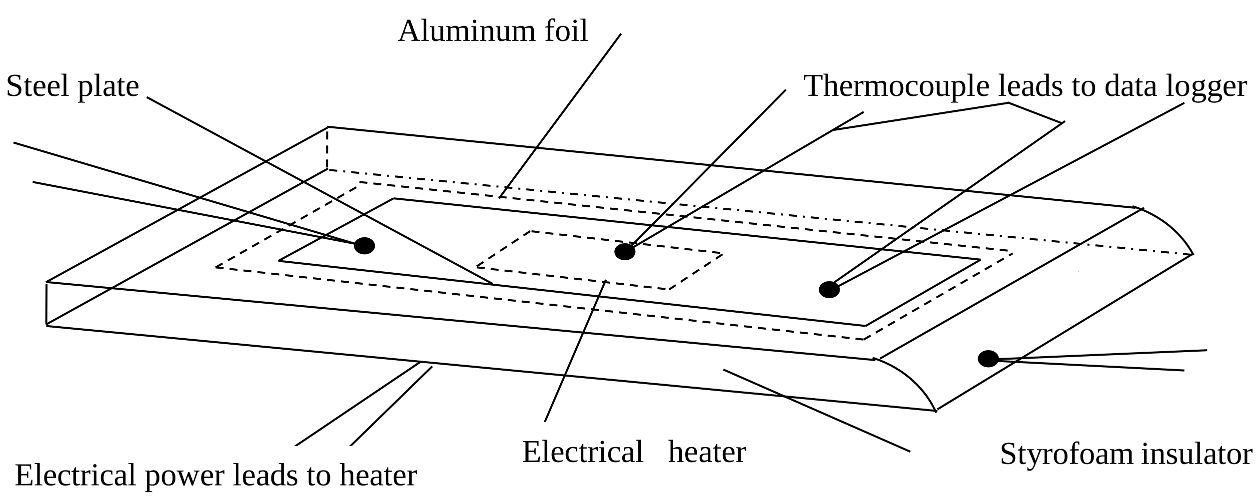

Figure 3.1: The assembly of Steel Plate, Heater and Insulation

The top surface of the steel plate was exposed to convective heat loss, whose heat transfer coefficient was determined based on the parameters such as plate tilt angle relative to horizontal air-flow / incident angle of air-flow onto the plate surface, air velocity and properties of air at one atmospheric pressure. The leading edge of the Styrofoam insulator was shaped like a wedge to reduce flow separation and blockage when the plate was horizontally positioned relative to horizontal air flow. The incident angle of horizontal air-flow relative to the plate surface was varied with plate tilt angle from 0^o to 90^o in a wind tunnel where air of different constant velocities was set. In order to obtain reliable data on velocity of air at the test section**,** Thermo-anemometer (Velocity Calc.) model 8357 TSI was used to measure the velocity of air in the wind tunnel at the test section. The insulated steel plate was then supplied with a constant electrical heat flux. To ensure steady heat flux to the plate, the electrical power supply to the heater was controlled by avariac as shown in Figure 3.2 below.

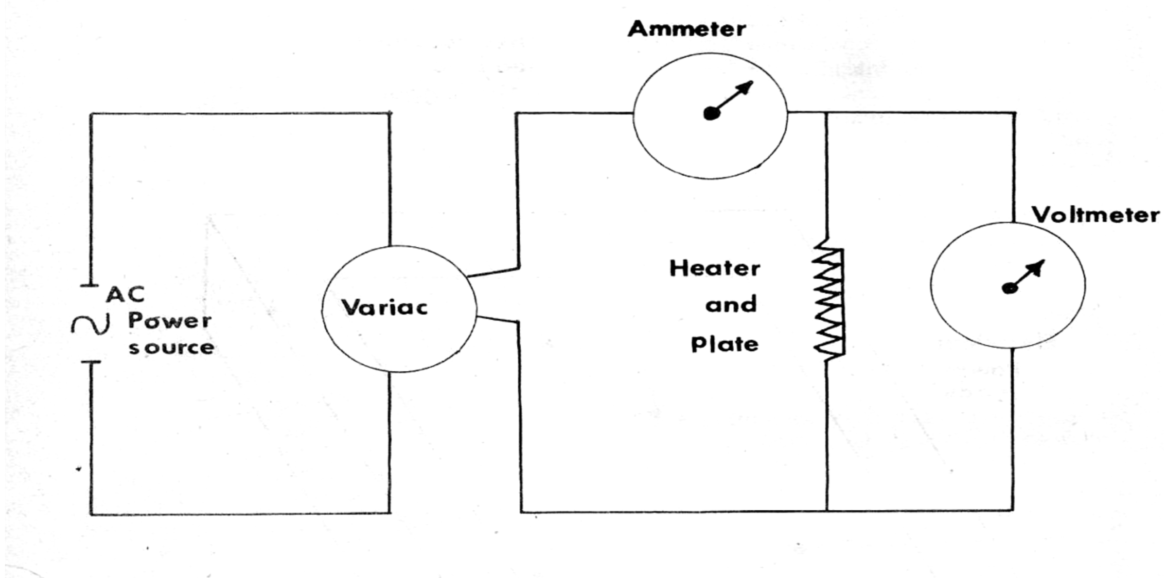

Figure 3.2: Electrical Power Supply Circuit

Temperature of the plate and insulating material was measured by 24 gauge copper-constantan thermocouples which were embedded and glued on the grooves made on both the plate and the Styrofoam insulator and then recorded by a digital data logger model Fluke-2286 A supplied by John Fluke MFG.CO., in U.S.A at steady-state condition. Concurrently, temperature of the ambient air was also measured and recorded by the same type of thermocouples and data logger respectively. The Prandtl number and temperature dependent air properties such as thermal conductivity, thermal diffusivity and viscosity were taken to be that of air at ambient temperature range covered. The study was conducted for wide range of constant air velocities. Electrical circuit analogue of heat transfer process shown in Figure 3.3 was used to identify heat transfer components such as conductive thermal resistance (R_k), radiation thermal resistance (R_r), convective thermal resistance (R_h), plate temperature (T_p), ambient air temperatures (T_a), temperature of air above the heated plate, (T_o), insulator's inner temperature (T_{ii}), insulator's external surface temperature (T_{ie}), electrical current (I) and electrical voltage (V). To ease work, all the data used in calculation were recorded when the plate was at steady state condition.

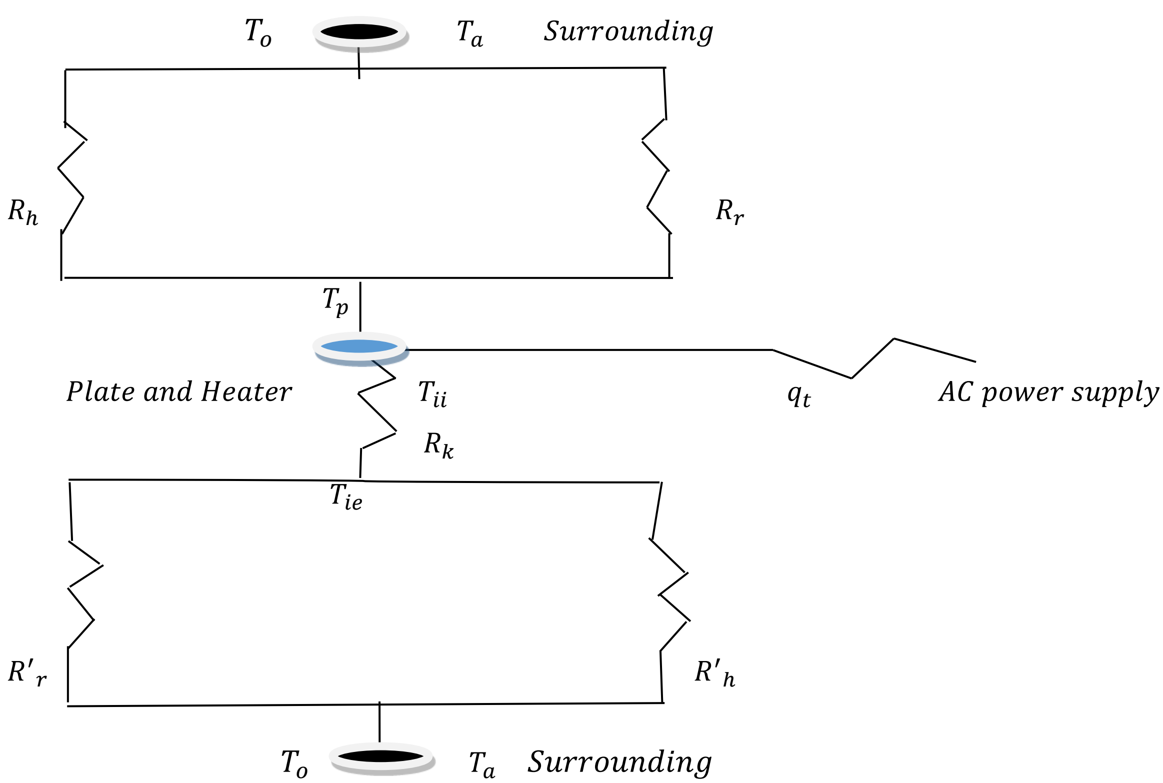

Figure 3.3: Electrical circuit analogue of heat transfer process

3.2 Research Methods

According to this study, the research method was quantitative while research design was experimental. The assembly of square steel plate, electrical heater, aluminum foils and insulating material as shown in Figure 3.1 was placed in a wind tunnel which was assembled in Maseno University Physics laboratory as shown in Figure 3.4. The assembled system in Figure 3.4 was further connected to data logger, power supply, air velocity calculator as shown in Figure 3.5**.** The plate dimensions were carefully chosen to minimize the wind tunnel blockage with an aim of keeping the back pressure at a low level. Air stream of constant velocity was set to move inside the wind tunnel via air blower (i.e. an electrical fan) positioned at one end of the tunnel which was far from the test section. To obtain the required air velocity, the air velocity control for the wind tunnel was designed to slowly change the pitch of the fan blades. To further obtain the required reliable air velocity result, Thermo-anemometer (Velocity Calculator) model 8357 TSI was used to measure the velocity of the oncoming horizontal air-flow at the test section. The incident angle of the oncoming horizontal air-flow was varied by tilting the insulated plate from 0^o (horizontal) to 90^o (vertical) on its axis of rotation where a turning handle was fixed. The pointer attached at one end of the insulator was moved along the scales of a wooden protractor from 0^o (horizontal) to 90^o each time horizontal air stream of a constant velocity was set.

For each incident angle of horizontal air-flow of a constant velocity set, the plate was electrically heated at the bottom by a constant heat flux supplied by the electrical heater to steady-state condition. The plate was properly insulated at its bottom and sides by 0.05m thick Styrofoam insulator of a low thermal conductivity of 0.029WmK. Heat loss through radiation was minimized by mounting both the plate and the heater on the polished surface of aluminum foil placed inside a 0.05m thick Styrofoam insulator. In order to ensure steady heat flux to the plate with a view to minimizing error in power supply, the electrical power supply to the heater was frequently controlled by avariac. The temperature of the plate was taken at steady state at an equal interval of time along the direction of air flow by 24 gauge copper-constantan thermocouples carefully glued in the grooves on the plates by thermal contact cement in order to maintain steady temperature on the plate. The temperatures were measured by thermocouples then recorded by digital data logger model Fluke-2286A by John Fluke MFG.CO., in U.S.A. Thermocouples were carefully aligned on the plate to ensure that each thermocouple junction did not disturb the air flow around each other. Moreover, temperature of the insulator and surrounding air were also measured simultaneously by thermocouples. By taking the Prandtl number and temperature dependent air properties such as thermal conductivity(k), thermal diffusivity (α) and viscosity($\boldsymbol{\nu}$) to be that of air at ambient temperature range covered at one atmosphere while basing the Nusselt and Reynolds numbers on plate length (L), the dependence of wind-related heat transfer coefficient (h_w) on incident angles of wind onto the flat plate was experimentally investigated in a wind tunnel assembled in Maseno university laboratory as shown in Figure 3.4 and 3.5. Electrical circuit analogue of heat transfer process shown in Figure 3.3 was used to identify heat transfer components such as radiation thermal resistance (R_r), conductive thermal resistance (R_k), convective thermal resistance (R_h), plate temperature (T_p), ambient air temperatures (T_a), surrounding surface temperature of the plate (T_o), insulator inner temperature (T_{ii}), insulator external surface temperature (T_{ie}), electrical current (I) and electrical voltage (V). To ease work, all that used in calculation were recorded when the plate was at thermal equilibrium state or steady state condition assuming that conductive heat losses from the plate at steady-state condition was in one direction only. The experiment was repeated four times with the same plate subjected to constant heat flux under the influence of horizontal air-flow of different constant velocities to minimize error and finally research data were recorded by suitable equipment shown in Figure 3.5.

The key dimensionless numbers such as the Nusselt, Prandtl and Reynolds numbers were correlated by $Nu = \gamma\ (RePr)^n$ to help come up with a single expression of wind related heat transfer coefficient as a function of air velocity and plate tilt angles/ incident angles of wind relative to the heated surface of the plate. Several graphs showing the relationship between wind-related heat transfer coefficient with air velocity and incident angles of horizontal air-flow were plotted using OriginPro application and descriptively analyzed to help determine the optimum plate tilt angle relative to wind for mounting the flat plate solar energy collectors to optimize their performance in the real environment dominated by wind and solar radiation. Graphs of wind-related heat transfer coefficient versus air velocity yielded several equations of heat transfer coefficient for various incident angles of wind onto the plate (θ_i). Most importantly, a single expression of (h_w) for the full possible range of the incident angles of wind onto plate from 0^o to 90^o was determined and compared with those available in literature as illustrated in Table 5.2. The determined expression of (h_w) would be adopted ultimately by the policy makers on renewable energy to upgrade solar energy technologies which have been applied without satisfactory justification. Moreover, the steady-state temperature of the electrically heated plate was influenced by incident angle of wind and magnitude of air velocity. The lowest steady-state temperature of the collector indicated the occurrence of rapid heat transfer rate from the collector and therefore, such like condition was considered appropriate for optimal operation of solar PV cells. On the other hand, the highest steady-state temperature attained by the plate was therefore, considered ideal for the optimal operation of solar thermal energy collectors because of very low convective heat transfer rate occurrence. Assuming that heat loss from the properly insulated heat energy absorber plate was transferred majorly by means of convection, wind-related heat loss coefficient was determined from the data obtained from the study conducted using the steady state energy balance equation1.38.

Figure 3.4 below shows an assembly of wind tunnel, blower and plate inside Maseno University Physics Laboratory.

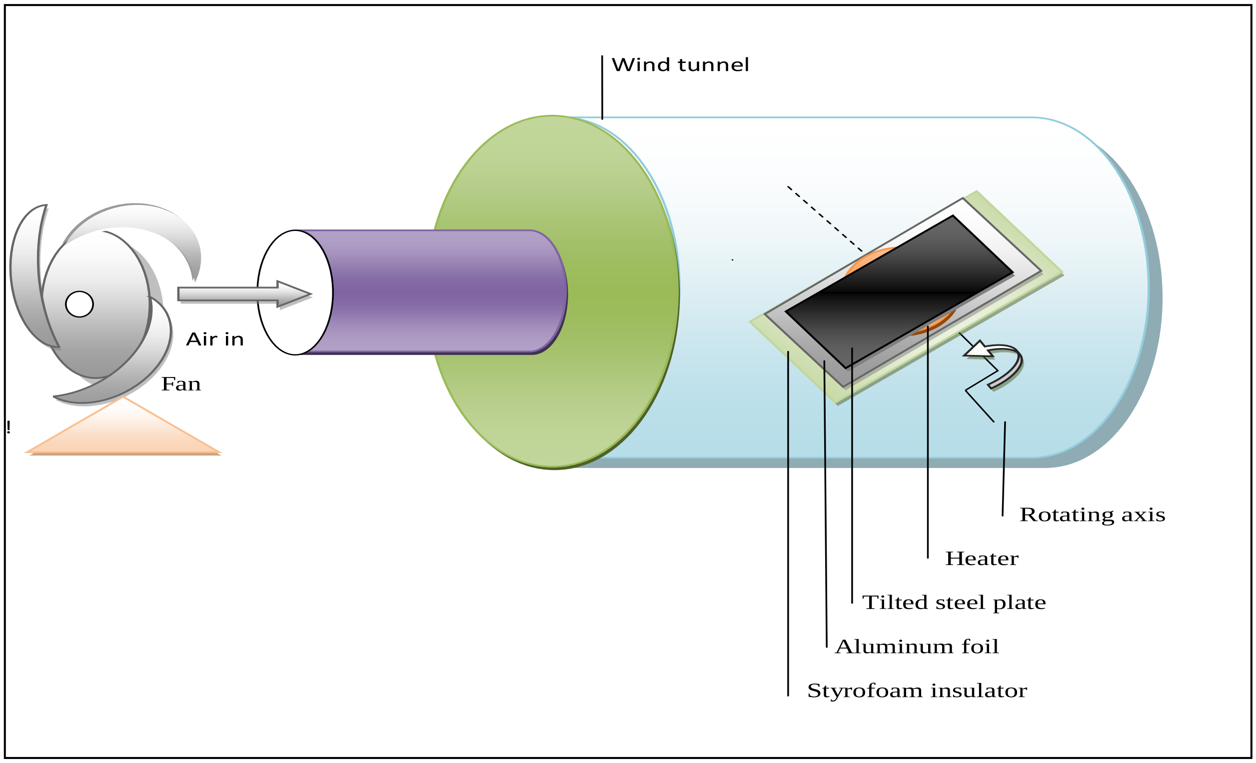

Figure 3.4: Wind tunnel, blower and plate assembly

Figure 3.5 below shows an experimental set-up for this study inside Maseno University Physics Laboratory.

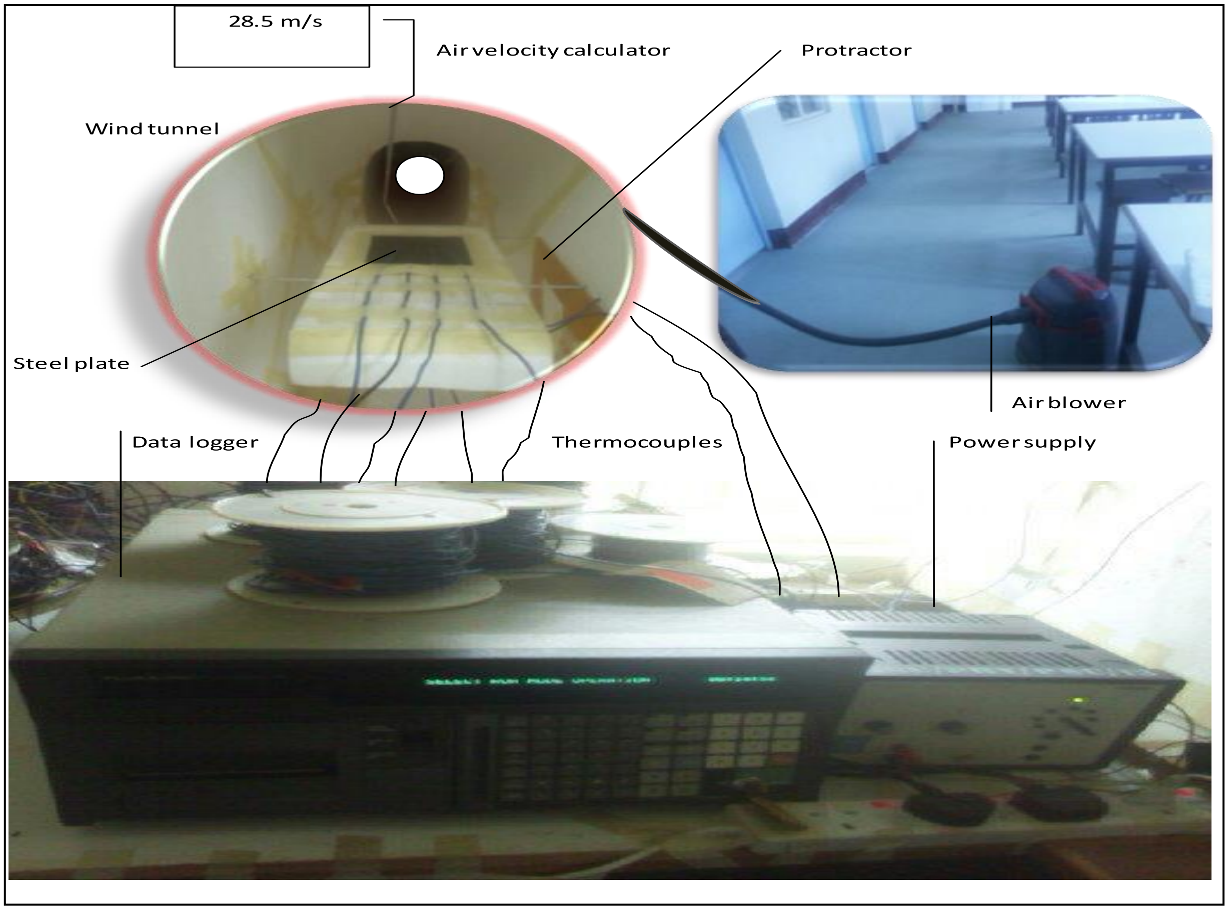

Figure 3.5: Experimental set-up

CHAPTER FOUR

RESULTS

4.1 Introduction

Chapter four focuses on the results of the study obtained from the investigation of the cooling effect of air on flat plate solar energy collectors and the dependence of wind-related heat transfer coefficient on the magnitude of air velocity and incident angle of wind on to the collector for the study conducted in a wind tunnel using a properly insulated square steel plate of side 0.125m. The tilted plate was supplied with constant heat flux to steady-state condition when subjected to horizontal air-flow of different constant velocities ranging from 0 m/s to 28.5 m/s. The following data on temperature were recorded: Plate wall temperature (T_p), plate surrounding surface temperature (T_o), ambient air temperature (T_a), internal temperature of an insulator (T_{ii}) and external temperature of an insulator (T_{ie}). Prandtl number and air properties such as thermal conductivity (k), thermal diffusivity (α) and viscosity ($\boldsymbol{\nu}$) were taken as that of ambient air temperature range covered at one atmosphere while basing the Nusselt and Reynolds numbers were based on the plate length. The dimensionless numbers associated with this study are Nusselt (Nu), Prandtl (Pr) and Reynolds (Re) whose correlation given by $Nu = \gamma\ (RePr)^n$ links wind-related heat transfer coefficient (h_w) with air velocity (u), incident angle of wind (θ_i), plate tilt angle (θ_p), plate length (L) and air properties at film temperature. The results of the study obtained for different incident angles of wind of various constant velocities ranging from 0 m/s to 28.5 m/s onto the plate were recorded in Table 4.1. The values of conduction heat loss (Q_k) radiation heat loss (Q_r) and wind-related heat transfer coefficient (h_w) in Table 4.1 were calculated from the equations 1.28, 1.29 and 1.38 respectively.

Table 4.1 below shows data collected on the effect of temperature, incident angle of wind (θ_i) and air velocity (u) on (h_w) over the ambient air temperature range covered at one atmosphere pressure.

Table 4.1: Effect of temperature, incident angle of wind (θ_i) and air velocity (u) on (h_w)

u (m/s)	θ_i°	T_P (°C)	T_a (°C)	$\Delta T = (T_P - T_a)$ (°C)	T_o (°C)	T_{ii} (°C)	T_{ie} (°C)	Q_k(W)	Q_r(W)	h_w (W/m²K)
0.0	90	48.1	28.5	19.6	41.6	50.9	29.1	0.198	0.002	2.04
	60	48.2	27.9	20.3	41.3	48.2	28.1	0.182	0.002	2.02
	30	49.3	28.8	20.5	41.0	48.5	28.6	0.180	0.003	2.00
	0	49.9	29.6	20.3	41.1	48.4	28.8	0.178	0.003	2.03
2.0	90	31.5	26.8	4.7	27.1	45.9	27.1	0.170	0.004	8.85
	60	31.8	27.1	4.7	27.5	46.3	27.5	0.170	0.000	8.90
	30	30.9	26.1	4.8	26.7	45.5	26.4	0.173	0.000	8.68
	0	31.8	26.8	5.0	29.5	45.7	27.4	0.166	0.004	8.37
4.0	90	29.8	27.2	2.6	27.2	43.2	27.3	0.144	0.000	16.73
	60	29.9	27.0	2.9	27.3	43.4	27.1	0.148	0.000	14.91
	30	29.8	26.6	3.2	27.3	43.4	27.0	0.149	0.000	13.50
	0	30.2	26.7	3.5	27.4	43.5	26.8	0.151	0.000	12.30
6.0	90	31.0	29.0	2.0	29.3	42.9	29.0	0.126	0.000	22.33
	60	30.7	28.3	2.4	29.0	42.8	28.5	0.130	0.000	18.50
	30	30.6	28.1	2.5	29.0	42.6	27.6	0.136	0.000	17.61
	0	30.2	27.5	2.7	28.9	44.5	27.6	0.153	0.000	15.90
12.0	90	31.9	30.4	1.5	31.6	44.1	28.7	0.140	0.000	29.17
	60	31.9	30.1	1.8	30.1	42.9	28.7	0.129	0.000	24.70
	30	30.3	28.3	2.0	29.6	43.6	29.5	0.128	0.000	22.23
	0	32.7	30.5	2.2	31.9	45.1	30.9	0.129	0.000	20.21
22.0	90	34.7	33.4	1.3	33.5	44.8	31.9	0.117	0.000	30.15
	60	33.3	31.6	1.7	31.2	42.7	29.0	0.124	0.000	23.57
	30	30.9	28.6	2.3	30.9	42.6	29.5	0.119	0.000	19.61
	0	34.1	31.6	2.5	31.6	43.5	30.7	0.116	0.000	18.0
28.5	90	33.3	31.3	2.0	32.6	44.2	30.1	0.128	0.000	22.26
	60	33.7	31.1	2.6	32.9	43.1	28.9	0.129	0.000	17.10
	30	30.1	27.0	3.1	31.3	41.7	27.0	0.133	0.000	14.26
	0	31.2	27.9	3.3	32.5	43.9	28.5	0.140	0.000	13.26

CHAPTER FIVE
DISCUSSION OF RESULTS

5.1 Introduction

Chapter five focuses on the discussion of the results obtained from the investigation of the cooling effect of air on flat plate solar energy collectors and the dependence of wind-related heat transfer coefficient on magnitude of air velocity and incident angles of air-flow (wind) onto a flat plate inclined at various angles relative to horizontal air-flow (wind), for the study conducted in a wind tunnel using a square steel plate of side 0.125m. The tilted plate was supplied with constant heat flux to steady-state condition when subjected to horizontal air-flow of different constant velocities. The ambient air temperature range upon which data on air properties at one atmosphere pressure were collected according to the results of this study in Table 4.1 is 26.1^{o}C to 33.4^{o}C. Within this temperature range, the values of Prandtl number (Pr) and air properties such as thermal conductivity (k), thermal diffusivity (α) and kinematic viscosity (ν) were taken as $Pr = 0.72$, $k = 0.026 W/mK$, $\alpha = 2.22 \times 10^{-5}\, m^2/s$ and $\nu = 1.6 \times 10^{-5}\, m^2/s$ respectively as reported in the work of Othieno (1985). By taking Prandtl number (Pr = 0.72) to be that of ambient air temperature range covered at one atmosphere while basing the Nusselt and Reynolds numbers on plate length, a strong variation of heat transfer coefficient (h_w) with air velocity (u) and incident angles of air-flow (θ_i) was reported in Figure 5.1a and 5.1b when the data in Table 5.1a and 5.1b respectively were plotted using OriginPro. Most importantly, the data in Table 5.1a and 5.1b were extracted from the original research data in Table 4.1. The analysis of the equations of the four curves of (h_w) shown in Figure 5.1a by OriginPro application shows that they are fourth order polynomial expressions of (h_w). The plotted curves of h_w against (u) m/s for various incident angles of air-flow (θ_i) in Figure 5.1a shows that wind-related heat transfer coefficient (h_w) is a strong function of air velocity (u) m/s and the incident angle of air-flow (θ_i). Other parameters such as thermal air properties were taken as that of ambient air temperature range covered at one atmosphere pressure. Plate length was also constant. The variation of (h_w) with air velocity and incident angles of air-flow in Tables 5.1a and 5.1b together with their respective Figure 5.1a and 5.1b, evidently justify the dependence of (h_w) on (u) and (θ_i).

Table 5.1a as extracted from the data in Table 4.1 shows the variation of wind-related heat transfer coefficient (h_w) with the incident angles of air-flow (θ_i) onto the plate at different air velocities (u).

Table 5.1a: Variation of (h) with air velocities (u) at different incident angles of air-flow (θ_i)

	Air velocity (u) m/s							
	0	2	4	6	12	22	28.5	Incident angles of air-flow (θ_i)
(h_w) W/m^{2}K	2.04	8.85	16.73	22.33	29.17	30.15	22.26	90 deg.
	2.02	8.90	14.91	18.50	24.70	23.57	17.10	60 deg.
	2.00	8.68	13.50	17.61	22.23	19.61	14.26	30 deg.
	2.03	8.37	12.30	15.90	20.21	18.00	13.26	0 deg.

Figure 5.1a is the plot of data in Table 5.1a above as extracted from Table 4.1 of the original research data. This Figure 5.1a shows the variation of (h_w) with air velocity (u) at different incident angles of horizontal air- flow on the plate (θ_i). Figure 5.1a therefore, illustrates the dependence of wind-related heat transfer coefficient (h_w) on air velocity (u) and plate tilt angles relative to air-flow (θ_i).

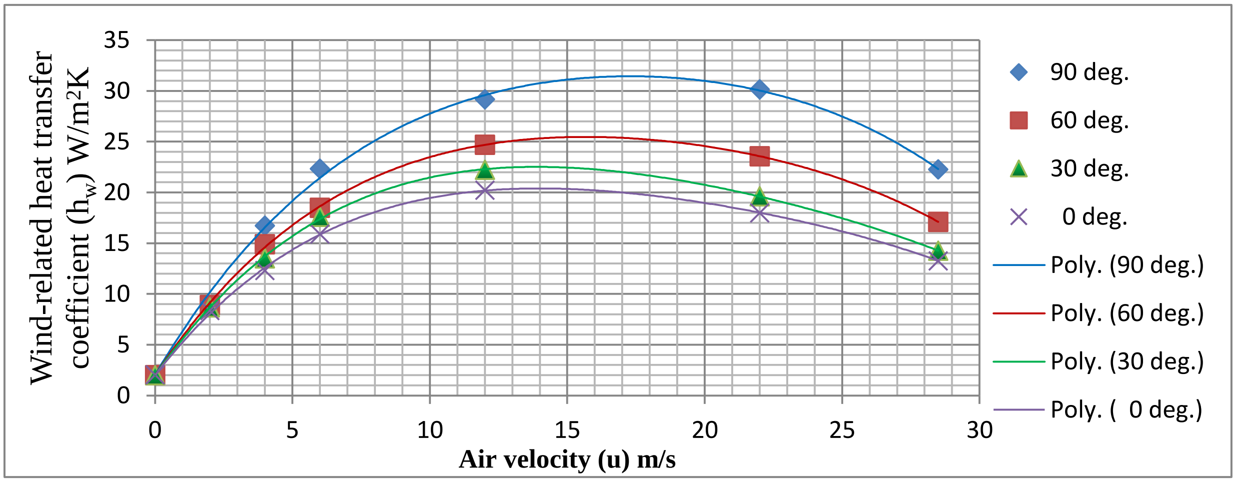

Figure 5.1 (a): Dependence of (h_w) on air velocity (u) at different incident angles of air-flow (θ_i)

Table 5.1b as extracted from the data in Table 4.1 shows the variation of convection heat transfer coefficient (h_w) with incident angles of air-flow (θ_i) onto the plate at different air velocities (u).

Table 5.1b: Variation of (h_w) with incident angles of air-flow (θ_i) at different velocities (u)

	Incident angles of air-flow (θ_i)				
	0 deg.	30 deg.	60 deg.	90 deg.	Air velocity (u) m/s
	2.03	2.00	2.02	2.04	0
	8.37	8.68	8.90	8.85	2
	12.30	13.50	14.91	16.73	4
	15.90	17.61	18.50	22.33	6
(h_w) W/m^2K	20.21	22.23	24.70	29.17	12
	18.00	19.61	23.57	30.15	22
	13.26	14.26	17.10	22.26	28.5

Figure 5.1b below results from the plot of data in Table 5.1b. It shows the variation (h_w) of with (θ_i) at different air velocities (u) and hence it justifies the dependence of (h_w) on air velocity (u) and the incident angles of air-flow on the plate (θ_i).

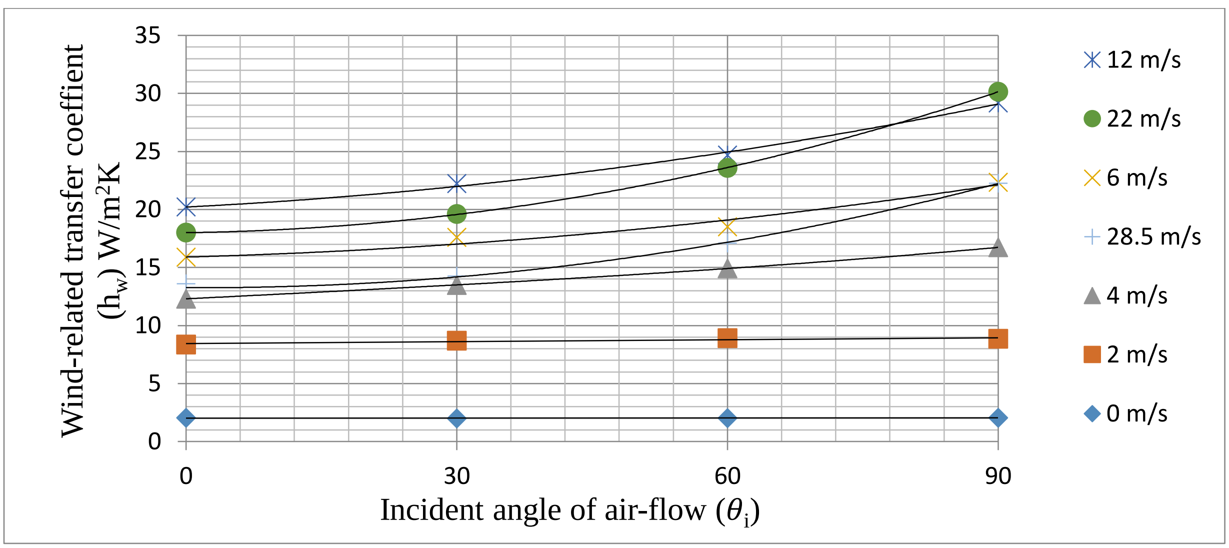

Figure 5.1 (b): Dependence of (h_w) on incident angles of air-flow (θ_i) at different air velocities (u)

Most importantly, in Figure 5.1a, the following four expressions of wind-related heat transfer coefficient (h_w) were obtained when data in Table 5.1a were plotted by OriginPro application.

For $\boldsymbol{\theta}_i = 90^o$: $h_w = 2 + 4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4$ 5.10

For $\boldsymbol{\theta}_i = 60^o$: $h_w = 2 + 4.05625u - 0.25447u^2 + 0.00733u^3 - 9.60722 \times 10^{-5}u^4$ 5.11

For $\boldsymbol{\theta}_i = 30^o$: $h_w = 2 + 3.79582u - 0.24063u^2 + 0.00626u^3 - 6.89032 \times 10^{-5}u^4$ 5.12

For $\boldsymbol{\theta}_i = 0^o$: $h_w = 2 + 3.45687u - 0.22659u^2 + 0.00629u^3 - 7.38319 \times 10^{-5}u^4$ 5.13

The above fourth order polynomial expressions of (h_w) obtained for different specific incident angles of wind onto the plate when viewed from top to bottom within their similar terms are observed to have varying coefficients of air velocity except in their constant terms which are all equal to 2 W/m^2K in still air. That is to say, when the equation 5.10 to 5.13 are viewed from top to bottom, a drop in the coefficients of u, u^2, u^3 and u^4 is observed when θ_i changes from 90^o to 0^o. The observed drop in the coefficient of (h_w) is caused majorly by the effect of variation of the incident angles of wind onto plate with plate tilt angles relative to wind and partly by the nature of flow, plate geometry such as plate length (L). Variation of incident angles of wind with plate tilt angles strongly influences the steady state temperature of plate which in turn influences the magnitude of heat transfer coefficient. Moreover, when u = 0 m/s, free convection exists and hence all the above suggested four equations of (h_w) reduce to h_o =2 W/m^2K regardless of the size of incident angles of wind onto the plate. Furthermore, for a particular incident angle of wind onto the plate for which γ is deemed constant, the coefficients of u, u^2, u^3 and u^4 in any given equation of curve of (h_w) also vary with the changing power of (n) on t_n in every term when u > 0 m/s. With reference to equation 5.10 to 5.13, the equation of a **particular curve** of (h_w) at a **particular angle** of incidence of wind (θ_i) of a given air velocity (u) onto the plate would be:

$$h_w = h_o + Au + Bu^2 + Cu^3 + Du^4 \quad \text{... ... ... 5.14}$$

In equation 5.14, heat transfer coefficient in still air is h_o. In windy environment, the value of (h_w) strongly depends on incident angles of wind (θ_i) onto the plate. In equation 5.14, the constants A, B, C and D represent parameters affecting wind-related heat transfer coefficient such as properties of air taken as that of ambient air temperature range covered (i.e. thermal conductivity, thermal diffusivity, viscosity, plate geometry (i.e. plate length and plate surface area exposed to convection), incident angle of wind, plate tilt angle relative to wind (θ_i) and the flow type (i.e. smooth /turbulent). With reference to equation 1.32 of this thesis, the stated parameters: A, B, C and D have been expressed as products of the constants like: $\gamma = f(\theta_i)$ and $t_n = f(k, L, \alpha) = kL^{n-1}\alpha^{-n}$. The value of t_n depends on the power of (n) which determines the binomial expansion coefficients of every term in the equation 5.14 of (h_w) as predetermined by equation 1.33. The equation 5.14 of the curve of (h_w) for a particular incident angle of wind (θ_i) onto the plate in terms the constants (t_n) and γ when air velocity $u \geq 0\ m/s$ becomes:

$$h_w = h_o + \gamma(t_i u + t_2 u^2 + t_3 u^3 + t_4 u^4) = h_o + \gamma \sum_{n=1}^{4} t_n u^n \qquad \ldots\ldots\ldots\ldots\ldots\ldots 5.15$$

In Figure 5.1a and 5.1b, a non-zero value of convection heat transfer coefficient (i.e. h_o =2 W/m^{2}K) in still air reported by Othieno (1985) and this study evidently justifies the significant cooling effect of free convection on flat plate solar energy collectors despite its very low values. A non-zero value of convection heat transfer coefficient when u = 0 m/s in this study disapproves the reports of Duffie and Beckmann (1980), and Sparrow *et al*. (1979) which suggested a zero value of convection transfer coefficient for a zero value of air velocity as shown in Table 5.2. Their suggestions are not true since a solar energy collector would indeed lose heat from its top cover by free convection under such conditions. Moreover, in a relatively low air velocity, wind-related heat transfer coefficient (h_w) is insensitive to incident angles of wind onto the plate. For instance, when air velocity was set from 0 m/s to 2 m/s and then incident angle of wind varied by tilting plate from 0^o (horizontal) to 90^o relative to wind, heat transfer coefficient (h_w) was observed to vary weakly and insignificantly. This evidently shows that incident angles of wind onto the plate at very low air speed didn't show significant effect on the value of (h_w) as shown in Figure 5.1a.

The best fit of the correlation of heat transfer coefficient with respect to air velocity from 0 m/s to 2 m/s assumes a linear trend because the curves of (h_w) converge to each other and become indistinguishable for all incident angles of wind on the plate. With regard to this, a single linear expression of (h_w) can acceptably be used for the four convergent heat transfer curves of (h_w). Moreover, at a relatively low air velocity, the magnitude of wind-induced thermal energy losses from the solar collectors are negligible for all plate tilt angles and hence mounting of solar collectors can take any form of plate tilt angle from 0^o (horizontal) to 90^o. The mean value of convection heat transfer coefficient in still air is approximately 2.0 W/m^2K with a standard deviation which is less than 0.015 when θ_p is varied from 0^o to 90^o. This gives a coefficient of variation below 4%. The variation of heat transfer coefficient with incident angle of wind strongly increased when air velocity was increased beyond 2m/s as supported by Figure 5.1a where the curves of (h_w) rapidly diverge and become highly distinguishable. In Figure 5.1a, it is evident that wind-induced thermal energy losses increase with the incident angles of wind**.** The magnitude of convection energy losses is higher in a horizontal plate than a vertical plate relative wind. That is, maximum and minimum cooling effect of air occur when incident angles of wind on the plate are 90^o and 0^o respectively. When air velocity is varied from 0 m/s to 28.5 m/s, wind-related heat transfer coefficient increases gradually to its peak value after which it decreases gradually depending on the size of incident angles of wind on the plate. The peak value of heat transfer coefficient in a horizontal plate ($\theta_i = 90^o$, $\theta_p = 0^o$) is higher than that of a vertical plate ($\theta_i = 0^o$, $\theta_p = 90^o$) relative to wind as illustrated in Figure 5.1a. This further indicates that rapid heat transfer occurs more in horizontal plates than vertical plates.

The current study has also revealed the unusual behavior of (h_w) in which the magnitude of (h_w) decreases with increasing air velocity (u) instead of increasing as shown in Figure 5.1a. The cause of this unique phenomenon is viscous heat dissipation (frictional heating) which results from large free stream velocity. That is, large free stream velocity would lead to large velocity gradients within the boundary layer and a substantial conversion of mechanical energy to thermal energy by viscous shear within the boundary layer. Significant rise in temperature of the ambient air (temperature jump) relative to walls of the plate and wind tunnel thus occurs due to viscous heat dissipation (frictional heating). Consequently, large temperature jump decreases the heat transfer rate by reducing the temperature gradients between the ambient air, the walls of the plate and wind tunnel as reported by Kays and Crawford (1993). Neglecting the temperature jump would therefore, lead to over-estimation of the values of heat transfer coefficient as reported by Tune *et* al. (2000). Therefore, it is clear that at relatively low air velocity, viscous heat dissipation is negligible and that is why nearly all the suggested expression of heat transfer coefficient (h_w) in the literature fairly estimate magnitude of convection heat transfer coefficients as shown in Table 5.2. However, at relatively high wind speed, it has been noted that the expressions of (h_w) which were formulated at relatively low wind speed like that of Sparrow and Tien (1977), Mc Adam (1954) and Duffie and Beckmann (1974) would overestimate thermal energy losses from flat plate solar energy collectors as illustrated in Table 5.2. Quantitative comparative analysis of values of wind-related heat transfer coefficient (h_w) of tilted flat plate solar energy collector has been done in Table 5.2 to show disparities on values of (h_w) given by the previous and currently suggested expressions of wind-related heat transfer coefficient (h_w). In Table 5.2, Prandtl number (Pr), kinematic viscosity (ν) and thermal conductivity (k) of ambient air within the temperature range covered at one atmosphere pressure were taken as 0.72, $1.6 \times 10^{-5} m^2/s$ and 0.026 W/mK respectively.

Table 5.2 below shows expressions of wind-related heat transfer coefficient (h_w) obtained from a square plate of a unit area.

Table 5.2: Expressions of wind-related heat transfer coefficient (h_w) of 1m² plate

Expressions of wind-related heat transfer coefficient (h_w) W/m²K	Incident angles of wind ($\boldsymbol{\theta}_i$)	0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0	24.0	26.0	28.0	30.0
		Air velocity (u) m/s															
Aduogo (2015) $2 + (4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4)$	90	2.0	10.2	16.6	21.4	25.1	27.7	29.6	30.7	31.3	31.4	31.0	30.0	28.5	26.2	23.1	19.0
Aduogo (2015) $2 + e^{-\sin(90-\theta_i)^{0.6783}}(4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4)$	90	2.0	10.2	16.6	21.4	25.1	27.7	29.6	30.7	31.3	31.4	31.0	30.0	28.5	26.2	23.1	19.0
Othieno (1985): $(k/L)(75+0.42Re^{0.6})$	70,80and 90	2.0	14.6	21.1	26.4	30.9	35.1	39.0	42.6	46.0	49.2	52.3	55.2	58.1	60.8	63.5	66.1
Aduogo (2015) $2 + 4.05625u - 0.25447u^2 + 0.00733u^3 - 9.60722 \times 10^{-5}u^4$	60	2.0	9.2	14.6	18.6	21.5	23.4	24.7	25.3	25.5	25.2	24.6	23.6	22.2	20.4	17.9	14.8
Aduogo (2015) $2 + e^{-\sin(90-\theta_i)^{0.6783}}(4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4)$	60	2.0	8.9	14.3	18.3	21.4	23.6	25.2	26.1	26.6	26.7	26.4	25.5	24.3	22.6	19.7	16.3
Watmuff*et al.*(1977): $2.8+3u$	60	2.8	8.8	14.8	20.8	26.8	32.8	38.8	44.8	50.8	56.8	62.8	68.8	74.8	80.8	86.8	92.8
Othieno (1985): $(k/L)(75+0.35Re^{0.6})$	60	2.0	12.5	17.9	22.3	26.1	29.6	32.8	35.8	38.6	41.3	43.9	46.3	48.7	51.0	53.3	55.4
Aduogo (2015): $2 + e^{-\sin(90-\theta_i)^{0.6783}}(4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4)$	50	2.0	8.6	13.8	17.7	20.7	22.7	24.2	25.1	25.6	25.7	25.4	24.6	23.4	21.7	19.0	15.7
Othieno (1985): $(k/L)(75+0.29Re^{0.6})$	50	2.0	10.7	15.2	18.8	22.0	24.9	27.5	30.0	32.3	34.6	36.7	38.7	40.7	42.6	44.5	46.3
Test, Lessmann and Joharry (1981): $8.55+2.56u$	50	8.6	13.7	18.8	23.9	29.0	34.2	39.3	44.4	49.5	54.6	59.8	64.9	70.0	75.1	80.3	85.4
Green, Kenna and Rawcliffe (1981): $3.0+7.4u^{0.5}$	45	3.0	13.5	17.8	21.1	23.9	26.4	28.6	30.7	32.6	34.4	36.1	37.7	39.3	40.7	42.2	43.5
Othieno (1985): $(k/L)(75+0.88Re^{0.5})$	30 and 40	2.0	10.1	13.5	16.1	18.3	20.2	22.0	23.6	25.1	26.5	27.8	29.1	30.3	31.4	32.5	33.6
Aduogo (2015) $2 + 3.79582u - 0.24063u^2 + 0.00626u^3 - 6.89032 \times 10^{-5}u^4$	30	2.0	8.7	13.7	17.4	19.9	21.5	22.3	22.5	22.3	21.5	20.7	19.6	18.2	16.6	14.7	12.5
Aduogo (2015) $2 + e^{-\sin(90-\theta_i)^{0.6783}}(4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4)$	30	2.0	8.2	13.1	16.7	19.5	21.5	22.9	23.8	24.2	24.3	24.0	23.2	22.1	20.6	18.0	14.9
Aduogo (2015) $2 + 3.45687u - 0.22659u^2 + 0.00629u^3 - 7.38319 \times 10^{-5}u^4$	0	2.0	8.1	12.6	15.8	18.1	19.5	20.1	20.4	20.2	19.7	19.0	18.1	16.9	15.5	13.8	11.8
Aduogo (2015) $2 + e^{-\sin(90-\theta_i)^{0.6783}}(4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4)$	0	2.0	7.7	12.2	15.5	18.1	19.9	21.2	22.0	22.4	22.5	22.2	21.5	20.5	19.1	16.7	13.8
Sparrow and Tien (1977): $0.931(k/L)Pr^{0.33}Re^{0.5}$	0,10and 20	0.0	7.8	11.0	13.4	15.5	17.2	19.0	20.5	21.9	23.3	24.5	25.7	26.9	28.0	29.0	30.0
Sparrow, Ramsey and Mass (1979): $0.86(k/L)Pr^{0.33}Re^{0.5}$	0	0.0	7.1	10.1	12.4	14.3	16.0	17.5	19.0	20.3	21.5	22.7	23.8	24.8	25.8	26.9	27.7
Othieno (1985): $(k/L)(75+2.90Re^{0.4})$	0,10 and20	2.0	10.3	12.9	14.8	16.4	17.8	19.0	20.1	21.0	22.0	22.8	23.6	24.4	25.1	25.8	26.5
Wang (1982): $(k/L_X)(3+0.0254Re_x^{0.8})$	0	0.1	8.1	14.0	19.4	24.4	29.2	33.7	38.1	42.4	46.6	50.7	54.7	58.7	62.5	65.8	70.1
Duffie and Beckmann (1980): $8.6u^{0.6}/L^{0.4}$	0	0.0	13.0	19.8	25.2	29.9	34.2	38.2	41.9	45.4	48.7	51.9	54.9	57.8	60.7	63.5	66.3
Mc Adam (1954) $5.7+3.8u$	0	5.7	13.3	20.9	28.5	36.1	43.7	51.3	58.9	66.5	74.1	81.7	89.3	96.9	105	112	120
		Wind-related heat transfer coefficient (h_w) W/m²K															

To compare the present and previous expressions of h_w, quantitative analysis of values of wind-related heat transfer coefficient (h_w) was done in Table 5.2 and further illustrated by Figure 5.2a, 5.2b, 5.2c and 5.2d. The disparities in values of h_w which were reported in Figure 5.2a, 5.2b, 5.2c and 5.2d resulted from the use of wind tunnels of different diameters in studying the effects of temperature variation and air velocity on convection heat transfer rate. Use of wind tunnels of different diameters may have led to variation of air speed, flow type (i.e. smooth/turbulent), heating effect of air friction and temperature gradient which ultimately affected convection heat transfer rate. In this study, relatively narrow wind tunnel was used and as a result, there was high frictional heating effect of high velocity air molecules which led to low temperature gradients and low convection heat transfer rate. Generally, in a relatively low wind speed, air friction in all wind tunnels was relatively low regardless of their diameters and hence variation of temperature gradient with air friction was weak in all types of wind tunnels used. Consequently, convection heat transfer rate was low and that is why small disparities occurred in values of h_w.

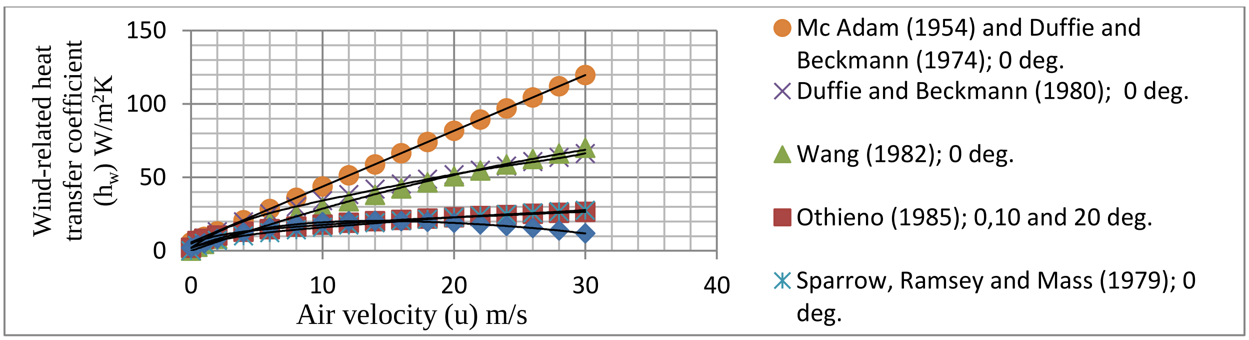

Figure 5.2a: Variation of heat transfer coefficient with air velocity when θ_i are 0º, 10º and 20º

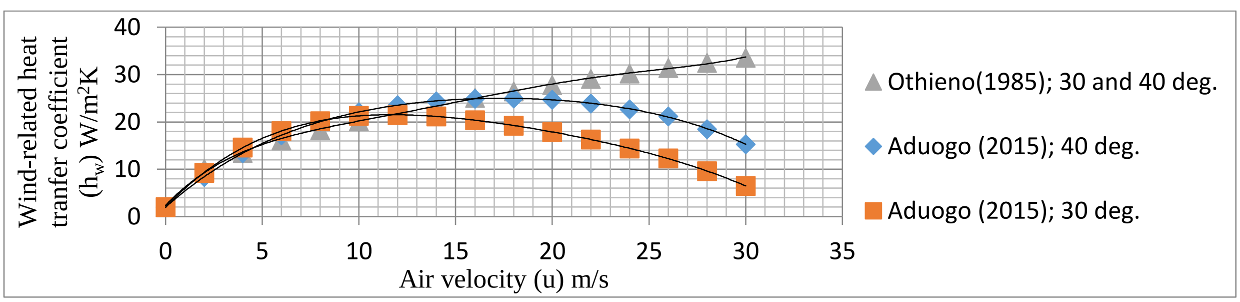

Figure 5.2b: Variation of heat transfer coefficient (h_w) with air velocity when θ_i are 30º and 40º

Figure 5.2c and 5.2d below show the variation of heat transfer coefficient with air velocity at different angles of incidence of wind θ_i onto the plate.

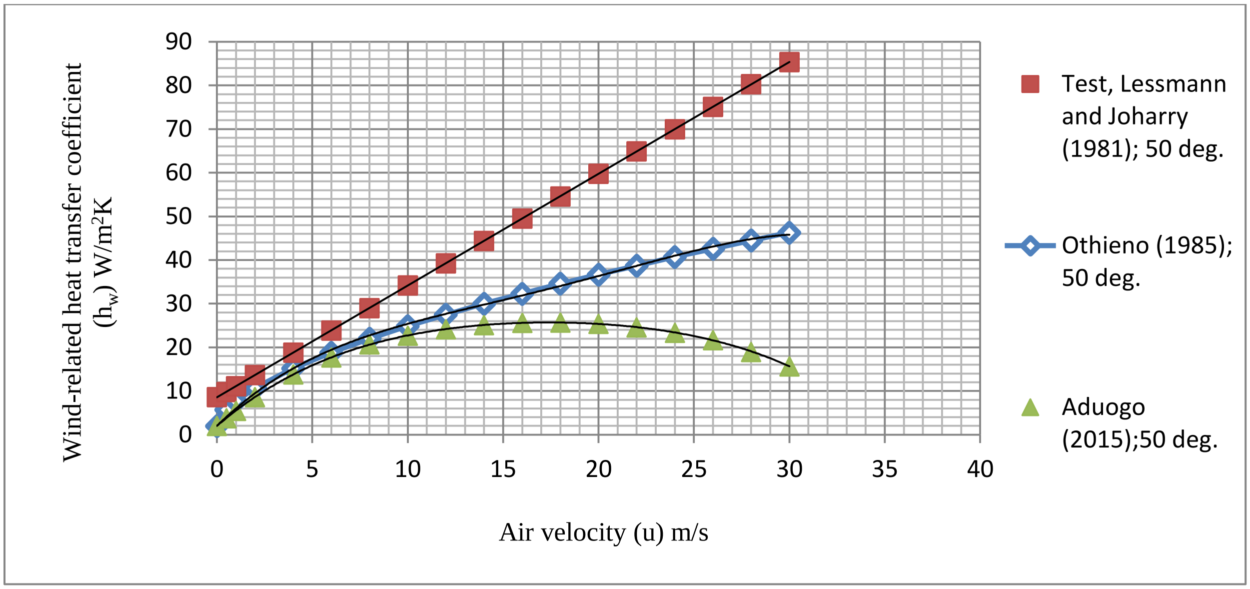

Figure 5.2c: Variation of heat transfer coefficient with air velocity when θ_i is 50º

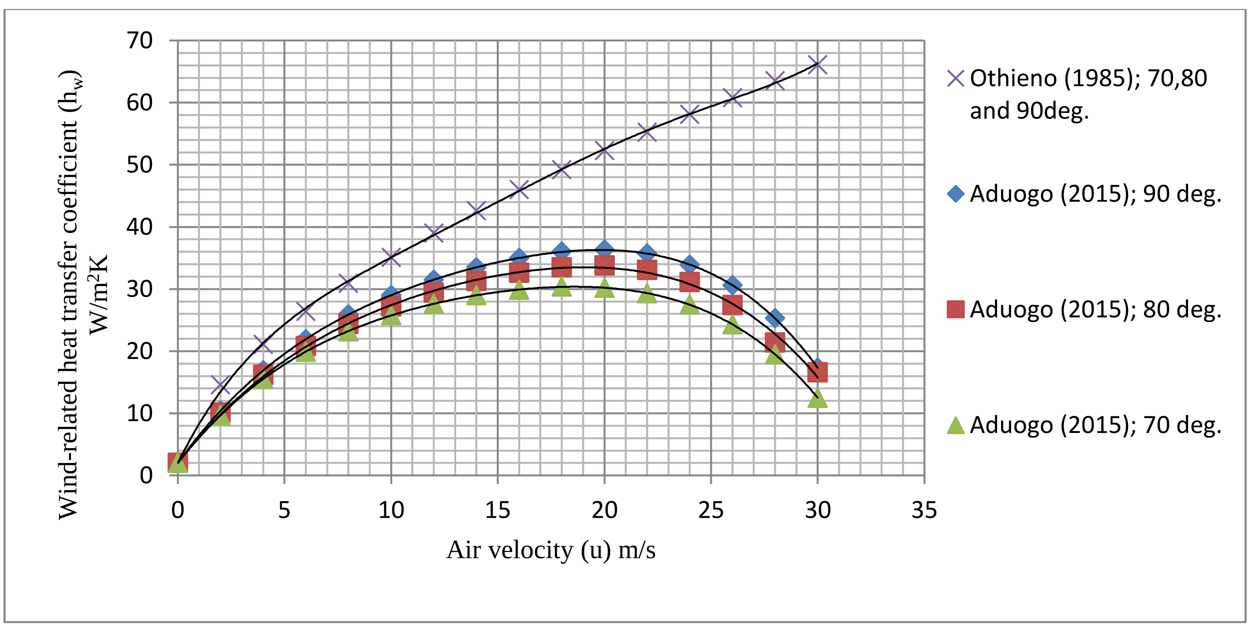

Figure 5.2d: Variation of heat transfer coefficient with air velocity when θ_i are 70º, 80º and 90º

In Figure 5.2a, when $\theta_i = 50^o$ and u $\leq$12 m/s, the expression of wind-related heat transfer coefficient reported by Othieno (1985) fairly estimated convective energy losses. However, when $\theta_i = 50^o$ and u > 12 m/s, the values of (h_w) are overestimated by the same equation since the frictional heating effect relatively lower the magnitude of heat transfer coefficient was never factored in at high wind speed. Furthermore, the expression of (h_w) suggested by Duffie and Beckman (1980) and Sparrow and Tien (1977) in Table 5.2 assume zero value of heat transfer coefficient in still air. This is not true according to the result of this study which shows h_o > 0 m/s in still air. In still air, a solar collector will lose heat from its top cover by natural convection under such conditions. However, the report given by Sparrow and Tien (1977) on the insensitivity of h_w on plate tilt angles at relatively low wind speed of below 2 m/s, is true according to the results of this study which show that the curves of (h_w) converge when u $\leq$ 2m/s. Quite interestingly, peak values of wind-related heat transfer coefficients were reported for every plate tilt angle relative to air-flow according to the results of this investigation. The idea of the existence of peak values of wind-related heat transfer coefficient has never appeared in all the expressions of (h_w) that are available in the literature. This is because all the previously suggested expressions of (h_w) were developed at relatively low air velocities and therefore, the reduction effect of viscous heat dissipation on values of (h_w) were never factored in.

Comparative analysis of the previous literature on expressions of (h_w) reveals lack of the single expression of wind-related heat transfer coefficient that specifies the dependence of (h_w) on plate tilt angles and most importantly, that which encompasses the full possible range of plate tilt angles relative to wind/incident angles of wind onto the plate. Othieno (1980) in his equation 2.4 attempted to come up with a single expression of (h_w). Unfortunately, the expression of (h_w) suggested by Othieno (1980) only specified the dependence of (h_w) on incident angles of wind by use of a constant instead of using a variable to show the variation of (h_w) with θ_i or θ_p. Quite surprisingly, according to the result of this study the four expressions of (h_w) suggested from the results of this study in Figure 5.1a can acceptably be unified by a single expression of (h_w) derived from the research data of this study as shown on the next page**.**

5.2 Derivation of the Single Expression of (h_w) for $0^o \leq \theta_i \leq 90^o$ and $u \geq 0$m/s

The single expression of (h_w) which encompasses the full possible range of incident angles of wind onto the plate from 0^o to 90^o is hereby derived from the equation (5.10) of (h_w) at $\theta_i = 90^o$ by determining the best value of the function $\gamma = f(\theta_i)$ in $\sum_{n=1}^{4}[\gamma t_n f(u)]_{max}$ in equation (5.10) which maps equation (5.10) to equation (5.13) of (h_w) at $\theta_i = 0^o$ as θ_i in γ changes from 90^o to 0^o. The summation $\sum_{n=1}^{4}[\gamma t_n f(u)]_{max}$ represents the difference between the value of wind-related heat transfer coefficient in wind (i.e. when u > 0 m/s) and still air (i.e. when u = 0 m/s) in equation (5.10) of (h_w) at $\theta_i = 90^o$. For the curve of (h_w) at $\theta_i = 90^o$, the values of (h_w) are maximum (i.e. $h_w = h_{(w)max}$) and $h_w = h_o$ when u = 0 m/s and hence:

When $\theta_i = 90^o$,

$$[h_{(w)max} - h_o] = \sum_{n=1}^{4}[\gamma t_n f(u)]_{max}$$

$$= [-1.07822 \times 10^{-4}u^4 + 0.00770u^3 - 0.26821u^2 + 4.59479u] \dots\dots\dots 5.16$$

Similarly, $[h_{(w)min} - h_o]$ would represent the difference between wind-related heat transfer coefficient in wind (i.e. when u > 0 m/s) and still air (i.e. when u = 0 m/s) in equation (5.13) of (h_w) at $\theta_i = 0^o$. For the curve of (h_w) at $\theta_i = 0^o$, the values of (h_w) are minimum (i.e. $h_w = h_{(w)max}$) and $h_w = h_o$ when u= 0 m/s and hence:

When $\theta_i = 0^o$,

$$[h_{(w)min} - h_o] = [-7.38319 \times 10^{-5}u^4 + 0.00629u^3 - 0.22659u^2 + 3.45687u] \dots\dots\dots 5.17$$

Most importantly, in Table 5.3, the equations of the curves of (h_w) at $\theta_i = 90^o$ and $\theta_i = 0^o$ with the maximum and minimum cooling effect of air on the plate respectively have been picked and used as the reference equations in the process of deriving the single expression of h_w for the full possible range of incident angles of wind onto the plate. The values of $[h_{(w)max} - h_o]$ and $[h_{(w)min} - h_o]$ from the equations of (h_w) at $\theta_i = 90^o$ and $\theta_i = 0^o$ respectively are to be computed when $u \geq 0$ m/s and then the results are tabulated as shown in Table 5.4.

Table 5.3 below shows the suggested expressions of convection heat transfer coefficients (h_w) and their corresponding magnitudes at different air velocities.

Table 5.3: Coefficients of (h_w) from the suggested expressions of (h_w) at different air velocities

Equation	θ_i		Expressions of (h_w)	Air velocity (u) m/s															
				0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
5.10	90°	$\boldsymbol{h_{(w)max}}$	$-1.07822 \times 10^{-4}u^4 + 0.00770u^3 - 0.26821u^2 + 4.59479u + 2$	2	10.2	16.6	21.4	25.1	27.7	29.6	30.7	31.3	31.4	31.0	30.0	28.5	26.2	23.1	19.0
5.11	60°	h_w	$-9.60722 \times 10^{-5}u^4 + 0.00733u^3 - 0.25447u^2 + 4.05625u + 2$	2	9.2	14.6	18.6	21.5	23.4	24.7	25.3	25.5	25.2	24.6	23.6	22.2	20.4	17.9	14.8
5.12	30°	h_w	$-6.89032 \times 10^{-5}u^4 + 0.00626u^3 - 0.24063u^2 + 3.79582u + 2$	2	8.7	13.7	17.4	19.9	21.5	22.3	22.5	22.3	21.5	20.7	19.6	18.2	16.6	14.7	12.5
5.13	0°	$\boldsymbol{h_{(w)min.}}$	$-7.38319 \times 10^{-5}u^4 + 0.00629u^3 - 0.22659u^2 + 3.45687u + 2$	2	8.1	12.6	15.8	18.1	19.5	20.1	20.4	20.2	19.7	19.0	18.1	16.9	15.5	13.8	11.8

Table 5.4 below shows the values of $[h_{(w)max} - h_o]$ and $[h_{(w)min} - h_o]$ computed from the expressions of h_w at θ_i = 90° and θ_i = 0° respectively when u ≥ 0 m/s. Convection heat transfer coefficient in still air (h_o) = 2 W/m^{2}K.

Table 5.4: The values of $[h_{(w)max} - h_o]$and$[h_{(w)min} - h_o]$when $u \geq 0m/s$ and h_o = 2W/m^{2}K

Reference expressions of (h_w)	θ_i	Air velocity (u) m/s →	0	2	4	6	**8**	10	12	14	16	18	20	22	24	26	28	30
$-1.07822 \times 10^{-4}u^4 + 0.00770u^3 - 0.26821u^2 + 4.59479u + 2$	90°	$\boldsymbol{h_{(w)max}}$ →	2	10.2	16.6	21.4	**25.1**	27.7	29.6	30.7	31.3	31.4	31.0	30.0	28.5	26.2	23.1	19.0
		$\gamma_{max}[tf(u)]_{max.} = h_{(w)max.} - h_o = h_{(w)max.} - 2$	0	8.2	14.6	19.4	**23.1**	25.7	27.6	28.7	29.3	29.4	29	28	26.5	24.2	21.1	17.0
$-7.38319 \times 10^{-5}u^4 + 0.00629u^3 - 0.22659u^2 + 3.45687u + 2$	0°	$\boldsymbol{h_{(w)min.}}$ →	2	8.1	12.6	15.8	**18.1**	19.5	20.1	20.4	20.2	19.7	19.0	18.1	16.9	15.5	13.8	11.8
		$\gamma_{min}[tf(u)]_{max.} = h_{(w)max.} - h_o = h_{(w)max.} - 2$	0	6.1	10.6	13.8	**16.1**	17.5	18.1	18.4	18.2	17.7	17	16.1	14.9	13.5	11.8	9.8

With data in Table 5.3 and 5.4 in place, consider a function of θ_i given as $\gamma = f(\theta_i) = e^{-sin(90-\theta_i)^{\psi}}$ in $\sum_{n=1}^{4}[\gamma t_n f(u)]_{max}$ in equation of h_w at θ_i=90° whose action on $\sum_{n=1}^{4}[\boldsymbol{t_n f(u)}]_{\boldsymbol{max}}$ damps $\sum_{n=1}^{4}[\boldsymbol{t_n f(u)}]_{\boldsymbol{max}}$ by a factor of $\boldsymbol{e^{-sin(90-\theta_i)^{\psi}}}$ as θ_i decreases from 90° to 0° thereby transforming the highest (maximum) curve of h_w at θ_i = 90° to the lowest (minimum) curve of h_w at θ_i = 0°. When θ_i = 90°, the value of γ is maximum at 1 and hence $\sum_{n=1}^{4}[\gamma t_n f(u)]_{max} = \gamma_{max} \sum_{n=1}^{4}[t_n f(u)]_{max} = \sum_{n=1}^{4}[t_n f(u)]_{max}$. So when γ = f (θ_i) =1, the values of the wind-related heat transfer coefficients remain the same in the equation of h_w at θ_i = 90°. However, when θ_i decreases from 90° to 0°, the value of γ decreases from its maximum value of 1 to a minimum value designated by γ_{min} at θ_i = 0°. Consequently, $\gamma_{max} \sum_{n=1}^{4}[t_n f(u)]_{max}$ of the equation of h_w at θ_i = 90° is finally transformed to $\gamma_{min} \sum_{n=1}^{4}[t_n f(u)]_{max}$ by γ_{min} and hence $h_{(w)max}$ reduces to $h_{(w)min}$ for a given air velocity u > 0 m/s. Therefore, in reference to equation 5.16, it is clear to say that when θ_i = 90 degrees, $\gamma = \gamma_{max}$ =1 and hence:

$$\gamma_{max} \sum_{n=1}^{4}[t_n f(u)]_{max} = h_{(w)max} - h_o \qquad \text{......................... 5.18}$$

Similarly, it is noted that when θ_i = 0°, $\gamma = \gamma_{min} = e^{-\sin 90^{\psi}}$, $h_{(w)max}$ becomes $h_{(w)min}$ and hence equation 5.18 of (h_w) at θ_i = 90° reduces to that of the curve of h_w at θ_i = 0° when γ_{min} damps $\sum_{n=1}^{4}[\boldsymbol{t_n f(u)}]_{\boldsymbol{max}}$. Therefore, in reference to equation 5.17, when θ_i = 0°, $\gamma = \gamma_{min} = e^{-sin(90)^{\psi}}$ and hence:

$$\gamma_{min} \sum_{n=1}^{4}[t_n f(u)]_{max} = h_{(w)min} - h_o \qquad \text{......................... 5.19}$$

Given that $\gamma = \gamma_{max}$=1 when θ_i = 90° and $\gamma_{min} = e^{-\sin 90^{\psi}}$ when θ_i = 0° for the curve of maximum and minimum cooling effect of wind on flat plate solar energy collector respectively, the ratio of $[h_{(w)min} - h_o]$ in equation 5.19 to $[h_{(w)max} - h_o]$ in equation 5.18 is constant (γ_{min}) which is determinable by equation 5.20.

$$\frac{\gamma_{min} \sum_{n=1}^{4}[t_n f(u)]_{max}}{\gamma_{max} \sum_{n=1}^{4}[t_n f(u)]_{max}} = \frac{\gamma_{min}}{\gamma_{max}} = \gamma_{min} = \frac{h_{(w)min} - h_o}{h_{(w)max} - h_o} = e^{-sin(90)^{\psi}} \qquad \text{.................. 5.20}$$

Using the equation 5.20, the values of γ_{min} for different air velocities ranging from 2 m/s to 30 m/s were computed at an interval of 2 m/s. For instance, when u = 2m/s, the value of

$\left[h_{(w)max} - h_o\right] = 8.2$ in equation of the curve of (h_w) at θ_i = 90° and $\left[h_{(w)min} - h_o\right] = 6.1$ in equation of the curve of (h_w) at θ_i = 0°, and hence the value of γ_{min} becomes:

$$\gamma_{min} = \frac{h_{(w)min} - h_o}{h_{(w)max} - h_o} = \frac{6.1}{8.2} = 0.7439 = e^{-sin(90)^{\psi}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 5.21$$

Similarly, when air velocity (u) = 8 m/s, the value of $\left[h_{(w)max} - h_o\right] = 23.1$ for the equation of (h_w) at θ_i = 90° and the value of $\left[h_{(w)min} - h_o\right] = 16.1$ for the equation of (h_w) when incident angle of wind on the plate θ_i = 0° and hence the value of γ_{min} becomes:

$$\gamma_{min} = \frac{h_{(w)min} - h_o}{h_{(w)max} - h_o} = \frac{16.1}{23.1} = 0.6970 = e^{-sin(90)^{\psi}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 5.22$$

The same procedure was further used to determine the values of γ_{min} when air velocity (u) = 4, 6,10,12,14,16,18,20, 22,24,26,28 and 30 m/s. Table 5.5 was then drawn for the values of γ_{min} after which the best value of γ_{min} which fits in all the values of (h_w) from the four suggested equations of the curves of (h_w) in Figure 5.1a into the single/unified expression of (h_w) to the highest possible degree of accuracy or rather with the least possible error was identified at u = 8 m/s. From the value of γ_{min} of the best fit of 0.6970, the corresponding constant ψ of best fit was determined. The constant ψ of the best fit moderates the damping effect of function (γ) on $\sum_{n=1}^{4}[tf(u)]_{max}$ to ensure the values of (h_w) from the suggested curves of (h_w) fit well into the formulated single expression of (h_w). The constant ψ is calculated from the equation 5.23 which is obtained by introducing natural logarithm on both sides of equation 5.20 [i.e. $\gamma_{min} = e^{-\sin(90)^{\psi}}$] and re-arranging the resulting equation to make ψ the subject of the formula.

$$\psi = \frac{\log[\sin^{-1}(-\ln \gamma_{min})]}{log 90} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.23$$

For instance, when $\gamma_{min} = 0.7439$, $\psi = \frac{log[\sin^{-1}(-\ln 0.7439)]}{log 90} = 0.6323$ and hence other values of γ_{min} and their corresponding values of ψ can be obtained using the same procedure given various air speeds and then the result tabulated. Table 5.5 shows the values of γ_{min} and their corresponding values of ψ at different air velocities. According the result of this study, the best value of ψ is 0.6783 when the best fitting value of γ_{min} is 0.6970.

Table 5.5 below shows the values of γ_{min} and their corresponding values of ψ_{min} as calculated from the reference equation 5.10 and 5.13 using equation 5.20 and 5.23 respectively.

Table 5.5: Values of γ_{min} and their corresponding values of ψ at θ_i = 0 degree

Reference Equation (Eq.)	θ_i	Air velocity (u) m/s →	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Eq. 5.10	90º	$\boldsymbol{h_{(w)max}}$ →	2	10.2	16.6	21.4	25.1	27.7	29.6	30.7	31.3	31.4	31.0	30.0	28.5	26.2	23.1	19.0
		$h_{(w)max.} - h_o = h_{(w)max.} - 2$	0	8.2	14.6	19.4	23.1	25.7	27.6	28.7	29.3	29.4	29	28	26.5	24.2	21.1	17.0
Eq. 5.13	0º	$\boldsymbol{h_{(w)min.}}$→	2	8.1	12.6	15.8	18.1	19.5	20.1	20.4	20.2	19.7	19.0	18.1	16.9	15.5	13.8	11.8
		$h_{(w)min.} - h_o = h_{(w)min.} - 2$	0	6.1	10.6	13.8	16.1	17.5	18.1	18.4	18.2	17.7	17	16.1	14.9	13.5	11.8	9.8
$\gamma = f(\theta_i) = \dfrac{h_{(w)min} - h_o}{h_{(w)max} - h_o}$				0.7439	0.7260	0.7113	γ-BEST 0.6970	0.6809	0.6558	0.6411	0.6212	0.6020	0.5862	0.5750	0.5623	0.5579	0.5592	0.5765
$At\ \theta_i = 0^o, \psi = \dfrac{log[\sin^{-1}(-ln\gamma_{min})]}{log90}$				0.6323	0.6505	0.6648	ψ-BEST 0.6783	0.6929	0.7149	0.7274	0.7439	0.7595	0.7721	0.7810	0.7911	0.7945	0.7935	0.7798

In Table 5.5, when θ_i = 0° and u = 8.0 m/s, the best value of γ_{min} = 0.6970 and its corresponding value of ψ_{min} is 0.6783. For these stated values of γ_{min} and ψ_{min}, error margin between the values of h_w of a particular expression of (h_w) at a particular value of θ_i and the formulated single expression of (h_w) for the full possible range of θ_i (i.e. 0° ≤ θ_i ≤ 90°) is the least. However, any other value of γ_{min} and its corresponding value of ψ_{min} shown in Table 5.5 would widen the error margin between the values of h_w of a particular expression of (h_w) at a particular value of θ_i and the formulated single expression of (h_w) for the full possible range of θ_i (i.e. 0° ≤ θ_i ≤ 90°). When the best fitting values of γ and ψ are substituted into equation 5.20, it is observed that when θ_i= 0°, $0.6970 = e^{-sin(90)^{0.6783}}$. The general equation of γ as a function of the incident angles of wind onto the plate (θ_i) in the range 0° ≤ θ_i ≤ 90° when $u \geq 0m/s$ would therefore, be:

$$\gamma = e^{-sin(90-\theta_i)^{0.6783}} \qquad \dots\dots\dots\dots\dots\dots\dots\dots 5.24$$

By substituting the value of γ in equation 5.24 to an earlier suggested reference equation 5.10 of the curve of (h_w) at θ_i = 90° and in line with equation 5.15, the single expression of (h_w) was obtained for the full possible range of incident angles of wind of different velocities onto the plate from 0 degree (θ_p= 90°/vertical plate) to 90 degrees (θ_p = 0°/horizontal plate).The single expression of wind-related heat transfer coefficient (h_w) for the full possible range of incident angles of wind onto the plate from 0° to 90° according the result of this study therefore, takes the form below:

$$h_w = 2 + e^{-sin(90-\theta_i)^{0.6783}} [4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4] ..5.25$$

Since both the plate tilt angles (θ_p) relative to wind and incident angles of wind (θ_i) onto the plate are complementary angles i.e. $(90 - \theta_i) = \theta_p$, h_w can as well be expressed in terms of plate tilt angles relative to wind (θ_p) as shown below:

$$h_w = 2 + e^{-sin(\theta_P)^{0.6783}} [4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4] \dots 5.26$$

In equation 5.25 and 5.26 above, it is observed that the magnitude of wind-related heat transfer coefficient (h_w) at any given incident angle of wind onto the plate/plate tilt angle relative to wind can be determined easily and accurately. To justify the convenience and accuracy of the formulated single expression of (h_w), the values of (h_w) for various incident angles of wind onto the plate at different constant air velocities were computed as shown in table 5.6.

Table 5.6 below shows the coefficients of (h_w) as obtained from the suggested single expression of wind-related heat transfer coefficient (h_w) for $0^o \leq \theta_i \leq 90^o$ and $u \geq 0$ m/s.

Table 5.6: Coefficients of (h_w) from the single expression of (h_w) for $0^o \leq \theta_i \leq 90^o$ and $u \geq 0$ m/s

					Air-velocity (u) m/s															
The single expression of (h_w)	θ_P	θ_i	$e^{-sin(90-\theta_i)^{0.6783}}$		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
$2 + e^{-\sin(90-\theta_i)^{0.6783}}[4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4]$	0º	90º	γ_{max}	1.000	2	10.2	16.6	21.4	25.1	27.7	29.6	30.7	31.3	31.4	31.0	30.0	28.5	26.5	23.1	19.0
	10º	80º		0.920	2	9.5	15.4	19.8	23.3	25.6	27.4	28.4	29.0	29.0	28.7	27.8	26.4	24.5	21.4	17.6
	20º	70º		0.876	2	9.2	14.8	19.0	22.2	24.5	26.2	27.1	27.7	27.8	27.4	26.5	25.2	23.5	20.5	16.9
	30º	60º		0.840	2	8.9	14.3	18.3	21.4	23.6	25.2	26.1	26.6	26.7	26.4	25.5	24.3	22.6	19.7	16.3
	40º	50º		0.809	2	8.6	13.8	17.7	20.7	22.7	24.2	25.1	25.6	25.7	25.4	24.6	23.4	21.7	19.0	15.7
	50º	40º		0.782	2	8.4	13.4	17.2	20.1	22.1	23.6	24.4	24.9	25.0	24.7	23.9	22.7	21.2	18.5	15.3
	60º	30º		0.758	2	8.2	13.1	16.7	19.5	21.5	22.9	23.8	24.2	24.3	24.0	23.2	22.1	20.6	18.0	14.9
	70º	20º		0.736	2	8.0	12.7	16.3	19.0	20.9	22.3	23.1	23.6	23.6	23.3	22.6	21.5	20.0	17.5	14.5
	80º	10º		0.716	2	7.9	12.5	15.9	18.5	20.4	21.8	22.5	23.0	23.1	22.8	22.0	21.0	19.5	17.1	14.2
	90º	0º	γ_{min}	0.697	2	7.7	12.2	15.5	18.1	19.9	21.2	22.0	22.4	22.5	22.2	21.5	20.5	19.1	16.7	13.8
					h_o	Wind-related convection heat transfer values (h_w) W/m^2K														

When heat transfer coefficients of the single expression of (h_w) on Table 5.6 were plotted against air velocities incident at different angles on the plate, several curves of h_w akin to those of Figure 5.1a were obtained as shown in Figure 5.3a. This clearly indicates that with only one (single) expression of (h_w), it is possible to produce distinguishable curves of (h_w) for different incident angles of wind of a particular velocity onto the plate or rather determine the magnitude of (h_w) for every incident angle of wind of a given velocity. The suitability of the single expression of (h_w) in determining the coefficients of (h_w) in solar energy technologies is therefore, justified.

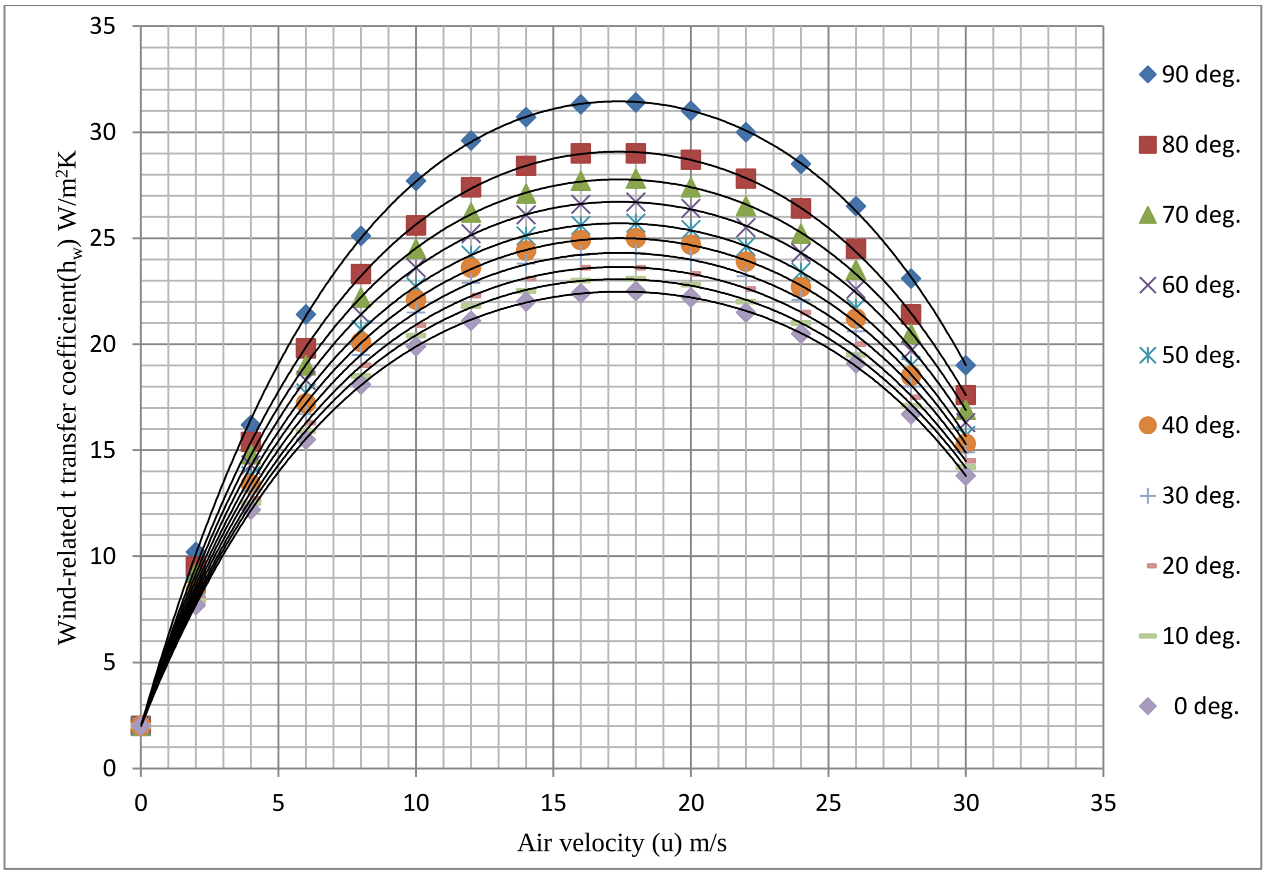

Figure 5.3a: Heat transfer coefficient as a function of air velocity incident at different θ_i angles

From Figure 5.3a, it is clear that the curves of wind-related heat transfer coefficient (h_w) are nonlinear but only reduce to a linear function of (u) at a relatively low air velocity ranging from 0 m/s to 2 m/s regardless of the incident angles of wind. Furthermore, from Table 5.6, the plot of heat transfer coefficients (h_w) generated by single expression of (h_w) against (θ_i) at different air velocities as shown in Figure 5.3b, further shows that free convection heat transfer coefficient is insensitive to plate tilt angles/incident angles of air-flow onto the plate provided air velocity is relatively low, just as reported by Sparrow et *al.* (1979) and Sparrow and Tien (1997). Figure 5.3b below shows the variation of (h_w) generated by the single expression of (h_w) with air velocity and incident angles of wind onto the plate.

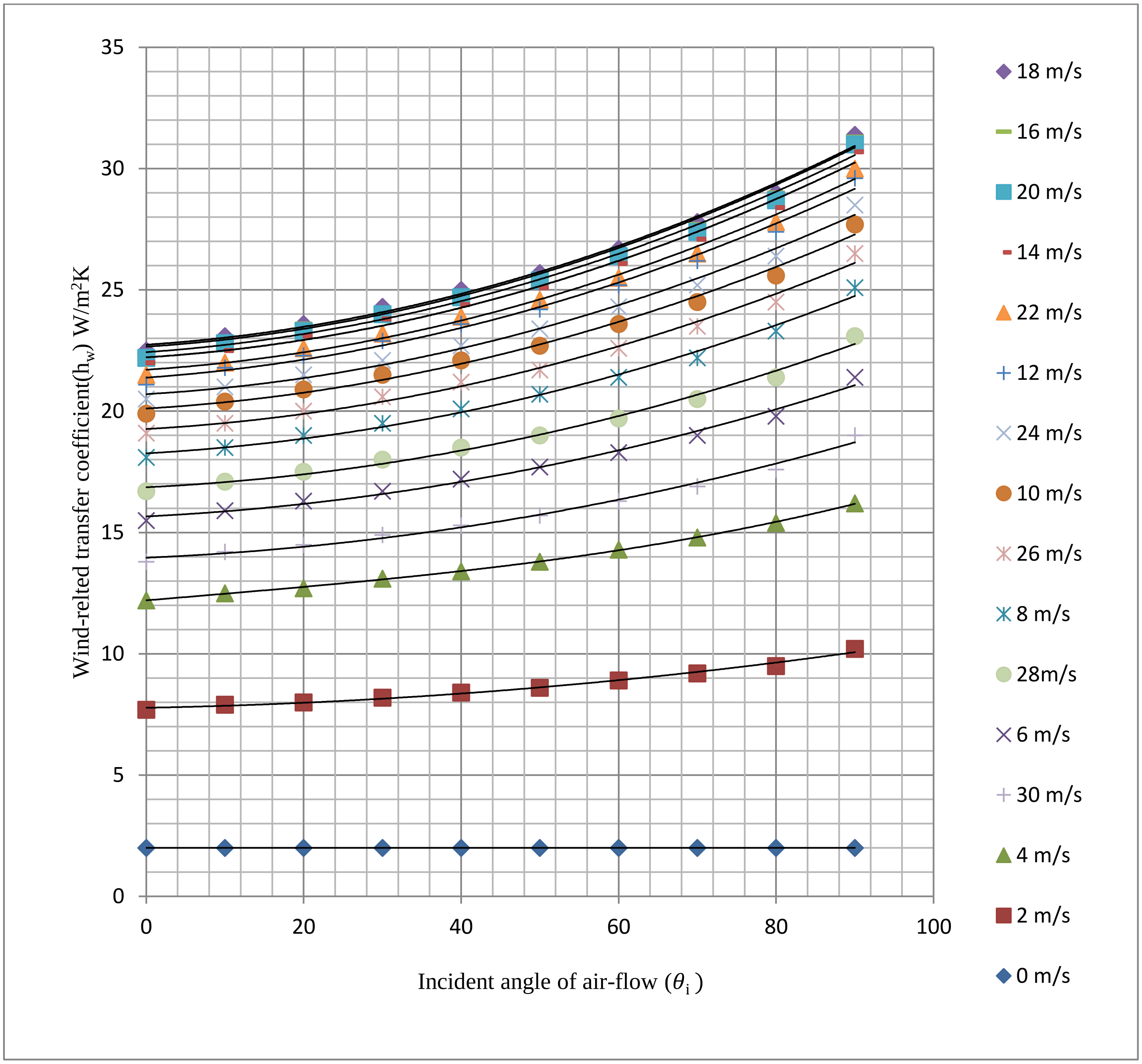

Figure 5.3b: Heat transfer coefficient (h_w) as a function of incident angle of air-flow

5.3 Conclusion

From the results of this study, it is shown that the cooling effect of air influences the performance of flat plate solar thermal and PV energy collectors since it contributes to thermal energy losses. The rate of cooling effect of air on flat plate solar energy collectors depends on the magnitude of air velocity and the incident angle of wind onto the plate. In still air, insignificant thermal energy losses occurred from solar energy collectors purely by natural convection as supported by a non-zero value of convection heat transfer coefficient in the work of Mc Adam (1954), Watmuff et al. (1977), Green et *al.* (1981), Test et *al.* (1981), Othieno (1985) and Aduogo (2015). In still air, convection heat transfer coefficient is insensitive to plate tilt angles just as reported by Sparrow and Tien (1977) and Othieno (1985) and further confirmed by the results of this study. Ideally, for the full possible range of incident angles of air-flow onto the flat plate which the plate tilt angles are complementary to, (h_o) is approximately constant (i.e. 2 W/m^2K) according to the results of this study. For instance, this study shows that the mean value of convection heat transfer coefficient in still air is approximately 2.0 W/m^2K with a standard deviation which is less than 0.015 when θ_p is varied from 0^o to 90^o. The results of this study in agreement with the repeated experiments in available literature further indicate that wind-related heat transfer coefficient is low and insensitive to plate tilt angles when air velocity is relatively low (i.e. $u \leq 2m/s$). In support of this, when air velocity is 2 m/s and below, the results of the study show that the curves of wind-related heat transfer coefficients converge to form a linear trend in regardless of the size of incident angles of wind onto the plate as shown in Figure 5.1a, 5.3a and 5.3b. However, when air velocity increases beyond 2 m/s, the variation of incident angles of wind with plate tilt angles relative to wind increases and this strongly influences the steady state temperature of plate and ultimately the magnitude of heat transfer coefficient.

Furthermore, wind-related heat transfer rate increases for the full possible range of incident angles of air-flow as air velocity increases beyond 2m/s after which at a certain air velocity, it gradually decreases by different amount depending on the incident angles of wind. This is due to the reduction effect of frictional heating due to high velocity air molecules on temperature gradient. That is to say, at high velocities of air, viscous heating and turbulent separation occur leading to an increase in entropy of the ambient air and the extent of internal energy distribution of random molecular activity of the ambient air. Consequently, loss in quality/useful/available energy occurs thereby leading to a decrease in wind-related heat transfer coefficient (h_w) at higher wind speed. For instance, in Figure 5.4, beyond air velocity of 20 m/s, the effect of frictional heating resulting from high velocity gradients lowers the temperature gradients which in turn lowers the magnitude of convection heat transfer coefficient The research finding further confirms the existence of peak values of heat transfer coefficient for every plate tilted relative to horizontal air-flow of a particular speed in a wind tunnel beyond which heat transfer rate gradually drops. Based on this information, very high air velocity is dangerous to solar PV panels operation due to its frictional heating effect which heats up the panel instead of cooling it. Most importantly, a single expression of wind-related heat transfer coefficient (i.e. equation 5.25) for the full possible range of incident angles of wind onto the plate has also been developed in this study. This fundamental equation 5.25 whose other version is equation 5.26 has proved to be very convenient and accurate in determining the rate of convection thermal energy losses from tilted flat plate solar energy collectors in natural environment since it neither underestimates nor overestimates the values of convection heat transfer coefficient. Most importantly, the suggested single expression of (h_w) specifies the dependent of (h_w) on the incident angles of wind (θ_i) onto the plate as well as plate tilt angles (θ_p) as shown in equation 5.26 contrary to the already existing literature on (h_w). Based on the third objective of this study, a summary of the formulated single expression of (h_w) in terms of θ_i and θ_p was given below:

$$h_w = t_n f(\theta_i\,, u)$$
$$= 2 + e^{-\sin(90-\theta_i)^{0.6783}}[4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4]$$
$$h_w = t_n f(\theta_p\,, u)$$
$$= 2 + e^{-\sin(\theta_p)^{0.6783}}[4.59479u - 0.26821u^2 + 0.00770u^3 - 1.07822 \times 10^{-4}u^4]$$

When u = 0 m/s, the two fundamental unified expressions of (h_w) above reduce to:

$$h_w = h_o = 2 W/m^2 K;$$

In conclusion, convection heat transfer occurs in both still air and moving air (wind) as illustrated in Figure 5.1a, equation 5.25 and 5.26. Cooling effect of air does influence the performance of flat plate solar energy collectors as justified by figure 5.3b and 5.4**.** Based on the findings of this study, the optimal tilt angle for the flat plate solar PV collectors is $\boldsymbol{\theta}_p = 0^o$ (i.e. when $\boldsymbol{\theta}_i = 90^o$/ horizontal) while for solar thermal panels; it is $\boldsymbol{\theta}_p = 45^o$ relative to the horizontal air-flow onto the plate surface. When air velocity is below 2m/s, both solar PV panels and solar thermal collectors' mounting angle, basically takes any form of inclination angle from 0^o to 90^o. Wind-related heat transfer coefficient (h_w) depends on the incident angles of wind onto the plate/ plate tilt angles relative to wind. The Figures 5.4 and 5.5 justify the dependence of convection heat transfer coefficient (h_w) on air velocity and incident angle of wind onto the electrically heated flat plate as earlier stated in the study objectives. Figure 5.4 and 5.5 show the dependence of wind-related heat transfer coefficient (h_w) on air velocity (u) and incident angles (θ_i) of air-flow (wind) onto the plate.

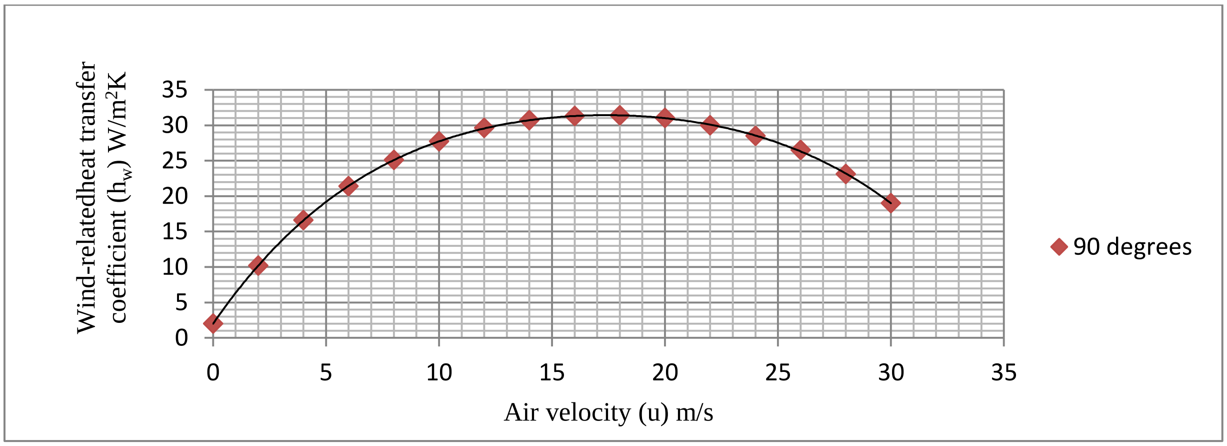

Figure 5.4: Curve of h_w as a function of air velocity at a constant incident angle of wind

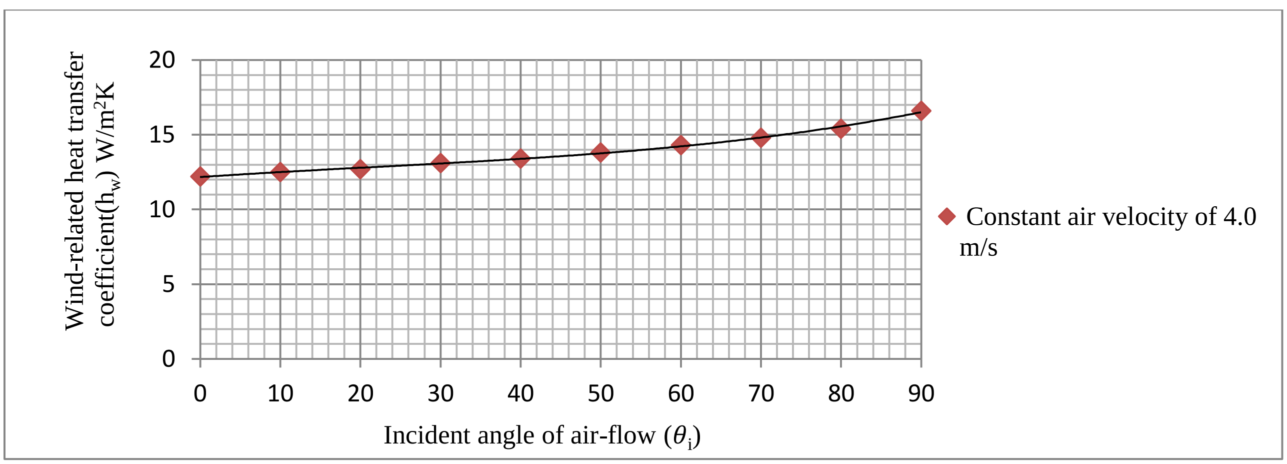

Figure 5.5: Curve of h_w as a function of incident angle of wind at a constant air velocity

5.4 Recommendations

The single expression of wind-related heat transfer coefficient (h_w) for the full possible range of incident angle of wind onto the collector is hereby proposed for use in solar energy technologies like flat plate solar PV panels and solar thermal collectors to improve their performance in a real environment. The suggested equation of (h_w) fairly estimates the rate of wind-related thermal energy losses from tilted flat plate solar collectors at both low and high air velocities. This is because it takes into account the reduction effects of viscous heat dissipation on convection heat transfer coefficient which was previously ignored by researchers in this field of study. With the adoption of the new research findings, solar energy technologies shall be tapped to their full potential in order to address the energy insecurity caused by the ballooning energy demand in both residential and industrial applications. Furthermore, global warming shall be reduced as a result of reduced consumption of conventional fuels which are emitters of greenhouse gases. Nevertheless, further research is needed to determine the implications of very high velocity of air on convection heat transfer rate from inclined heated surfaces relative to horizontal air-flow. This would help in confirming the convergence of curves of wind-related heat transfer coefficient at very high wind speeds and finally to confirm the oscillatory trend of the curves of wind-related heat transfer coefficient reported in the current study in order to comprehend the dynamics of energy flow from the inclined heated surfaces in a real environment. The findings of the study shall be disseminated through publications and scientific journals to ensure full exploitation and implementation of solar energy technologies by energy policy makers, implementers such as solar thermal and PV panels' installers. Furthermore, the results of the study will serve as references for researchers.

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