CFD Simulation of the Natural Convection of Pinned Plate Solar Absorber

By

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of the requirements for the
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CERTIFICATION OF APPROVAL

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Approved by,

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September 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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NUR AQILAH MOHD SUHAIMI
Date:

ABSTRACT

This paper corresponds to the natural convection heat transfer study on Solar Panel technology. Main principle of this study is to increase efficiency of solar panel rate of absorption by studying heat transfer activity on solar absorber plate. Introduction of modification on solar absorber plate induced variance heat transfer activity. The study aims to exhibit effect of these variables modification on natural convection heat transfer activity on solar absorber plate.

CFD (Computational Fluid Dynamics) Simulation is tool to study the fluid flow properties by simulating model with various variables. In this experiment, ANSYS 14 is used for simulation and raw data of temperature and velocity at outlet imported into calculation part which configured earlier. Final result of Nusselt number, Rayleigh number, and Reynolds Number then tabulated in tables and plotted in graphs. These dimensionless numbers represent heat transfer activity, which discussed thoroughly.

There are four (4) manipulated variables in this experiment, 1) degree of absorber plate inclination, 2) height of cone-shape pin installed on absorber plate, 3) passage length of absorber plate and 4) solar irradiance input.

Finally, all the result then compared with other correlations configured earlier and convection flow properties studied for comprehensive study.

ACKNOWLEDGEMENT

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CHAPTER 1: INTRODUCTION

1.1 Background Study

Solar energy is one of the renewable energy that becomes today’s hope in order to reduce dependency on non-renewable energy. With a lot of advantages mainly on long term effects and greene technology, solar energy become one of the most reliable yet vast discoveries made day by day upon this technology. Two major type of solar energy conversion is using thermal energy and light energy.

Main mechanism for heat absorption on solar collector is natural convention. Natural convection is a type of heat transportation in between fluid and absorber medium where the fluid motion is driven by no force and only depends upon surrounding characteristics such as different temperature gradient, buoyancy and fluid density. Therefore, in this project, angle of inclination for solar absorber plate introduced as variable mechanism. Natural convection activity represented by Nusselt number and Rayleigh number, become parameters of governing equation.

Numeral research studies from various energy associates all across the world analyze and improvise technique to enhance efficiency and productivity of this solar system. Intriguing way to increase solar absorption activity is by introducing non-flat solar collector, as for this project case, staggered pinned plate solar absorber. As per study by Y. Varol and H. F. Oztop (2007) shown that, natural convention heat transfer and fluid flow will be affected in a good way which is more heat transfer recorded on the surface [1]. Proposing pins present on surface of solar absorber stimulate turbulence effect on fluid flow, thus furthering the studies of turbulence effect of this natural heat convection.

CFD (Computational Fluid Dynamics) Simulation is one of the ways to predict the result of heat transfer activity after actual experimental and numerical calculation. By using CFD Simulator for example ANSYS 14, time consumption reduced and many properties and variables can be conducted. This increase ability and validity of the project.

1.2 Problem Statements

Previous project investigating Analytical and Experimental Work on Convective Heat Transfer in Solar Collector (Tong Seng Peow, 2011) produced remarkable result on temperature behavior using flat plate solar collector. In this project, proceeding same objective in investigating natural convection behavior on modified pinned solar collector design.

a. To study the effect of four manipulated variables which are inclination of solar absorber plate, diameter and arrangement style of pin on surface of solar plate, passage length of solar absorber plate and solar isolation irradiance input.
b. To visualize the effect of manipulated variables and obtain theoretical value of experiment result. By using CFD (Computational Fluid Dynamics) which enables user to study and investigate dynamics fluid flow of certain process.
c. To study and analyze visual results and numerical results obtained from CFD simulation. By building computational model of system, user can apply various physics and chemistry properties on the system and simulate the system to produce desired theoretical results. To ensure comprehensive study on this project, raw result from CFD Simulation then calculated to produce end result to represent heat transfer natural convection activity.

1.3 Objectives

The objective of this project is to investigate natural convection heat transfer activity on modified pinned solar absorber with 4 (four) manipulated variables. By using CFD Simulation method, all these four (4) variables simulated in software and end result is compared comprehensively based on heat transfer activity indicated by several parameters. Comprehensive study on heat transfer activities on the surface and effects of the modification.

1.4 Relevancy of Project

This project is relevant as for analysis for efficiency of solar panel, which indicates by natural convection heat transfer activity. The result of the experiment conducted can be implied in overall objective of increasing efficiency of absorption of solar panel.

To conduct this experiment, following data and software needed:-

a. Ambiance and working temperature at field work experiment.
b. Ambience velocity at field work.
c. ANSYS 14 and CATIA V5 for modeling simulation.

All the results then analyze by configuring governing equations and correlations to achieve final parameter to indicate heat transfer activity.

1.5 Scope of Study

The scope of tudy for this project is to investigate natural convection heat transfer activity on modified pinned solar absorber with 4 (four) manipulated variables:-

a. Inclination angle of solar absorber plate,
b. Height and type of pin on surface of solar absorber plate,
c. Passage length of pinned solar absorber plate.
d. Solar irradiation.

1.6 Feasibility of Project

Feasibility can be defined as the state or degree of being easily or conveniently done. In this project, this experiment of CFD Simulation is conveniently achievable to be conducted. With 8 months of two (2) semesters, the author believes that this project able to be finished and analyzed by end of period of study.

CHAPTER 2: LITERATURE REVIEW

2.1 Solar Energy as Promising Renewable Energy

Renewable energy is energy that generated from natural resources and will be replenished naturally and has longer sustainability period. Examples of widely known and operated renewable energy are wind, solar, bio-mass and geothermal energy. Most of develop countries are in progress of experimenting and moving on to renewable energies instead of fully depending on oil and gas energy. China, United States and Germany become largest sharer in sales of green energy technology products they manufacture [2]. This result from third edition of Clean Economy, Living Planet published in recently published shown that most of develop countries are moving on to invent high efficiency green technology for their own country usage and sales.

2.1.1 Thermal Energy and Light Energy Provided by the Sun

Our shiny bright sun provides two important energies which are widely used by human beings thermal energy and light energy. Thermal energy that provides heat is used to increase temperature and domestically used in urban houses as source of energy for water heater. The amount of solar energy that strikes the Earth in one hour is more than enough to provide all of the Earth’s energy needs for a complete year [3]. With abundance of solar energy that goes wasted to environment, this phenomenon induced energy technologist and engineers to think about using it for better purpose. Solar light energy is extracted by using photovoltaic cells to retrieve its light energy carried by sun radiation and converted into electricity. Meanwhile, thermal energy is converted into electricity by converted heat gained from the Sun and heat up fluid and produce steam for turbine generator which eventually produce energy.

2.2 Basic Flat Plate Solar Energy Collector System

According to Solar Collector System patent [4], basic design for solar collector system must consist of;

i. A frame member – to support whole solar collector system and acts as insulator to reduce loss of heat to environment. Must be weather tight to reduce losses of heat to surrounding. Apart from that, material selected must be weather-proof for long term usability.

ii. Supported by collector support which able to withstand all weight of solar collector and must be weather-proof for longer term usage.

iii. A top transparent covers (glazing) supported by the frame member, to allow penetration of solar radiation into solar collector system and yet reduce upward heat loss from solar absorber plate (as wavelength reflected radiation is reduced and unable to penetrate glazing cover).

iv. For solar thermal collector system, risers (tubes) filled with fluid to store heat gained from solar energy and transport them to generator.

v. Beneath the solar absorber plate, one layer of insulation installed to prevent heat loss because heat loss at bottom part of system.

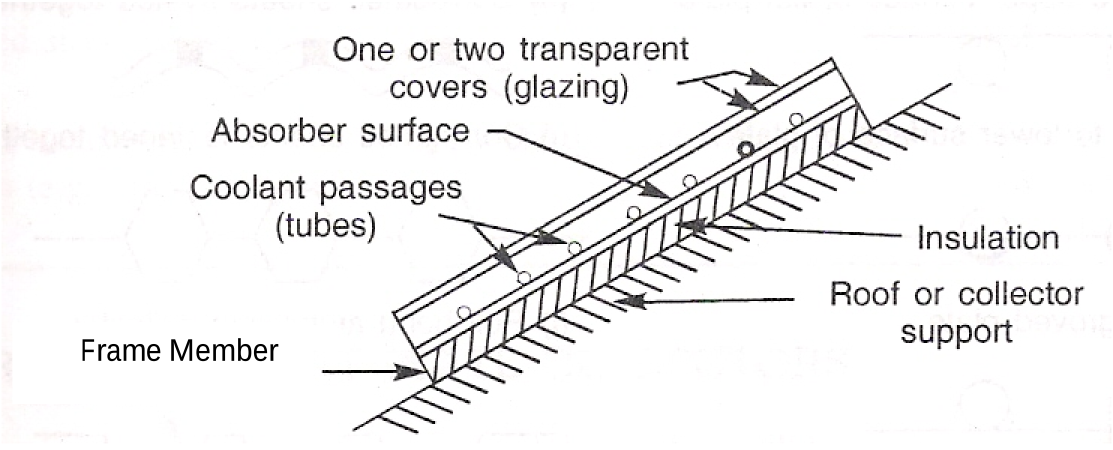


Figure 2.1: Basic Solar Collector System Patent [4]

2.3 Natural Convection and Radiation

2.3.1 What is Natural Convection and Radiation?

Convection is the study of heat transport processes affected by the flow of fluids [5]. Bejan (2004) stated that two principles of First Law of Thermodynamic which are mass conservation and force balance. These two principles used to solve many heat transfer cases. This energy expression (2.1), is taking count all perspectives of heat transfer methods into one complete equation of energy.

$$
\begin{aligned}
&(\text{rate of energy accumulation in the control volume })_1 = \\
&(\text{net transfer energy by fluid flow})_2 \; + \; (\text{net transfer by conduction})_3 \; + \\
&(\text{rate of internal heat generation})_4 - \\
&(\text{net work transfer from control volume to its enviroment})_5 \qquad (2.1)
\end{aligned}
$$

Equation (2.1) describing all aspect that need to be considered in doing analytical investigation on convection heat transfer on certain controlled volume model. All specific internal energies on each of aspect of model are taken into consideration for energy analysis on element 1,2,3, and 4. Heat flux; rate of energy transfer based on controlled surface area also introduced inside this equation at element 3 and to make this energy analysis become more reliable, heat flux must be calculated based on x-direction and y-direction of the surface. Rate of internal heat generation of the model is calculated at element 5. To gain reliable result of heat transfer case of solar absorber plate with pinned surface, all these 5 (five) elements must be considered important and only on specific reason it can be ignored.

Natural convection heat transfer occurs inside the solar collector due to buoyancy and temperature differences between cover and absorber. Y. Varol and H.F. Oztop [1] stated that number of studies shown that the aspect ratio is the most important parameter affecting the heat and fluid flow. Higher heat transfer rate is obtained at lower aspect ratio but for a certain limit value for Grashof Number. Grashof Number is dimensionless value which compares ratio of buoyancy to the viscosity of fluid flow.

2.3.2 Prandtl Number

Prandtl number (Pr) is dimensionless parameter relates to represent ratio of diffusion of momentum to diffusion of heat in fluid [6]. This factor is subjected to fluid only. Pr number ranges from 0.7 – 0.8 for common gaseous. High viscosity determines higher number of Pr for some oils, Pr number reach 10^5.

$$\text{Prandtl Number, Pr} = \frac{\text{Kinematic Viscosity}}{\text{Thermal Diffusivity}} = \frac{\upsilon}{\alpha} \tag{2.2}$$

2.3.3 Grashof Number and Rayleigh Number

Grashof Number (Gr) is a measure of the relative magnitudes of the buoyancy forces and the opposing friction force acting on the fluid [7]. Rayleigh number (Ra) is dimensionless parameter relates with natural convection which include the kinematic viscosity and thermal diffusivity of the material calculated [7]. Value of Ra is indicator for laminar or turbulence of natural convection boundary layer, which already composed by properties of air (kinematic viscosity and thermal diffusivity), hydraulic diameter and temperature difference.

$$\text{Grashof Number, } Gr = \frac{g\beta(T_a - T_f)(D_h)^3}{V^2} \tag{2.3}$$

$$\beta = \frac{1}{T_f} \tag{2.4}$$

$$\text{Rayleigh number, } Ra = Gr \cdot Pr \tag{2.5}$$

$$T_f = \frac{T_1 + T_2}{2} \tag{2.6}$$

Where,

g = gravitational force,
β = coefficient of thermal expansion of the fluid,
T_a = Temperature of absorber plate (Kelvin),
T_f = Mean temperature (Kelvin),
$T_1 + T_2$= Temperature at cold and hot surface,

$$\left.\begin{array}{ll} V & = \text{Kinematic Viscosity,} \\ K & = \text{Thermal Diffusivity,} \end{array}\right\} \text{Properties based on } T_f$$

D_h = Hydraulic Diameter

2.3.4 Nusselt Number

Nusselt number (Nu) is ratio of convective to conductive heat transfer perpendicular to boundary layer of the surface [8]. Based on formula 2.7 and 2.8, they show usage of Rayleigh number, degree of inclination, Prandtl number, and properties of air. This completely covers all 4 variables of experiment.

i. Harrolds et al. correlation [9];

a) Based on Figure 2.2, for inclined rectangular cavity of 0° < θ < 70° and $\frac{H}{L} \geq 12$;

$$Nu = 1 + 1.44\left[\left(1 - \frac{1708}{Ra \cdot \cos\theta}\right)\left(1 - \frac{1708(\sin 1.8\theta)^{1.6}}{Ra \cdot \cos\theta}\right)\right] + \left[\left(\frac{Ra \cdot \cos\theta}{5830}\right)^{\frac{1}{3}} - 1\right] \quad (2.7)$$

b) Based on Figure 2, for vertical rectangular cavity (90° from horizontal) and $10 < \frac{H}{L} < 40$;

$$Nu = 0.42 \cdot Ra^{\frac{1}{4}} \cdot Pr^{0.012} \cdot \left(\frac{H}{L}\right)^{-0.3} \quad (2.8)$$

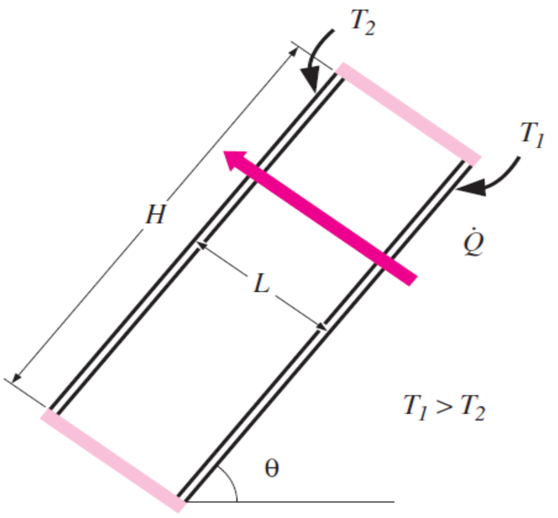


Figure 2.2 Inclined Rectangular Cavity

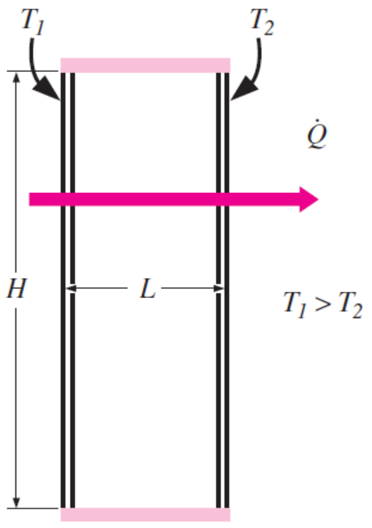


Figure 2.2 Vertical Rectangular Cavity

Where,
Ra = Rayleigh Number,
Pr = Prandtl Number.
θ = Inclination of surface horizontally,
β = coefficient of thermal expansion of the fluid

ii. Based on Dittus- Boelter correlation [10];

$$Nu = 0.023 \cdot {Re_{Dh}}^{\frac{4}{5}} \cdot Pr^{n} \qquad (2.9)$$

Where,

n = 0.4 for heating, and n = 0.3 for cooling,

Prandtl Number = $0.7 \leq Pr \leq 160$,

Reynolds Number = $Re_{Dh} \geq 10\ 000$,

$\frac{L}{D} \geq 10$

This correlation is applicable to be implied for pure heat transfer process from environment without additional temperature assistance. And always anticipate the correlation accuracy is around 15% similar.

iii. Based on Sieder-Tate correlation [11];

$$Nu = 0.027 \cdot {Re_{Dh}}^{\frac{4}{5}} \cdot Pr^{\frac{1}{3}} \cdot \left(\frac{\mu}{\mu_s}\right)^{0.14} \qquad (2.10)$$

Where,

Prandtl Number = $0.7 \leq Pr \leq 16\ 700$,

Reynolds Number = $Re_{Dh} \geq 10\ 000$,

$\frac{L}{D} \geq 10$,

μ = fluid viscosity at the bulk fluid temperature,

μ_s = fluid viscosity at the heat-transfer boundary surface temperature.

Note the usage of fluid viscosity properties at hot and cold temperature, to ensure that temperature changes due to convection included into calculation.

iv. Based on Gnielinski correlation [12];

$$Nu = \frac{\left(f/_{8}\right)(Re_{Dh}-1000)Pr}{1+12.7\left(f/_{8}\right)^{\frac{1}{2}}\left(Pr^{1/_{3}}-1\right)} \qquad (2.11)$$

Where,

Darcy friction factor developed by Petukhov [7], $f = (0.79 \ln(Re_{Dh}) - 1.64)^{-2}$

Prandtl Number = $0.5 \leq Pr \leq 2000$,

Reynolds Number = $3000 \leq Re_{Dh} \leq 5\,X\,10^{6}$

Gnielinski correlation includes the friction factor, which is called Darcy Friction Factor. There are two ways to acquire value for friction factor, by Moody chart or correlation developed by Petukhov.

2.3.4 Reynolds Number

Reynolds number is dimensionless number to signify the properties of boundary layer of fluid which in pertaining of their subjects' length, viscosity and velocity of fluid [13]. The number for flow to be identified as turbulent is must be more than 50,000. Based on **Figure 2.3**, the laminar profile is approximately parabolic, whilst turbulence profile has less changes and more linear. More turbulence the fluid flow, more energy and momentum is transported by macroscopic elements inside the fluid.

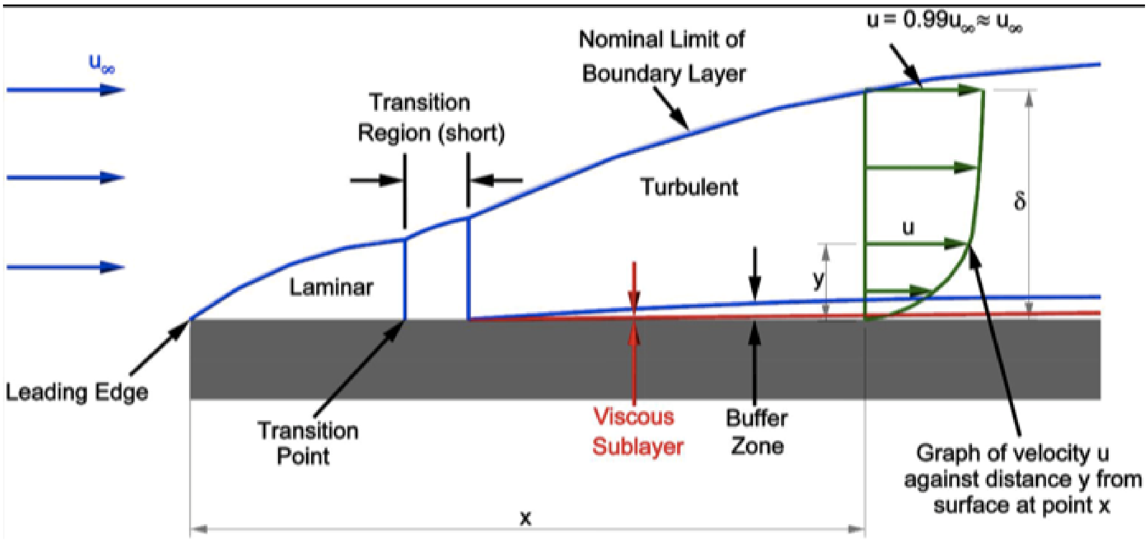


Figure 2.3 Typical Boundary Layer Flow Regimes on Flat Plate [14].

To calculate Reynolds number [13],

$$Re_{Dh} = \frac{\rho V D_h}{\mu} = \frac{V D_h}{v} \quad (2.12)$$

$$D_h = \frac{4A}{P} \quad (2.13)$$

Where,

V = free stream velocity (m/s)
μ = dynamic viscosity of air ($kg/m.s$)
D_h = Hydraulic Diameter (m)
ρ = density of air (kg/m^3)
A = Cross-sectional area for constant air flow (m^2)
P = Wetted perimeter (m)

For fluid flow through a pipe or duct, the limit of laminar, transition and turbulent flows :-

Laminar Flow : $Re_{Dh} < 2300$
Transition Flow: $2300 < Re_{Dh} < 4000$
Turbulent Flow : $Re_{Dh} > 4000$

2.3.6 Laminar Convection, Turbulence Convection and Mixed Convection

Each of fluid flow must be identified their behavior to ensure further study on fluid properties can be conducted with precise respond**. Figure 2.4** shows the regimes to conduct validation on flow properties of vertical enclosure.

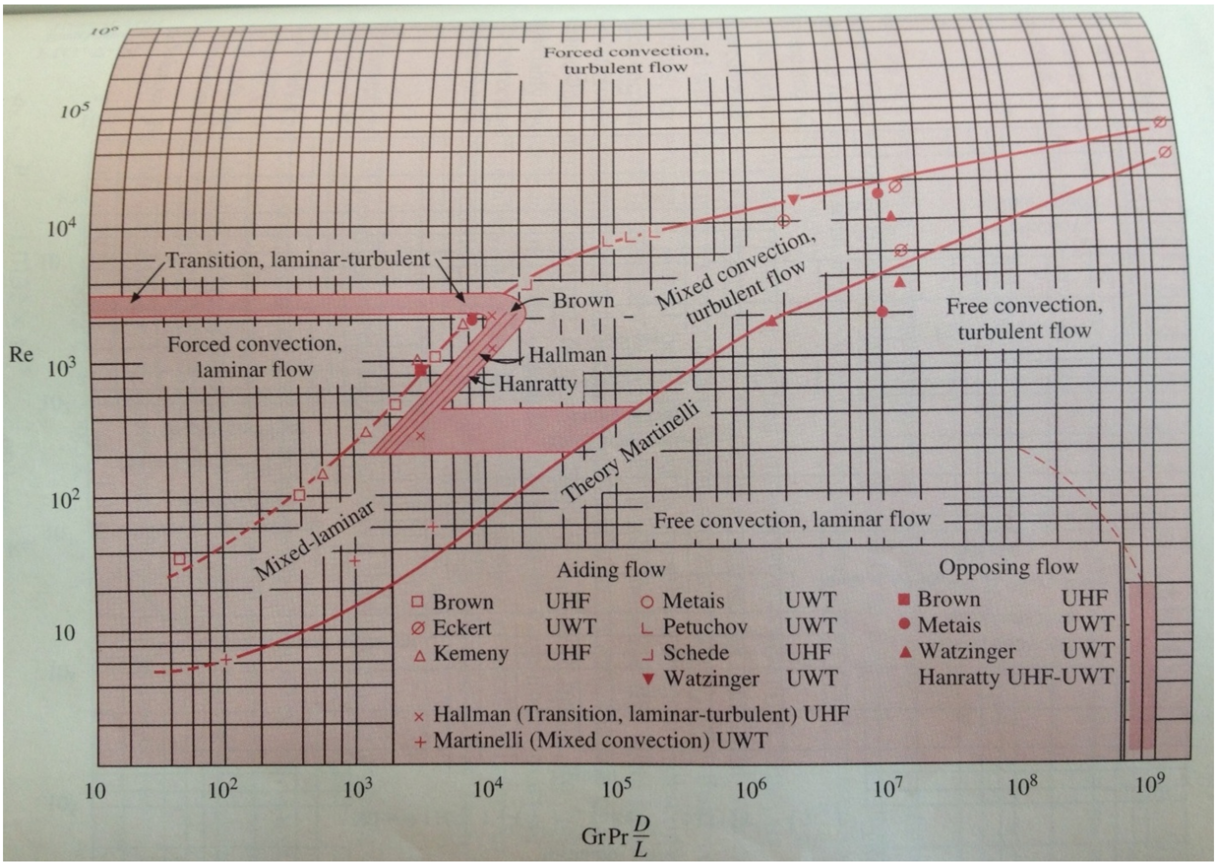


Figure 2.4 Regimes of free, forced and mixed convection for flow through vertical tubes [13].

2.4 Effect of Heat Transfer Performance of Pinned Surface in Natural Convection

2.4.1 Effect of Inclination Pinned Surface of Radiation and Convection

Alessio and Kamisnski[15] stated that natural convection and heat transfer from radiation at inclined array pinned fins, when inclination is at 30° and 60° (from horizontal) resulted lower heat transfer rate. The edge of the fins exhibited higher rate of heat transfer than the centre of array. This is due to enhanced radiation and natural convection conveyed at certain location of the arrays. Sparrow and Vemuri [16] investigated same prospect of effect of pin fin arrays on natural convection heat transfer and resulted in best orientation for highest heat transfer rate is vertical fins with horizontal base plate and surfacing upwards. And lowest rate of heat transfer recorded is vertically finned with donwfacing base plate.

Sertkaya, Bilir, and Kargici [17] studies that if the fin is installed upwards (base is horizontal) the obstruction due to base plate can be reduced thus exhibited more heat transfer rate on finned surface solar absorber. Lateral fluid flows prevent air (fluid) drawn into the fins and enhancing turbulence effect.

2.4.2 Effect of Different Height of Pinned Installed on Surface

The height of pin becomes subject of manipulated variable as there are certain minimal and maximum height for the turbulence and heat transfer enhancement to take effect. Misumi and Kitamura (1999) [18] enhancement technique was developed for natural convection heat transfer, and modification of fins utilized as heat transfer promoter. Experimental surfaces with 5mm height fins (which exceed the boundary layer thickness) achieved highest result compare to un-modified vertical flat place.

Tsuji, Kajitani and Nishino (2007) [19] by using heat transfer enhancement (promoter), heat transfer coefficient increased by a maximum value of approximately 37%. This natural convection able to be enhanced their productivity of heat transfer by promoting heat transfer activity in between air (fluid) and absorber (solid) surface. This enhancement can be applied in future project as to increase productivity of absorption that directly increase productivity of solar panel generating electricity.

2.5 CFD Simulation Enhancing Fluid Flow Studies

2.5.1 Validity of Simulating Heat Transfer Project

During CFD building simulation, there are mass, momentum and energy conservation that will form the foundation for semi-empirical models in the software. These conservations that have been derived is calculated to study the characteristics of a displacement ventilation flow pattern. As for the project, it focused more on the convection flow from heat sources and the vertical temperature and contaminant distribution (Morton 1956; Mundt 1996)[20][21]. The difficult part for this project is to constraint the natural behavior of ambient surrounding effect on the surface of solar absorber. As mentioned before, all the energy conservations must be mathematically correct in order to reduce the number of error and difference in between simulation result and experimental work result.

CFD become main technical technique for researchers to do simulation of an indoor air flow pattern. The capability of CFD to answer and virtually derives fluid flow pattern on certain system causing this CFD method to be widely developed. With ability to predict fluid flow, result of system simulation can be studied and become comparative analyze with experimental works. Regardless of this CFD ability to simulate and outcome a virtual answer for researcher, yet, exclusive data must be prepared and boundary conditions of fluid flow must be taken care before starting any building of the system. This can increase the reliability and sensitivity of the CFD and validate the results.

Though the CFD can be such a magnificent helper for any fluid flow study, yet the validity of result still become issue of concern. It is because specific discretization and the numerical input parameters must be correctively input in order to get validate and acceptable result [22]. Chen (1997) [22] indicated the necessity of experimental work in order to validate any CFD simulation result for fluid flow system modeling.

2.5.2 Energy Models Provided in Fluent and their Configurations

During CFD simulation, one of crucial part to determine success of result is to configure and utilize correct model. In ANSYS Fluent, there are few models give which is k-ε Equation Models and also Reynolds Stress Models. Yakinthos, Vlahostergios, and Goulas (2007) [23] conclude that Reynolds Stress Models able to provide good result especially when it concerns for the velocity distribution, yet left for the user/reader to choose which one of models provided to be used for CFD Simulation process. Also emphasized inside their published article, Reynolds Stress Models require higher working computer and time consuming compared to other low end models. Awbi (1998) [24] cited; accurate prediction of surface heat transfer require the uses of a low Reynolds number k-ε Equation Models. This shown that, 20 years back, by using CFD simulation, it is profound that using k-ε Equation Models is highly recommended for natural convection study. Later after Reynolds Stress Models introduced, researchers start to study this effectiveness on predicting accurately on natural behavior.

CHAPTER 3: METHODOLOGY

3.1 Gantt Chart

Table 3.1 Gantt chart for FYP1 and FYP2

Project Tasks	**Final Year Project I**														
	W1	*W2*	*W3*	*W4*	*W5*	*W6*	*W7*	*W8*	*W9*	*W10*	*W11*	*W12*	*W13*	*W14*	*W15*
Project Title Selection	▨	▨													
Preliminary Research Work															
Literature Review		▨	▨	▨	▨										
Research Methodology		▨	▨	▨	▨										
Extended Proposal Defense						🟥									
Configuring parameters						▨	▨	▨							
Formulation of governing equation								▨	▨						
Design Modeling								▨	▨	▨	▨	▨			
Data analysis							▨	▨	▨	▨	▨	▨	▨	▨	▨
Comparative analysis												▨	▨		
Report writing		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Proposal Defense									🟨						
Interim Report														🟥	

Project Tasks	**Final Year Project II**														
	W1	*W2*	*W3*	*W4*	*W5*	*W6*	*W7*	*W8*	*W9*	*W10*	*W11*	*W12*	*W13*	*W14*	*W15*
Continuation work of FYP 1	▨	▨													
Design Modeling	▨	▨	▨	▨	▨										
Analytical Analysis			▨	▨	▨	▨	▨	▨							
Result Analysis			▨	▨	▨	▨	▨	▨							
Report writing	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
Progress Report								🟥							
Pre-EDX preparation									▨	▨	▨				
Pre-EDX (Poster Presentation)											🟨				
Draft Report												🟥			
Dissertation													🟥		
Technical Paper													🟥		
Oral Presentation														🟨	
Project Final Dissertation															🟥

🟨	Presentation	🟥	Submission	▨	Process

3.2 Procedure

3.2.1 Process Flow Chart

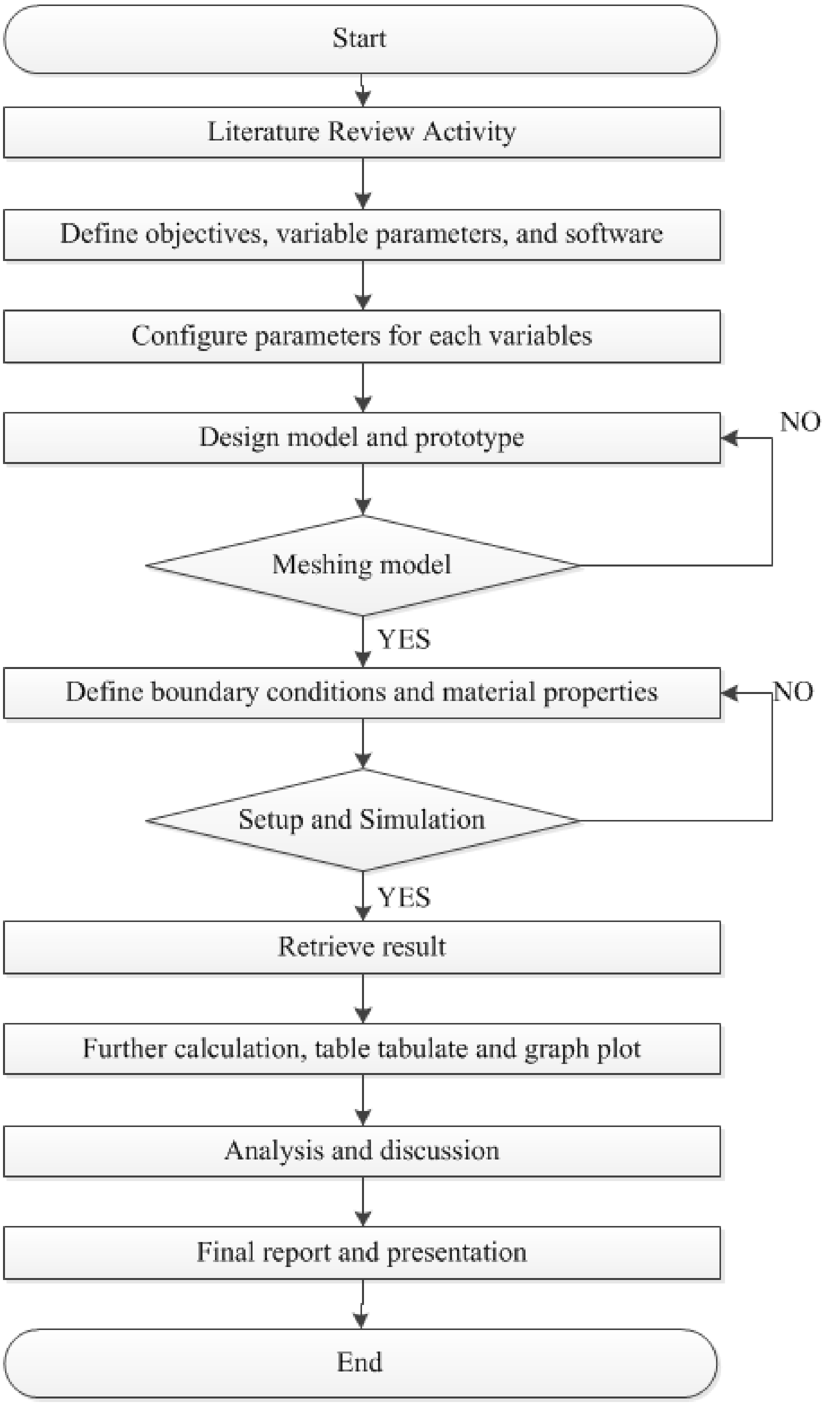


Figure 3.1 Process Flow Chart for this project

3.2.2 List of Activities

A. Identify manipulated variables needed to be investigated.
    a. Inclination angle horizontally of Solar Panel. (10^o, 30^o, 50^o, 70^o, 90^o)
    b. Solar Irradiation (200 $\frac{W}{m^2}$, 400 W/m^2, 600 W/m^2, 800 W/m^2, 1000 W/m^2).
B. Identify heat transfer equations and governing equations to be applied
    a. For Grashof Number, use **Formula (2.3)** and for Rayleigh Number, use **Formula (2.5)** ,

$$Gr = \frac{g\beta(T_1 - T_2)(L_C)^3}{V\kappa}$$

$$Ra = Gr \cdot Pr$$

    b. For primary Nusselt Number, use Harrolds et. al. correlation **Formula (2.7)** for inclined angle, and **Formula (2.8)** for vertical cavity.
        i. , for inclined rectangular cavity of 0° < θ < 70° and $\frac{H}{L} \geq 12$;

$$Nu = 1 + 1.44\left[\left(1 - \frac{1708}{Ra \cdot \cos\theta}\right)\left(1 - \frac{1708(\sin 1.8\theta)^{1.6}}{Ra \cdot \cos\theta}\right)\right] + \left[\left(\frac{Ra \cdot \cos\theta}{5830}\right)^{\frac{1}{3}} - 1\right]$$

        ii. vertical rectangular cavity (90° from horizontal) and $10 < \frac{H}{L} < 12$

$$Nu = 0.42 \cdot Ra^{\frac{1}{4}} \cdot Pr^{0.012} \cdot \left(\frac{H}{L}\right)^{-0.3}$$

    c. For Reynolds Number, use **Formula (2.12)** relative with hydraulic diameter.

$$Re_{DH} = \frac{VD_H}{v}$$

    d. For rate of heat transfer per specific area, use **Formula (2.14)** relative with hydraulic diameter

$$\frac{\dot{Q}}{A} = kNu\frac{T_{outlet} - T_{ambient}}{D_H}$$

C. Configure parameters for Solar Panel prototype and characteristics length of each variable. By using CATIA V5, designing and modeling phase is run before import all models to simulation phase.

D. By using ANSYS 14, all design models are imported for next step of CFD Simulation. Configure all simulations setup (Models, Energy Equation, Viscous (Reynolds Stress Models) and Radiation Models). Identify correct timesteps and iterations unit number for simulation running time.

E. Retrieve desired data (Velocity at Outlet, Temperature at Outlet) and import them to Excel formulae table which for Rayleigh Number, Nusselt Number and Reynolds Number calculation.

F. Tabulate data, plot graph, and analyze.

    a. For Nusselt number comparison, use Dittus- Boelter correlation **Formula (2.9),** Sieder-Tate correlation **Formula (2.10),** and Gnieliens correlation **Formula (2.11).** These three (3) correlation used to compare their result with primary Nusselt Number.

    b. Identify type of flow that induced by modified solar absorber either natural convection laminar flow, natural convection turbulence flow, mixed convection laminar flow or mixed convection turbulence flow. Identify by using **Figure 2.4** Graph of Flow Regimes.

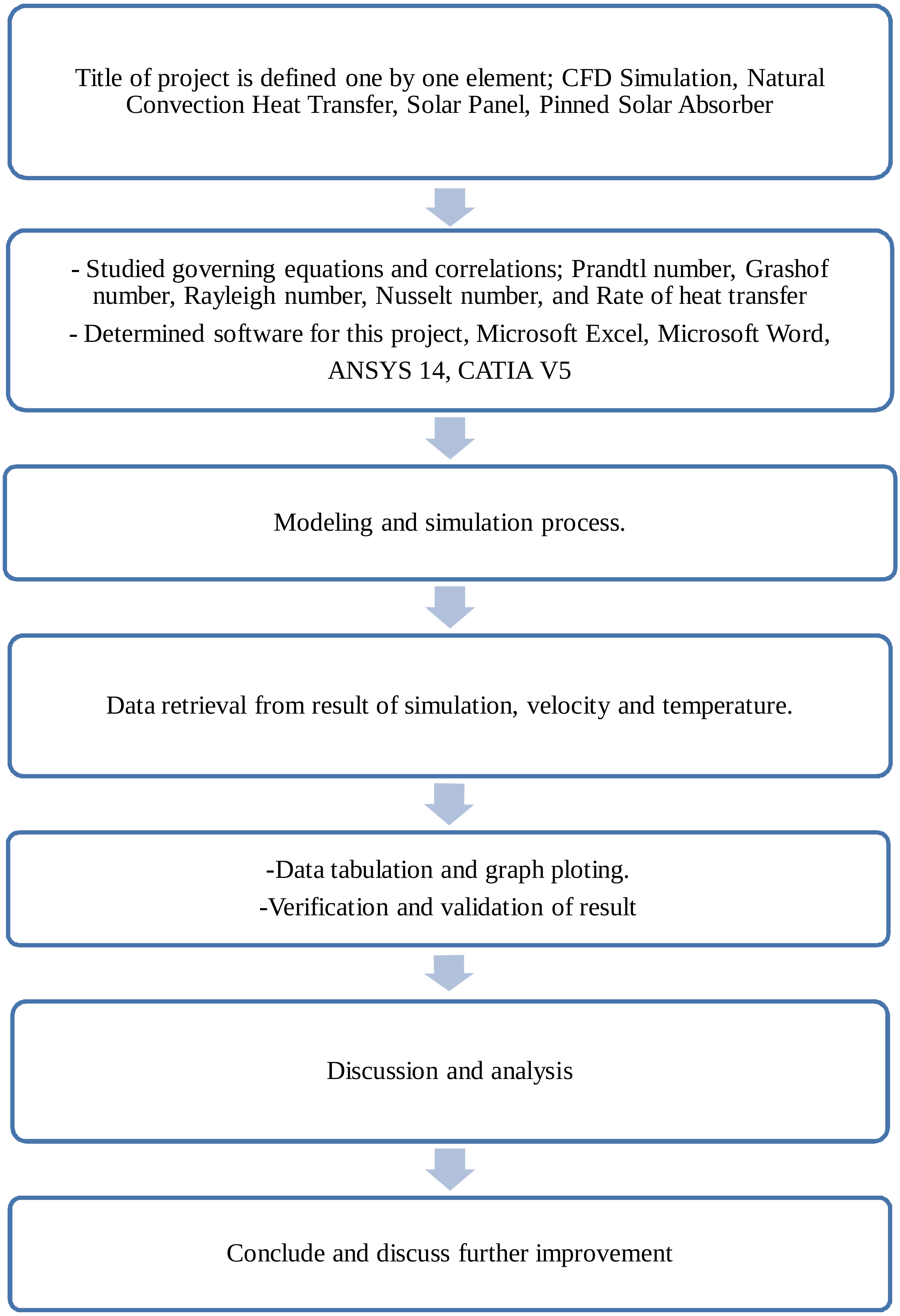
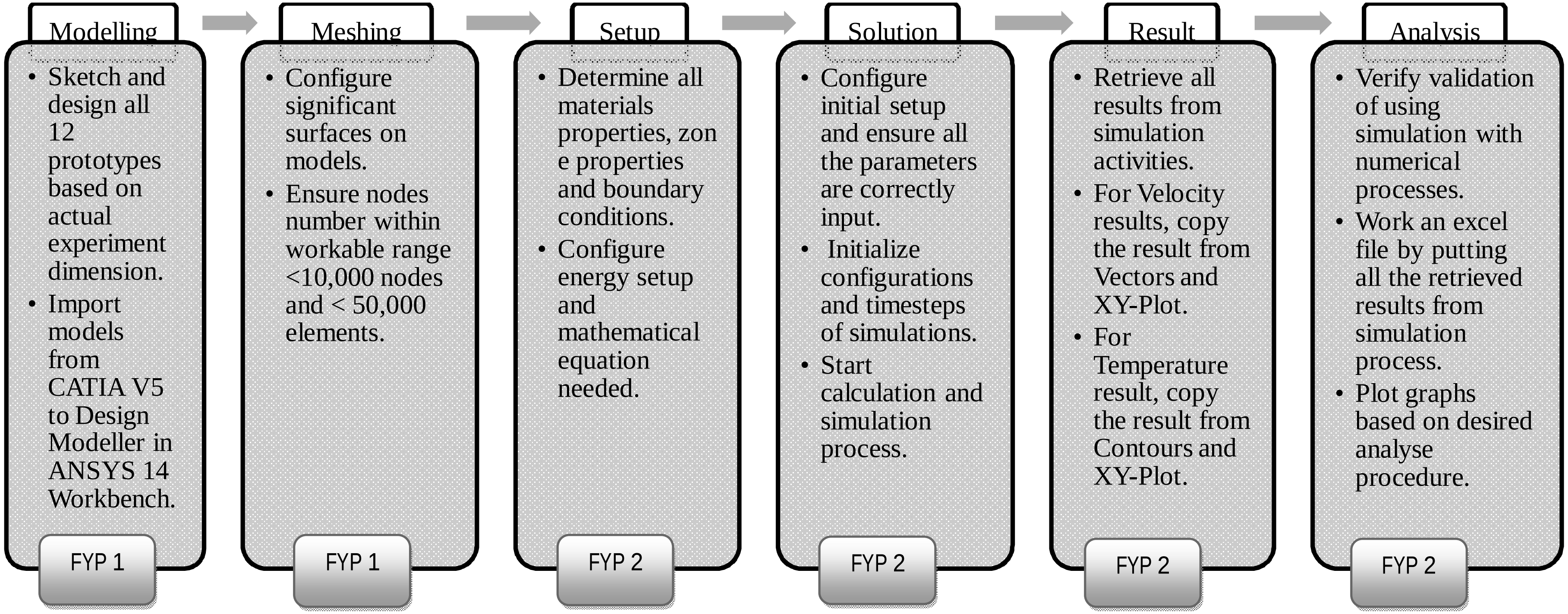


Figure 3.2 Work Flow activities for this project

3.2.3 Process of CFD Simulation



Modelling
- Sketch and design all 12 prototypes based on actual experiment dimension.
- Import models from CATIA V5 to Design Modeller in ANSYS 14 Workbench.

FYP 1

Meshing
- Configure significant surfaces on models.
- Ensure nodes number within workable range <10,000 nodes and < 50,000 elements.

FYP 1

Setup
- Determine all materials properties, zone properties and boundary conditions.
- Configure energy setup and mathematical equation needed.

FYP 2

Solution
- Configure initial setup and ensure all the parameters are correctly input.
- Initialize configurations and timesteps of simulations.
- Start calculation and simulation process.

FYP 2

Result
- Retrieve all results from simulation activities.
- For Velocity results, copy the result from Vectors and XY-Plot.
- For Temperature result, copy the result from Contours and XY-Plot.

FYP 2

Analysis
- Verify validation of using simulation with numerical processes.
- Work an excel file by putting all the retrieved results from simulation process.
- Plot graphs based on desired analyse procedure.

FYP 2

Figure 3.3 Work flow for CFD Simulation using CATIA V5 and ANSYS FLUENT

3.3 Modeling and Simulation Procedure

3.3.1 Design Modeling Activity

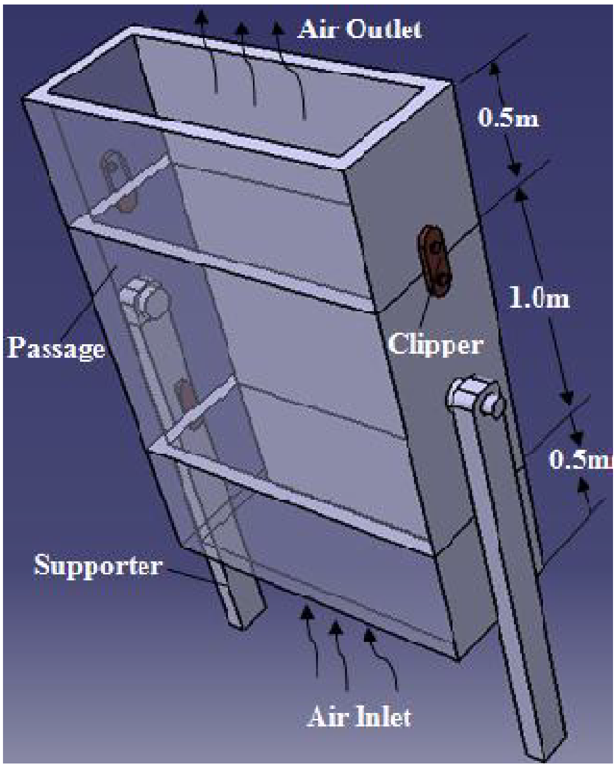


Figure 3.4 Isometric View of Overall Solar Collector

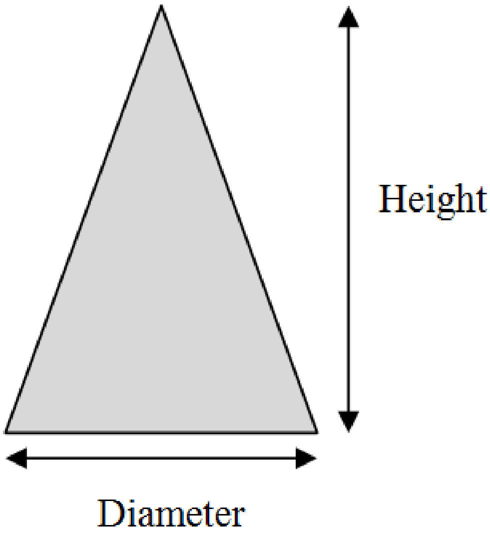


Figure 3.5 Front View of Pin

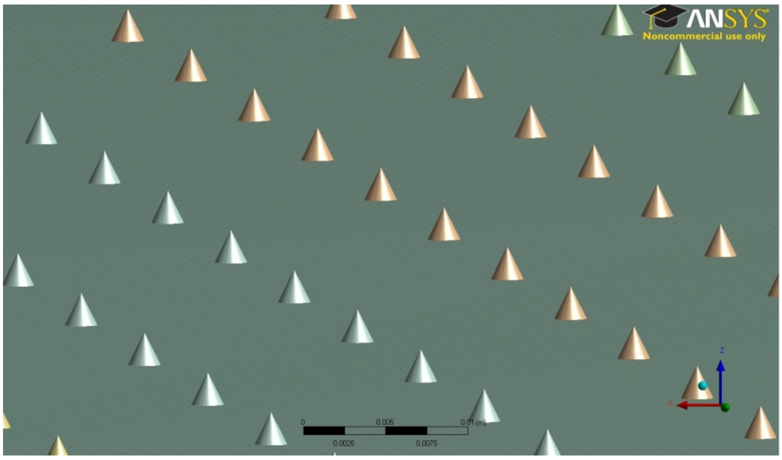


Figure 3.6 Picture of 2mm Pin in Staggered Arrangement

Figure 3.6 shows pin modified on surface of flat plate solar panel to induce turbulence and investigate heat transfer effect.

3.3.2 Design Meshing Activity

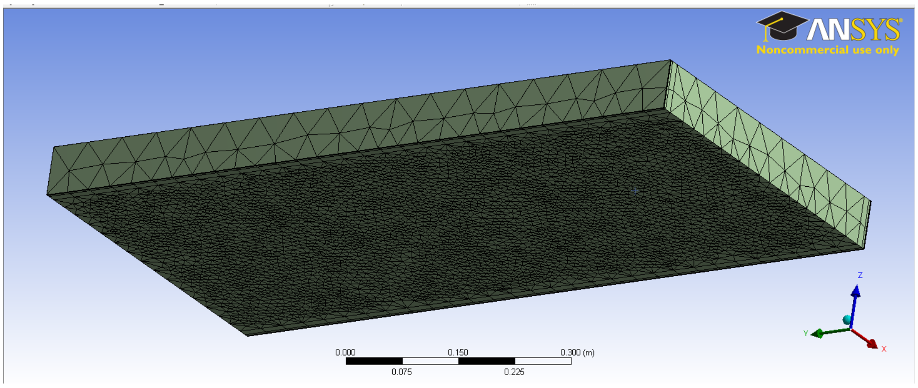
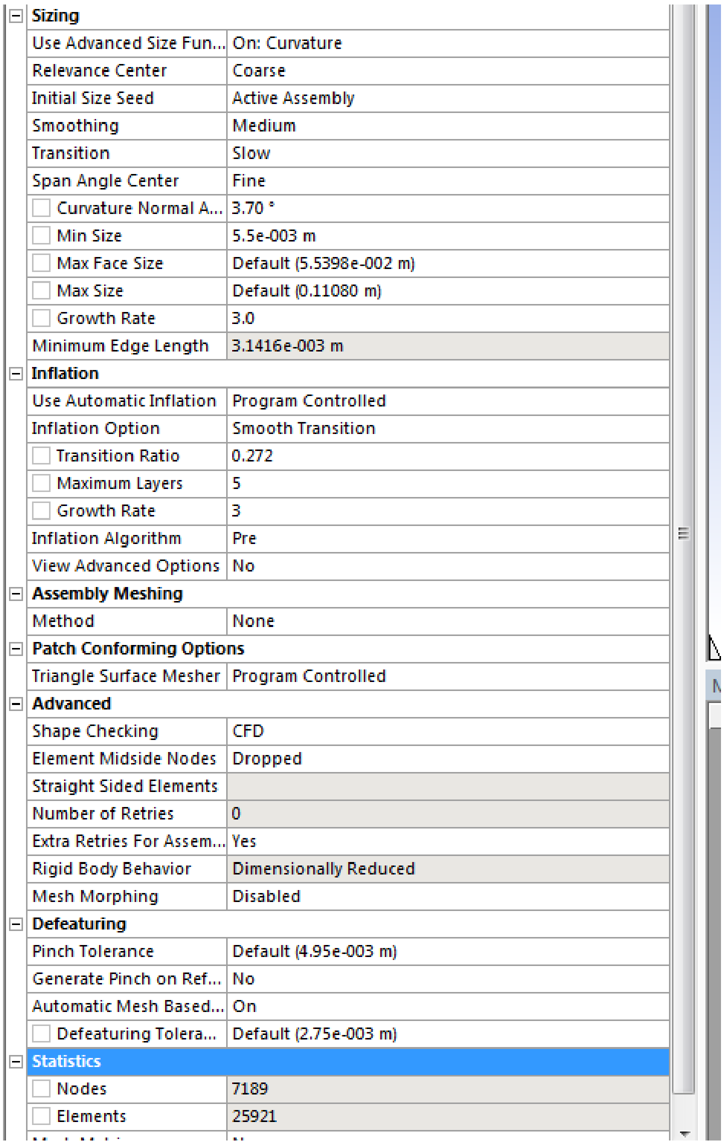


Figure 3.7 Picture of Solar Panel Model Finished Meshing

Figure 3.7 shows model of solar panel of 1000mm and 2mm pinned ready to be simulated in Setup Phase. Meshing is procedure of configuring all the nodes existed on the surface to ensure smooth simulation on next phase. The higher the nodes meshed, the better the result, but time consumed to run the simulation will increase.



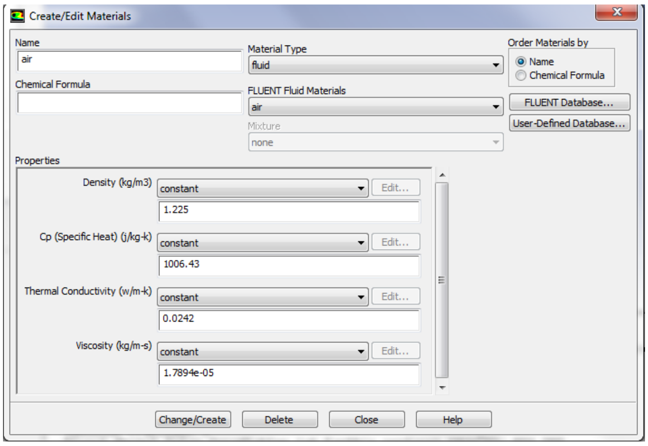
Sizing	
Use Advanced Size Fun...	On: Curvature
Relevance Center	Coarse
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Slow
Span Angle Center	Fine
☐ Curvature Normal A...	3.70 °
☐ Min Size	5.5e-003 m
☐ Max Face Size	Default (5.5398e-002 m)
☐ Max Size	Default (0.11080 m)
☐ Growth Rate	3.0
Minimum Edge Length	3.1416e-003 m
Inflation	
Use Automatic Inflation	Program Controlled
Inflation Option	Smooth Transition
☐ Transition Ratio	0.272
☐ Maximum Layers	5
☐ Growth Rate	3
Inflation Algorithm	Pre
View Advanced Options	No
Assembly Meshing	
Method	None
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Advanced	
Shape Checking	CFD
Element Midside Nodes	Dropped
Straight Sided Elements	
Number of Retries	0
Extra Retries For Assem...	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Default (4.95e-003 m)
Generate Pinch on Ref...	No
Automatic Mesh Based...	On
☐ Defeaturing Tolera...	Default (2.75e-003 m)
Statistics	
☐ Nodes	7189
☐ Elements	25921

Figure 3.8 Setup and Configuration of Meshing

Based on **Figure 3.8**, is the configuration data for meshing phase. The total nodes indicated there are around 7000 nodes for 1000mm length. Number is increasing for higher length meshed.

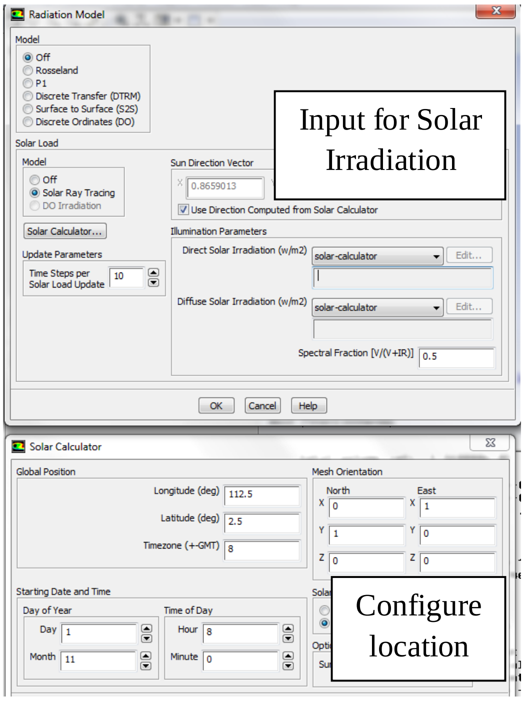
3.3.3 Setup

Based on **Figure 3.9**, Air, Aluminum, Perspex and Wood properties are determined in this Materials Data. This is to ensure that correct simulation similar with experimental field is run.



Name: air
Chemical Formula:
Material Type: fluid
FLUENT Fluid Materials: air
Mixture: none
Order Materials by: ● Name ○ Chemical Formula
Density (kg/m3): constant, 1.225
Cp (Specific Heat) (j/kg-k): constant, 1006.43
Thermal Conductivity (w/m-k): constant, 0.0242
Viscosity (kg/m-s): constant, 1.7894e-05

Figure 3.9 Materials Properties in Setup Phase



Model: ● Off ○ Rosseland ○ P1 ○ Discrete Transfer (DTRM) ○ Surface to Surface (S2S) ○ Discrete Ordinates (DO)
Solar Load Model: ○ Off ● Solar Ray Tracing ○ DO Irradiation
Sun Direction Vector: X 0.8659013
☑ Use Direction Computed from Solar Calculator
Time Steps per Solar Load Update: 10
Direct Solar Irradiation (w/m2): solar-calculator
Diffuse Solar Irradiation (w/m2): solar-calculator
Spectral Fraction [V/(V+IR)]: 0.5

Longitude (deg): 112.5
Latitude (deg): 2.5
Timezone (+-GMT): 8
Mesh Orientation: North X 0, Y 1, Z 0; East X 1, Y 0, Z 0
Day of Year: Day 1, Month 11
Time of Day: Hour 8, Minute 0

Figure 3.10 Radiation Model and Solar Tracing in Setup

The value of radiation is determined in **Figure 3.10**. There are two ways of configure value of radiation, by manually key in desired Illumination Parameters or by using Solar Calculator.

By using Solar Calculator, ANSYS FLUENT will determine the value of radiation of certain position by key in longitude and latitude of the location, and by hours of running.

As this Solar Calculator is uncertain, and the exact value of value of radiation is unknown for that relative timing, thus in this project, we are using manually input.

CHAPTER 4: RESULT AND DISCUSSION

4.1 Validation

The purpose of validation is to ensure Radiation model in ANSYS 14 Setup is verified to be applied for this experiment. There are two application designed for simulation purpose specifically for radiation model, first by using solar tracing by key in local longitude and longitude of experiment place, second is by key in desired irradiance value. In this section, comparison for result of simulation by key in desired irradiance value with experimental field work data. Both are on same manipulated variables. Result is based on **Table A1.**

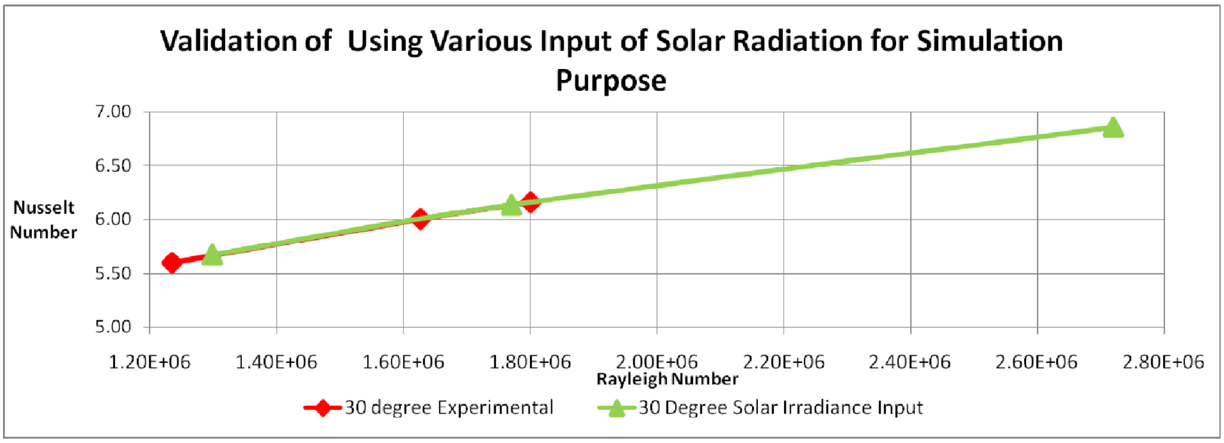


Figure 4.1 Graph for Various Solar Irradiation Input

4.1.1 Discussion

Based on **Figure 4.1**, the difference between using experimental field work and simulation on software is from 1% - 11%. This is acceptable range of result, considering environmental effect on the result of experimental work. Experimental work relatively quite lower compared to simulation as humidity and unstable wind speed become main obstacle to achieve stable and acceptable result. Meanwhile for both study cases, results are on same shape indicates that both results have similar pattern but slightly lower value of Nusselt number and Rayleigh number.

With this result of validation, this is an acceptance to use simulation result as result for this study case.

4.2 Effect of Solar Radiation on Heat Transfer Convection Activity

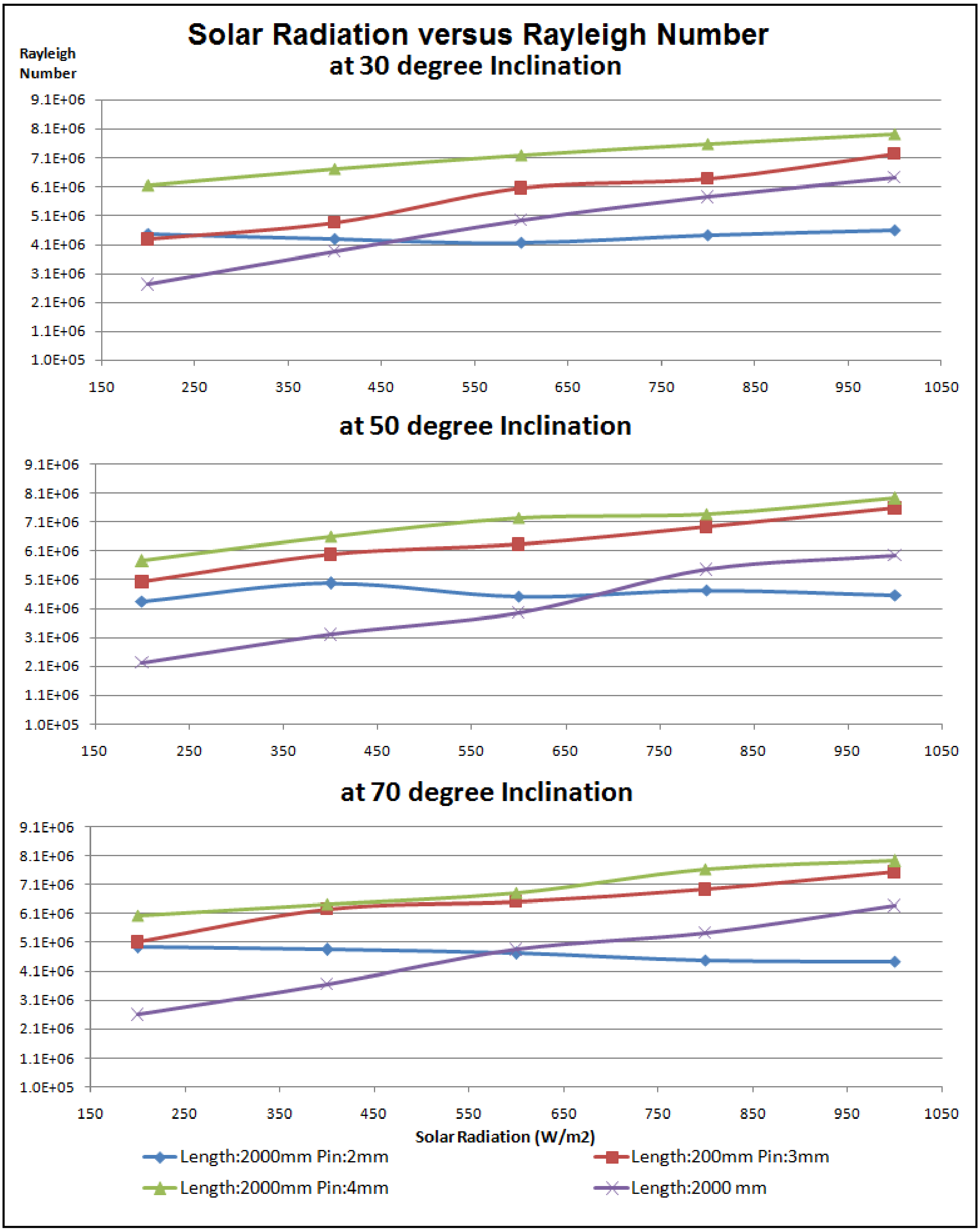


Figure 4.2 Graph of 2000mm Solar Plate with different Pin Height and Solar Inclination

4.2.1 Discussion

Figure 4.2 shows effect of altering solar irradiance input into simulation process. Effect is at different value for Rayleigh number. As discussed earlier at **Section 2.3.3**, stated Rayleigh number is dimensionless value for natural convection activity. Therefore, high Rayleigh number indicates high activity of natural convection. Graphs plotted from tables of result taken from **Appendix A4, Appendix A7, Appendix A10** and **Appendix A13**.

Result taken at 2000mm absorber plate because at this length because most stable value recorded throughout the experiment. Degree of inclination taken is at 30^o until 70^o because at this range, highest activity of convection recorded on the plate.

Outcome:-

a. The increment of heat transfer natural convection is proportional with increment of solar irradiance input for all 2000mm absorber plate (3mm pin, 4mm pin, and with no pin) except for 2mm pin which recorded linear and horizontal line.
b. 2000mm absorber plate without pin modification recorded the least activity of heat transfer which Rayleigh number is around 2.0 X 10^6, compared to 2000mm absorber plate with 4mm pin, around 6.0 X 10^6.*(Those values taken at 200 W/m2 solar radiations).*
c. For 2mm pin and 3mm pin, both pin height recorded varied result but stable within their range of 4.0 X 10^6 to 5.0 X 10^6. *(Those values taken at 200 W/m2 solar radiations).*

Reason for less activity of heat transfer recorded for 2mm pin modification is because pin height is not reaching enough height to break layer of flow barrier for 2000mm length of absorber plate. Meanwhile for 3mm and 4mm pin modification, stable increment of activity recorded with increment of solar irradiance input. This shows that both 3mm and 4mm pin modification successfully break flow layer which initiating high activity of heat transfer on surface of absorber plate.

4.3 Heat Transfer Convection Activity based on Various Variables

Rayleigh number represents convection activity occurred based on degree of inclination of the absorber plate and also various input of solar irradiance. Nusselt number represents temperature difference due to 4 manipulated variables.

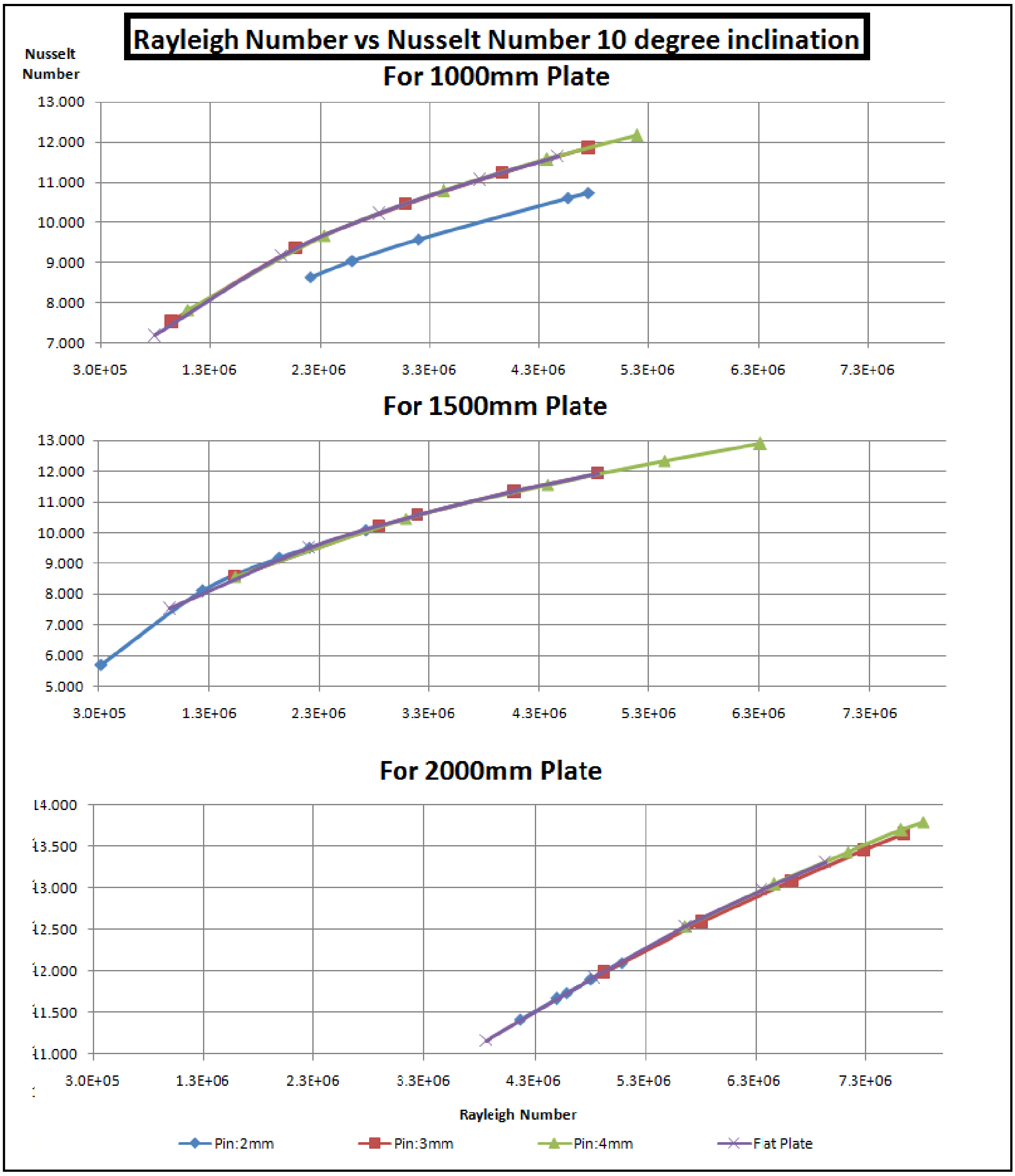


Figure 4.3 Graphs for Heat Transfer Convection Activity for 10^o Inclination

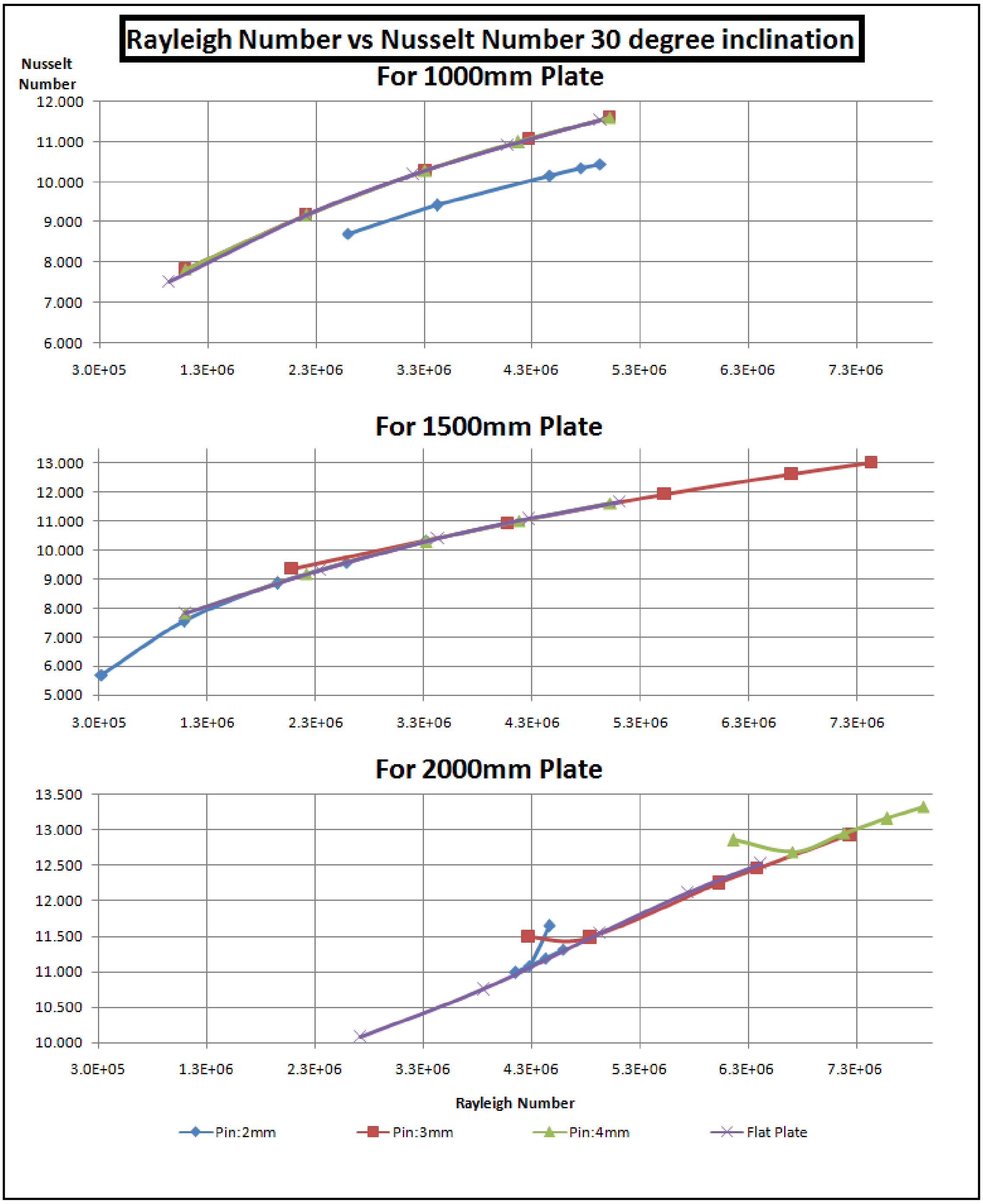


Figure 4.4 Graphs for Heat Transfer Convection Activity for 30° Inclination

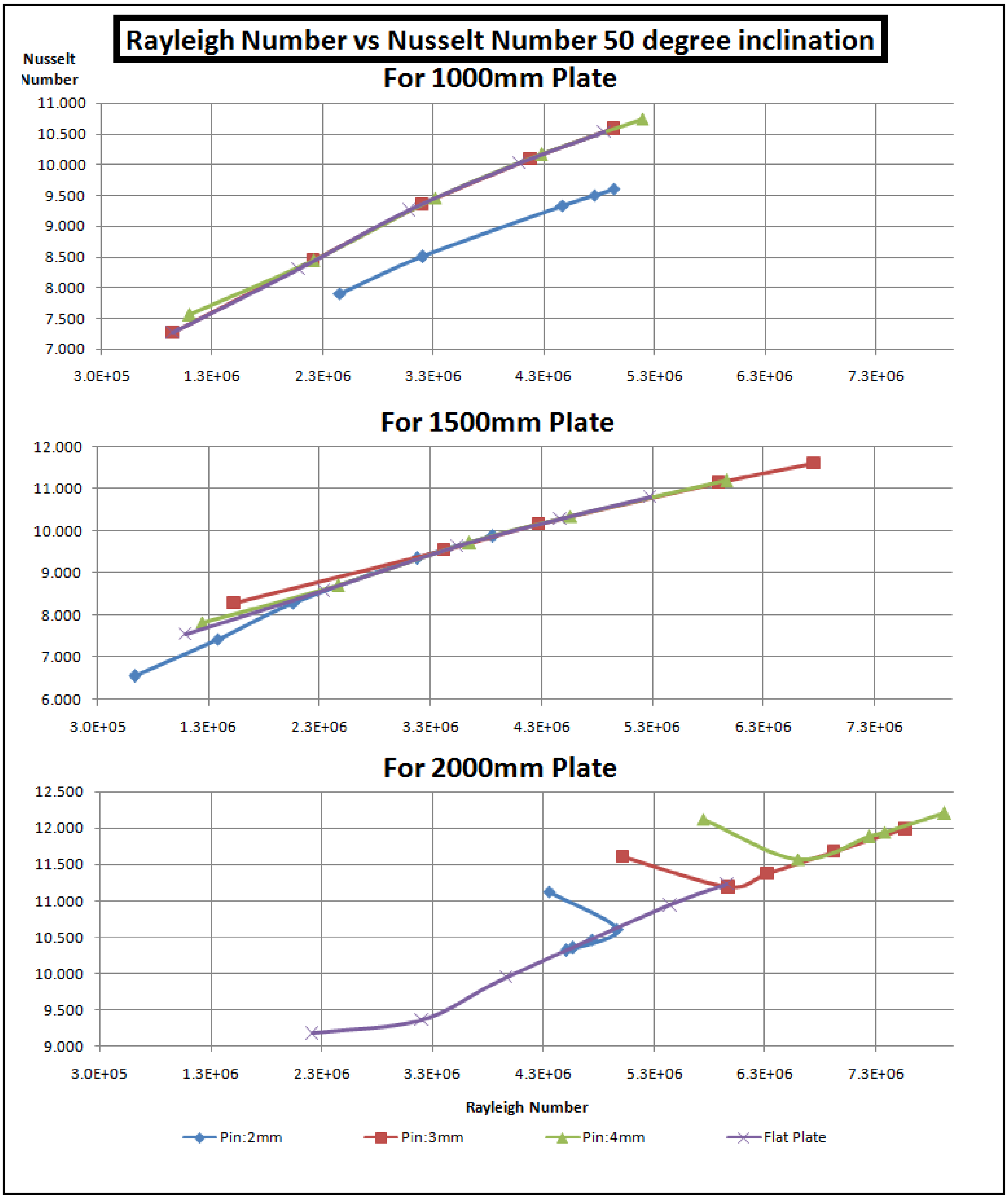


Figure 4.5 Graphs for Heat Transfer Convection Activity for 50^o Inclination

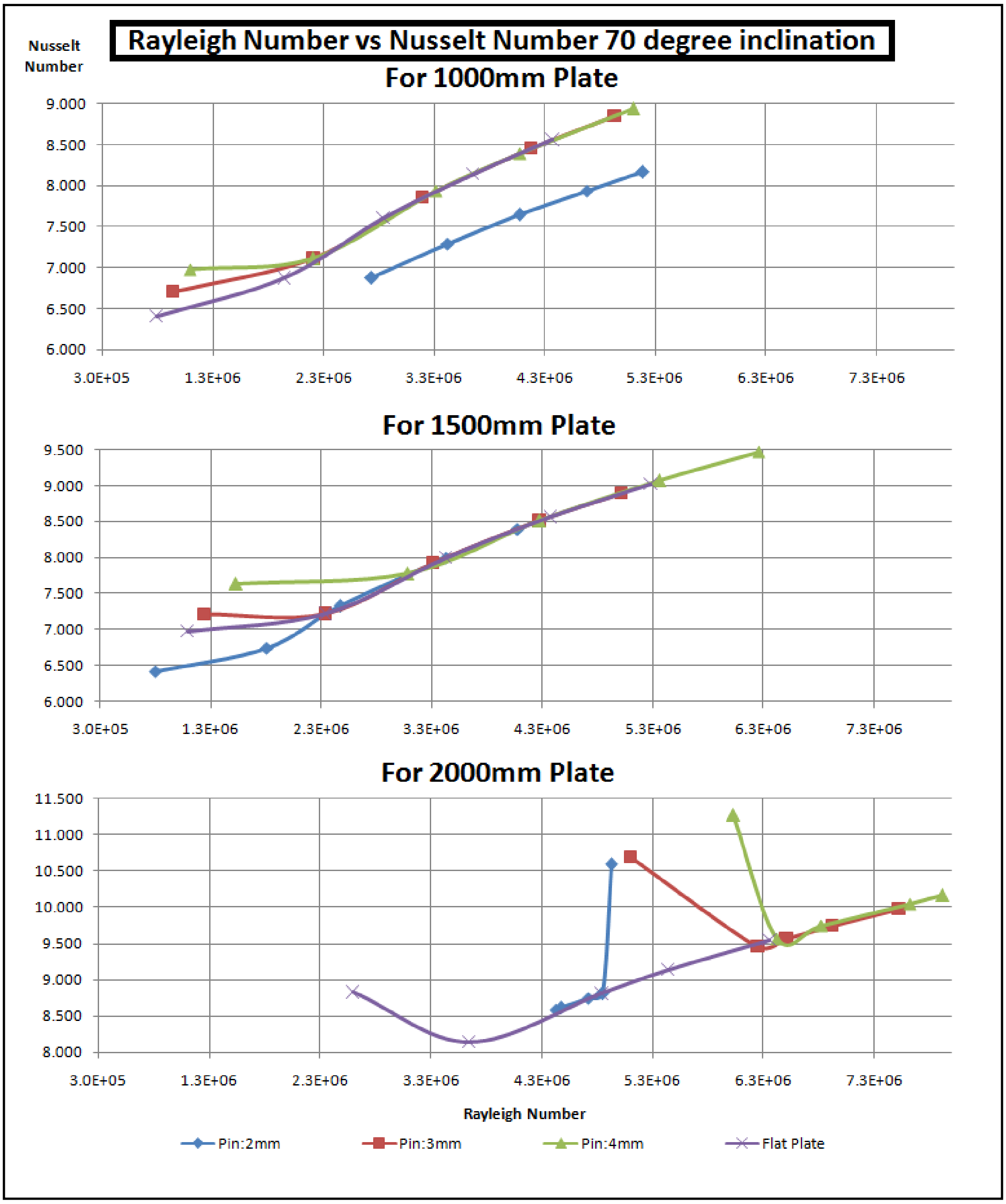


Figure 4.6 Graphs for Heat Transfer Convection Activity for 70^o Inclination

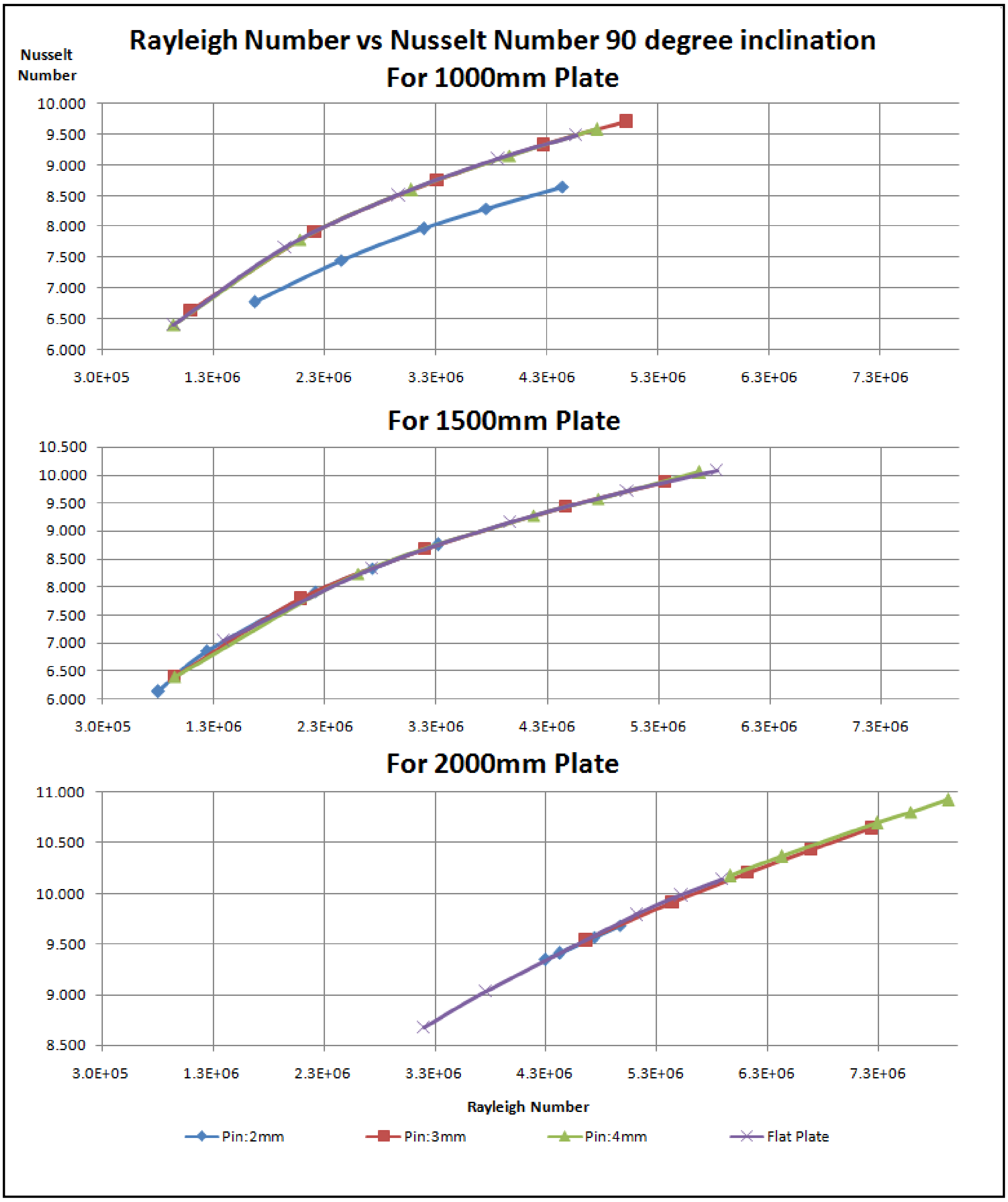


Figure 4.7 Graphs for Heat Transfer Convection Activity for 90° Inclination

4.3.1 Discussion

Figure 4.2 – Figure 4.7 show result of Rayleigh Number and Nusselt Number in relation with degree of inclination of absorber plate. As discussed earlier in **Section 2.3.3** and **Section 2.3.4**, importance of Rayleigh number and Nusselt number as indicator for heat transfer activity. Most of notations that related with Rayleigh number and Nusselt number represent heat transfer activity regardless convection or conduction, unless mentioned.

Outcome:-

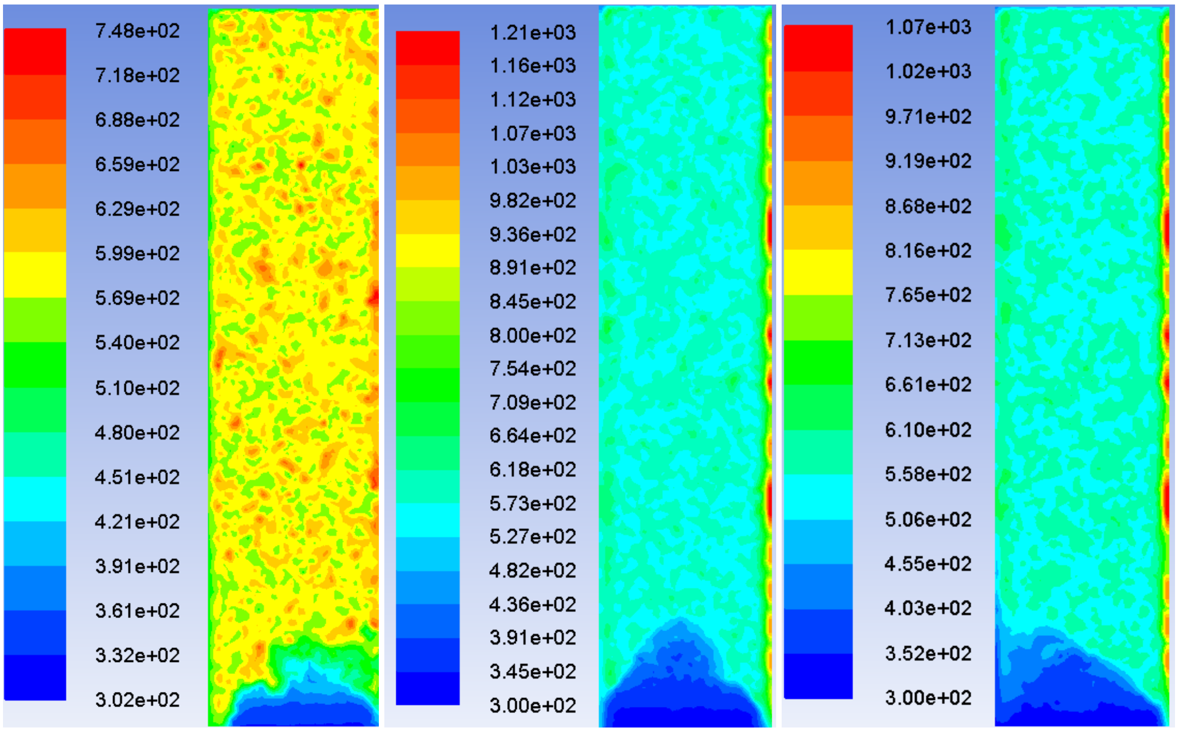
a. Based on all graphs, as Rayleigh number increasing, Nusselt number increasing.
b. 4mm pin recorded highest activity of heat transfer based on value of Rayleigh number and Nusselt number, while for 2000mm absorber plate recorded the highest activity of heat transfer. Whilst for 10^o inclination recorded highest heat transfer activity.
c. Best modification is recorded by 2000mm absorber plate with 4mm pin, at 10^o inclination.
d. Meanwhile for 30^o and 50^o of inclination, all absorber plates (1000mm, 1500mm and 2000mm) recorded most stable and highest in average of Nusselt number and Rayleigh number.
e. Alessio and Kamisnski stated when inclination is at 30^o and 60^o, resulted lowest heat transfer, for this case, 60^o and 90^o exhibit lowest heat transfer.

These discoveries show that 30^o and 50^o of inclination is most favorable to be continued for mass production as for it stability at variance solar irradiance. Especially when the experiment simulated at Malaysia's location which is tropical island that has high humidity level and at average 800 W/m^2 solar irradiance. Which explain 10^o inclination recorded highest heat transfer activity due to different level and location of experiment. It appears that different pin height recorded varied result for heat transfer activity.

2000mm absorber plate recorded highest activity of heat transfer activity because high surface area, increase the portion to absorb thermal energy from solar. High Nusselt number recorded for 2000mm absorber plates which indicates at this plate convection heat transfer activity is higher, and high Rayleigh number recorded means that most of the flow is turbulence convection.

4.4 CFD Simulation on Temperature Distribution and Velocity Magnitude

Simulation at 45^{o} inclination at 1 000 *W/m2*, blue area (outlet area) is the one taken into consideration for calculation.



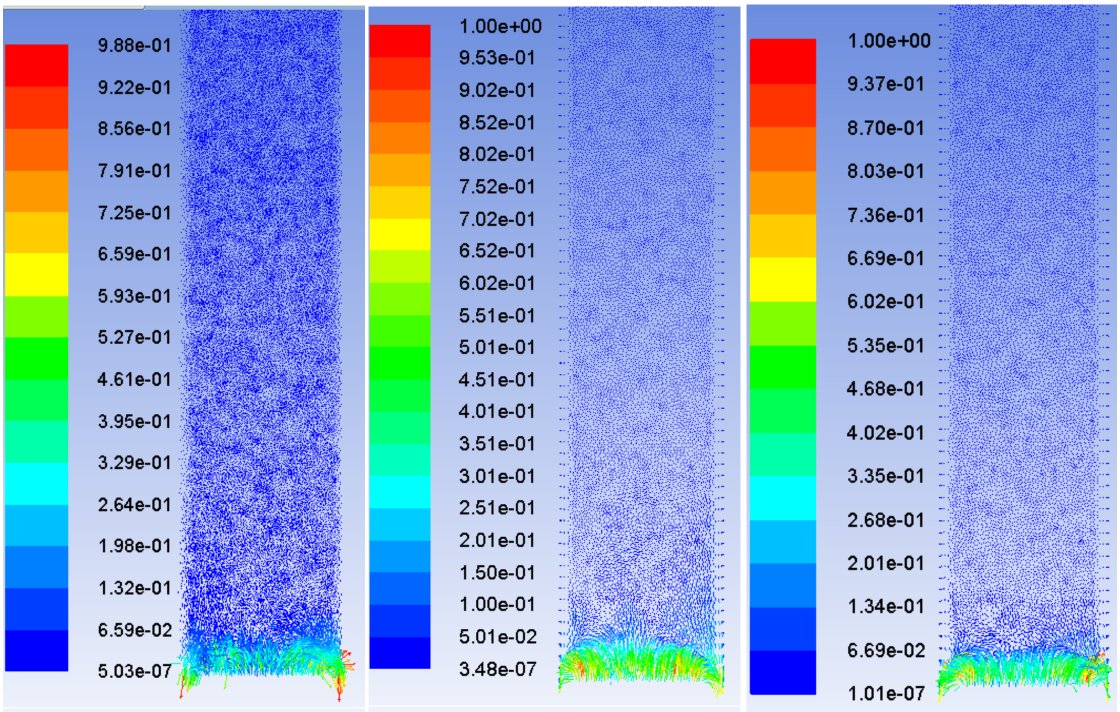
Pin Height 2mm Pin Height 3mm Pin Height 4mm

Figure 4.8 Contours Temperature Distribution for 2000mm absorber plate

4.4.1 Discussion for Contour Temperature Result

Figure 4.8 shows 3 different contour temperatures copied from simulation result .At 2mm pin, more distinguishable difference of temperature distribution and high temperature recorded at surface (except outlet) compared to 3mm and 4mm pin. Therefore, for calculation, lower heat transfer activity recorded for 1000mm length despite high temperature distribution.

3mm and 4mm pin have similar portion of distribution with 4mm is slightly higher in temperature value. Even though 2mm records high temperature value distribution, but this cannot be exact parameter indicator to accept 2mm height, as those temperatures recorded in simulation is limited to 500K (maximum working temperature for aluminum). Temperature distribution is likely to be studied compared to value displayed by simulation result.



Pin Height 2mm   Pin Height 3mm   Pin Height 4mm

Figure 4.9 Vectors Velocity Distribution for 2000mm Absorber Plate

4.4.2 Discussion for Vectors Velocity Distribution

Based on **Figure 4.9**, 2mm pin shows slightly lower velocity distribution simulated at outlet area compared to 3mm and 4mm pin, but with lower flow of strength vector velocity. At 2mm also, velocity flow is un-ordered at middle part of the plate. Nevertheless, all value of velocity recorded shows that the flow is turbulence convection flow with more than 2,300 Reynolds number (refer to **Appendix A2 – Appendix A13** for detailed values).

Changes of velocity distribution and values are less even with increment of solar irradiance. This is due to the setting at beginning of simulation to set velocity of surrounding is at 1.2 *m/s* and 70 *mm* X 480 *mm* opening for rectangular duct. Chen (1997) indicated necessity to conduct experimental work field in order to validate the result especially considering environment factor.

4.5 Nusselt number with Different Correlations and Fluid Flow Properties

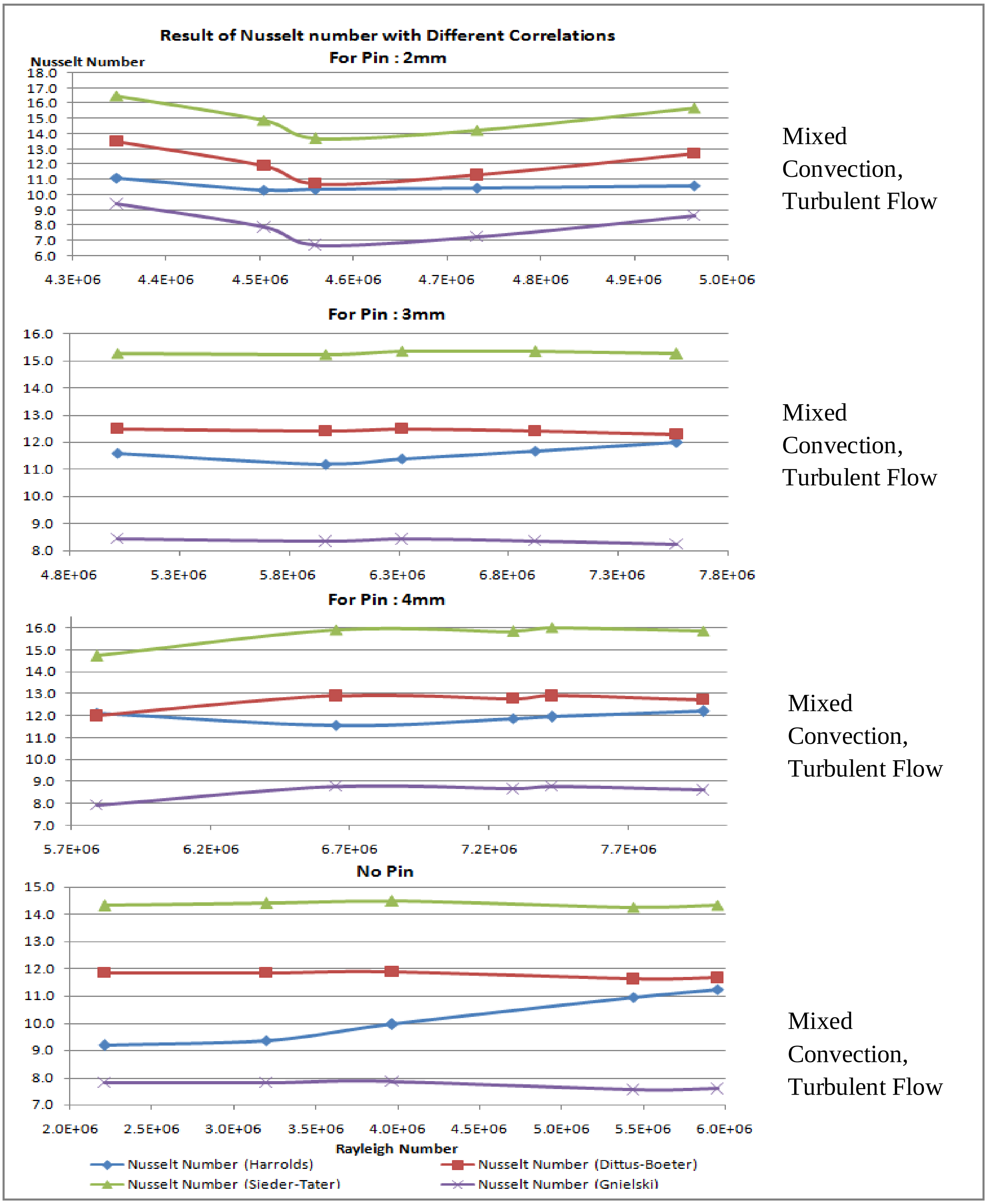


Figure 4.10 Comparison of Different Nusselt Number Correlations and Properties of Fluid Flow

4.4.1 Discussion

Harrolds correlation is the one in this experiment used to calculate Nusselt number, whilst other three (3) correlations Sieder-Tater, Dittus-Boeter and Gnielski correlations used to compare Nusselt number value. Graphs in **Figure 4.10** are from 2000mm length of absorber plate at 90o inclination, because 3 correlations do not represent Nusselt number specifically for inclined plate.

Gnielski and Dittus-Boeter correlations are closer to the value of Harrold' Nusselt number, compared to Sieder-Tate which relatively high in difference. Based on Winterton (1998), difference recorded for Dittus-Boeter correlation is around 15%, therefore proven in this experiment result. Gnielski correlation developed by including Darcy Friction Factor; increase the sensitivity of its result. Compared to Sieder-Tate and Dittus-Boeter correlations which solely depend on Reynolds number and Prandtl number.

Based on Figure 2.4 regimes for free, forced and mixed convection for flow at vertical (90O inclination), all four (4) fluid flows are mixed between forced and natural convection with turbulent flow. As been known that, when deals with natural convection heat transfer, the end result always unstable due to environment factor. With the result of fluid flow, thus for future experimen, researcher will be able to configure relatively higher sensitive correlations.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This project case's objectives successfully delivered and all the results produced throughout this timeline become new discovery for Solar Panel Intervention.

Based on objectives of investigating natural convection heat transfer activities (based on Nusselt number and Rayleigh number) subsequent to modification, these are few conclusions:-

a. The highest average heat transfer activity is from 30^o to 50^o inclination angle.
b. The highest heat transfer activity based on pin modified is 4mm height pin.
c. 2000mm passage length discovered to has highest heat transfer activity.
d. For solar irradiance, increasing the value of solar irradiation increasing the heat transfer activity.

   The best mix and match for this project is 2000mm passage length, with 4mm pin height, installed at 30^o to 50^o inclination angle with total irradiation simulated is 1000 W/m^2.

Experimenting and analyzing with natural convection heat transfer always need extra precaution and has least expectation over the result. Nevertheless, with abundance research papers and journals published based on this heat transfer field, ensure easier path for new emerged researchers to conduct experiment.

With all the objectives are successfully achieved, this CFD Simulation natural convection heat transfer for pinned plate solar absorber open wide doors of new development. Especially for high technology of CFD Simulation, researcher able to predict effects of modification on temperature distribution and velocity flow for heat transfer activity.

Current modification of pin on absorber plate matched with length of absorber plate generate variance of result which each of them up for interpretation. Turbulence of fluid flow induced by height of pin indicates that bright future of improvement in increasing solar panel ability to absorb thermal energy from the Sun.

5.2 Recommendations

For future research for this experiment, here are few recommendations:-

a. For more reliable result from CFD Simulation, increase the meshing nodes and elements to ensure more sensitive calculation process ran and simulated by ANSYS 14. Increase stability of result by try-and-error method while configuring the right setup for simulation. Note that, to ensure CFD Simulation result is relatively near with experiment result, always take note on experimental field result.
b. Increase more manipulated variables especially for height of pin, length of absorber plate, and also modification on pin arrangement and location. For future, experiment the pin by placing in downward instead of upward and parallel arrangement.

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APPENDICES

List of Appendix

Appendix A1

Table A1: Validation Table

Validation Data

Purpose : To justify ability of ANSYS to produce indifference result by comparing Solar Tracing and Manual-Key-In Insolation

Length of plate: 2000mm Height of Pin : 2mm Degree of Inclination : 30

Time	Insolation (W/m2)	T outlet (K)	T film (K)	Tfilm ©	V outlet (m/s)	V ambient (m/s)	V mean (m/s)	Rayleigh number	Reynolds Number	Nusselt Number	Difference
30 degree Experimental											
10:00 AM	368.70	325	310.5	37.5	0.52	1.2	0.861	1.24E+06	3.81E+03	5.60	1%
2:00 PM	502.93	325	313.7	40.7	0.56	1.2	0.878	1.63E+06	3.98E+03	6.00	2%
12:00 AM	665.83	329	315.3	42.3	0.46	1.2	0.831	1.80E+06	3.27E+03	6.16	11%
30 Degree Solar Irradiance Input											
[redacted]	368	320	311.0	38.0	0.47	1.2	0.835	1.30E+06	3.41E+03	5.67	[redacted]
[redacted]	502	328	315.0	42.0	0.50	1.2	0.850	1.77E+06	3.55E+03	6.13	[redacted]
[redacted]	665	348	325.0	52.0	0.68	1.2	0.940	2.72E+06	4.57E+03	6.86	[redacted]

Appendix A2

Table A2: Result Table for 1000mm Absorber Plate and 2mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	317	309.5	0.500	0.850	3.11E+06	2.2E+06	3.66E+03	8.640
400	10	320	311.0	0.510	0.855	3.66E+06	2.6E+06	3.71E+03	9.037
600	10	325	313.5	0.520	0.860	4.51E+06	3.2E+06	3.73E+03	9.585
800	10	338	320.0	0.530	0.865	6.43E+06	4.6E+06	3.66E+03	10.608
1000	10	340	321.0	0.540	0.870	6.69E+06	4.8E+06	3.71E+03	10.733
200	30	320	311.0	0.507	0.854	3.66E+06	2.6E+06	3.68E+03	8.717
400	30	327	314.5	0.517	0.859	4.83E+06	3.4E+06	3.68E+03	9.423
600	30	337	319.5	0.527	0.864	6.29E+06	4.5E+06	3.65E+03	10.162
800	30	340	321.0	0.537	0.869	6.69E+06	4.8E+06	3.69E+03	10.343
1000	30	342	322.0	0.547	0.874	6.95E+06	4.9E+06	3.74E+03	10.453
200	50	319	310.5	0.510	0.855	3.46E+06	2.5E+06	3.71E+03	7.907
400	50	325	313.5	0.520	0.860	4.51E+06	3.2E+06	3.73E+03	8.503
600	50	337	319.5	0.530	0.865	6.29E+06	4.5E+06	3.67E+03	9.336
800	50	340	321.0	0.540	0.870	6.69E+06	4.8E+06	3.71E+03	9.500
1000	50	342	322.0	0.550	0.875	6.95E+06	4.9E+06	3.76E+03	9.600
200	70	321	311.5	0.456	0.828	3.85E+06	2.7E+06	3.31E+03	6.870
400	70	327	314.5	0.466	0.833	4.83E+06	3.4E+06	3.32E+03	7.294
600	70	333	317.5	0.476	0.838	5.74E+06	4.1E+06	3.34E+03	7.643
800	70	339	320.5	0.486	0.843	6.59E+06	4.7E+06	3.36E+03	7.938
1000	70	345	323.5	0.496	0.848	7.31E+06	5.2E+06	3.36E+03	8.164
200	90	313	307.5	0.490	0.845	2.35E+06	1.7E+06	3.63E+03	6.771
400	90	319	310.5	0.500	0.850	3.46E+06	2.5E+06	3.63E+03	7.457
600	90	325	313.5	0.510	0.855	4.51E+06	3.2E+06	3.65E+03	7.966
800	90	330	316.0	0.520	0.860	5.29E+06	3.8E+06	3.67E+03	8.293
1000	90	337	319.5	0.530	0.865	6.26E+06	4.4E+06	3.66E+03	8.648

Appendix A3

Table A3: Result Table for 1500mm Absorber Plate and 2mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	304	303.0	0.475	0.8375	4.57E+05	3.2E+05	3.61E+03	5.692
400	10	310	306.0	0.480	0.8400	1.75E+06	1.2E+06	3.59E+03	8.098
600	10	315	308.5	0.485	0.8425	2.74E+06	1.9E+06	3.58E+03	9.175
800	10	317	309.5	0.490	0.8450	3.11E+06	2.2E+06	3.59E+03	9.512
1000	10	321	311.5	0.495	0.8475	3.83E+06	2.7E+06	3.59E+03	10.089
200	30	304	303.0	0.496	0.8480	4.57E+05	3.2E+05	3.77E+03	5.692
400	30	309	305.5	0.500	0.8500	1.53E+06	1.1E+06	3.74E+03	7.543
600	30	315	308.5	0.503	0.8515	2.74E+06	1.9E+06	3.71E+03	8.850
800	30	320	311.0	0.507	0.8535	3.64E+06	2.6E+06	3.67E+03	9.582
1000	30	326	314.0	0.510	0.8550	4.67E+06	3.3E+06	3.64E+03	10.290
200	50	306	304.0	0.475	0.8375	9.01E+05	6.4E+05	3.59E+03	6.550
400	50	311	306.5	0.480	0.8400	1.95E+06	1.4E+06	3.58E+03	7.431
600	50	316	309.0	0.485	0.8425	2.91E+06	2.1E+06	3.55E+03	8.284
800	50	325	313.5	0.490	0.8450	4.48E+06	3.2E+06	3.50E+03	9.343
1000	50	331	316.5	0.495	0.8475	5.44E+06	3.9E+06	3.49E+03	9.872
200	70	307	304.5	0.497	0.8485	1.12E+06	8.0E+05	3.76E+03	6.419
400	70	314	308.0	0.500	0.8500	2.55E+06	1.8E+06	3.69E+03	6.741
600	70	319	310.5	0.503	0.8515	3.48E+06	2.5E+06	3.67E+03	7.325
800	70	327	314.5	0.507	0.8535	4.83E+06	3.4E+06	3.61E+03	8.004
1000	70	333	317.5	0.510	0.8550	5.74E+06	4.1E+06	3.57E+03	8.394
200	90	307	304.5	0.502	0.8510	1.12E+06	8.0E+05	3.80E+03	6.134
400	90	310	306.0	0.505	0.8525	1.75E+06	1.2E+06	3.78E+03	6.850
600	90	317	309.5	0.509	0.8545	3.11E+06	2.2E+06	3.73E+03	7.913
800	90	321	311.5	0.513	0.8565	3.83E+06	2.7E+06	3.72E+03	8.334
1000	90	326	314.0	0.515	0.8575	4.67E+06	3.3E+06	3.68E+03	8.755

Appendix A4

Table A4: Result Table for 2000mm Absorber Plate and 2mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	334	318.0	0.497	0.849	5.88E+06	4.2E+06	3.47E+03	11.417
400	10	347	324.5	0.499	0.850	6.79E+06	4.8E+06	3.19E+03	11.905
600	10	359	330.5	0.502	0.851	7.17E+06	5.1E+06	2.96E+03	12.099
800	10	361	331.5	0.505	0.853	6.34E+06	4.5E+06	2.75E+03	11.668
1000	10	373	337.5	0.510	0.855	6.46E+06	4.6E+06	2.58E+03	11.736
200	30	337	319.5	0.489	0.845	6.29E+06	4.5E+06	3.39E+03	11.645
400	30	343	322.5	0.494	0.847	6.03E+06	4.3E+06	3.11E+03	11.079
600	30	350	326.0	0.499	0.850	5.86E+06	4.2E+06	2.88E+03	10.986
800	30	364	333.0	0.505	0.853	6.24E+06	4.4E+06	2.67E+03	11.188
1000	30	379	340.5	0.509	0.855	6.47E+06	4.6E+06	2.49E+03	11.308
200	50	336	319.0	0.496	0.848	6.12E+06	4.3E+06	3.44E+03	11.128
400	50	349	325.5	0.501	0.851	6.99E+06	5.0E+06	3.19E+03	10.608
600	50	353	327.5	0.503	0.852	6.34E+06	4.5E+06	2.93E+03	10.316
800	50	366	334.0	0.509	0.855	6.67E+06	4.7E+06	2.74E+03	10.463
1000	50	375	338.5	0.516	0.858	6.42E+06	4.6E+06	2.57E+03	10.351
200	70	342	322.0	0.491	0.846	6.95E+06	4.9E+06	3.36E+03	10.588
400	70	351	326.5	0.498	0.849	6.83E+06	4.9E+06	3.07E+03	8.812
600	70	361	331.5	0.503	0.852	6.65E+06	4.7E+06	2.81E+03	8.744
800	70	370	336.0	0.508	0.854	6.30E+06	4.5E+06	2.59E+03	8.615
1000	70	380	341.0	0.511	0.856	6.24E+06	4.4E+06	2.44E+03	8.590
200	90	335	318.5	0.496	0.848	6.05E+06	4.3E+06	3.47E+03	9.344
400	90	349	325.5	0.500	0.850	6.99E+06	5.0E+06	3.18E+03	9.686
600	90	352	327.0	0.504	0.852	6.23E+06	4.4E+06	2.94E+03	9.410
800	90	366	334.0	0.508	0.854	6.67E+06	4.7E+06	2.74E+03	9.571
1000	90	375	338.5	0.512	0.856	6.57E+06	4.7E+06	2.58E+03	9.535

Appendix A5

Table A5: Result Table for 1000mm Absorber Plate and 3mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	308	305.0	0.560	0.880	1.33E+06	9.5E+05	4.21E+03	7.520
400	10	316	309.0	0.565	0.883	2.93E+06	2.1E+06	4.15E+03	9.348
600	10	324	313.0	0.570	0.885	4.34E+06	3.1E+06	4.10E+03	10.458
800	10	332	317.0	0.586	0.893	5.59E+06	4.0E+06	4.12E+03	11.249
1000	10	340	321.0	0.590	0.895	6.69E+06	4.8E+06	4.06E+03	11.857
200	30	309	305.5	0.590	0.895	1.54E+06	1.1E+06	4.42E+03	7.824
400	30	317	309.5	0.595	0.898	3.11E+06	2.2E+06	4.36E+03	9.172
600	30	326	314.0	0.601	0.901	4.67E+06	3.3E+06	4.29E+03	10.290
800	30	335	318.5	0.603	0.902	6.02E+06	4.3E+06	4.20E+03	11.073
1000	30	343	322.5	0.615	0.908	7.07E+06	5.0E+06	4.19E+03	11.603
200	50	308	305.0	0.614	0.907	1.33E+06	9.5E+05	4.62E+03	7.263
400	50	317	309.5	0.619	0.910	3.11E+06	2.2E+06	4.54E+03	8.440
600	50	325	313.5	0.623	0.912	4.51E+06	3.2E+06	4.46E+03	9.359
800	50	334	318.0	0.625	0.913	5.88E+06	4.2E+06	4.37E+03	10.094
1000	50	342	322.0	0.629	0.915	6.95E+06	4.9E+06	4.30E+03	10.588
200	70	308	305.0	0.561	0.881	1.33E+06	9.5E+05	4.22E+03	6.710
400	70	317	309.5	0.565	0.883	3.11E+06	2.2E+06	4.14E+03	7.110
600	70	325	313.5	0.570	0.885	4.51E+06	3.2E+06	4.08E+03	7.855
800	70	334	318.0	0.575	0.888	5.88E+06	4.2E+06	4.02E+03	8.451
1000	70	342	322.0	0.580	0.890	6.95E+06	4.9E+06	3.96E+03	8.852
200	90	309	305.5	0.551	0.876	1.54E+06	1.1E+06	4.13E+03	6.638
400	90	317	309.5	0.560	0.880	3.11E+06	2.2E+06	4.10E+03	7.913
600	90	326	314.0	0.565	0.883	4.67E+06	3.3E+06	4.04E+03	8.755
800	90	335	318.5	0.570	0.885	6.02E+06	4.3E+06	3.97E+03	9.330
1000	90	343	322.5	0.575	0.888	7.07E+06	5.0E+06	3.92E+03	9.712

Appendix A6

Table A6: Result Table for 1500mm Absorber Plate and 3mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	312	307.0	0.362	0.781	2.15E+06	1.5E+06	2.69E+03	8.579
400	10	322	312.0	0.370	0.785	4.00E+06	2.8E+06	2.67E+03	10.216
600	10	325	313.5	0.375	0.788	4.51E+06	3.2E+06	2.69E+03	10.570
800	10	333	317.5	0.381	0.791	5.74E+06	4.1E+06	2.67E+03	11.336
1000	10	341	321.5	0.385	0.793	6.82E+06	4.8E+06	2.64E+03	11.923
200	30	316	309.0	0.391	0.796	2.93E+06	2.1E+06	2.87E+03	9.348
400	30	333	317.5	0.398	0.799	5.74E+06	4.1E+06	2.79E+03	10.921
600	30	349	325.5	0.406	0.803	7.77E+06	5.5E+06	2.72E+03	11.931
800	30	366	334.0	0.412	0.806	9.43E+06	6.7E+06	2.64E+03	12.627
1000	30	380	341.0	0.421	0.811	1.05E+07	7.4E+06	2.60E+03	13.025
200	50	312	307.0	0.367	0.784	2.15E+06	1.5E+06	2.73E+03	8.278
400	50	327	314.5	0.371	0.786	4.83E+06	3.4E+06	2.64E+03	9.542
600	50	335	318.5	0.379	0.790	6.02E+06	4.3E+06	2.64E+03	10.162
800	50	354	328.0	0.385	0.793	8.31E+06	5.9E+06	2.55E+03	11.150
1000	50	367	334.5	0.389	0.795	9.51E+06	6.8E+06	2.49E+03	11.598
200	70	310	306.0	0.338	0.769	1.75E+06	1.2E+06	2.53E+03	7.212
400	70	318	310.0	0.346	0.773	3.30E+06	2.3E+06	2.53E+03	7.219
600	70	326	314.0	0.351	0.776	4.67E+06	3.3E+06	2.51E+03	7.931
800	70	335	318.5	0.358	0.779	6.02E+06	4.3E+06	2.49E+03	8.506
1000	70	343	322.5	0.362	0.781	7.07E+06	5.0E+06	2.47E+03	8.895
200	90	308	305.0	0.397	0.799	1.33E+06	9.5E+05	2.99E+03	6.399
400	90	316	309.0	0.404	0.802	2.93E+06	2.1E+06	2.97E+03	7.792
600	90	325	313.5	0.411	0.806	4.51E+06	3.2E+06	2.94E+03	8.679
800	90	337	319.5	0.416	0.808	6.29E+06	4.5E+06	2.88E+03	9.434
1000	90	347	324.5	0.425	0.813	7.55E+06	5.4E+06	2.87E+03	9.873

Appendix A7

Table A7: Result Table for 2000mm Absorber Plate and 3mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	342	322.0	0.455	0.828	6.95E+06	4.9E+06	3.11E+03	11.986
400	10	353	327.5	0.465	0.833	8.20E+06	5.8E+06	3.08E+03	12.588
600	10	365	333.5	0.475	0.838	9.34E+06	6.6E+06	3.05E+03	13.082
800	10	377	339.5	0.485	0.843	1.03E+07	7.3E+06	3.02E+03	13.453
1000	10	385	343.5	0.495	0.848	1.08E+07	7.6E+06	3.02E+03	13.648
200	30	335	318.5	0.450	0.825	6.02E+06	4.3E+06	3.14E+03	11.495
400	30	341	321.5	0.460	0.830	6.82E+06	4.8E+06	3.15E+03	11.483
600	30	356	329.0	0.470	0.835	8.51E+06	6.0E+06	3.09E+03	12.250
800	30	361	331.5	0.480	0.840	8.99E+06	6.4E+06	3.12E+03	12.451
1000	30	376	339.0	0.490	0.845	1.02E+07	7.2E+06	3.06E+03	12.923
200	50	343	322.5	0.457	0.829	7.07E+06	5.0E+06	3.11E+03	11.603
400	50	355	328.5	0.467	0.834	8.41E+06	6.0E+06	3.08E+03	11.189
600	50	360	331.0	0.477	0.839	8.90E+06	6.3E+06	3.11E+03	11.375
800	50	370	336.0	0.487	0.844	9.75E+06	6.9E+06	3.09E+03	11.683
1000	50	383	342.5	0.497	0.849	1.07E+07	7.6E+06	3.05E+03	11.992
200	70	344	323.0	0.462	0.831	7.19E+06	5.1E+06	3.14E+03	10.693
400	70	359	330.5	0.472	0.836	8.80E+06	6.3E+06	3.08E+03	9.462
600	70	363	332.5	0.482	0.841	9.17E+06	6.5E+06	3.11E+03	9.571
800	70	370	336.0	0.492	0.846	9.75E+06	6.9E+06	3.12E+03	9.739
1000	70	382	342.0	0.502	0.851	1.06E+07	7.5E+06	3.09E+03	9.973
200	90	339	320.5	0.462	0.831	6.56E+06	4.7E+06	3.18E+03	9.534
400	90	348	325.0	0.472	0.836	7.66E+06	5.4E+06	3.17E+03	9.910
600	90	357	329.5	0.482	0.841	8.61E+06	6.1E+06	3.16E+03	10.204
800	90	366	334.0	0.492	0.846	9.43E+06	6.7E+06	3.15E+03	10.437
1000	90	376	339.0	0.502	0.851	1.02E+07	7.2E+06	3.14E+03	10.644

Appendix A8

Table A8: Result Table for 1000mm Absorber Plate and 4mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	309	305.5	0.503	0.852	1.54E+06	1.1E+06	3.77E+03	7.824
400	10	318	310.0	0.521	0.861	3.30E+06	2.3E+06	3.81E+03	9.666
600	10	327	314.5	0.529	0.865	4.83E+06	3.4E+06	3.77E+03	10.781
800	10	336	319.0	0.547	0.874	6.16E+06	4.4E+06	3.80E+03	11.571
1000	10	345	323.5	0.554	0.877	7.31E+06	5.2E+06	3.75E+03	12.167
200	30	309	305.5	0.495	0.848	1.54E+06	1.1E+06	3.71E+03	7.824
400	30	317	309.5	0.515	0.858	3.11E+06	2.2E+06	3.77E+03	9.172
600	30	326	314.0	0.537	0.869	4.67E+06	3.3E+06	3.84E+03	10.290
800	30	334	318.0	0.540	0.870	5.88E+06	4.2E+06	3.77E+03	10.998
1000	30	343	322.5	0.545	0.873	7.07E+06	5.0E+06	3.71E+03	11.603
200	50	309	305.5	0.488	0.844	1.54E+06	1.1E+06	3.66E+03	7.555
400	50	317	309.5	0.496	0.848	3.11E+06	2.2E+06	3.63E+03	8.440
600	50	326	314.0	0.521	0.861	4.67E+06	3.3E+06	3.72E+03	9.452
800	50	335	318.5	0.526	0.863	6.02E+06	4.3E+06	3.66E+03	10.162
1000	50	345	323.5	0.537	0.869	7.31E+06	5.2E+06	3.64E+03	10.744
200	70	309	305.5	0.477	0.839	1.54E+06	1.1E+06	3.58E+03	6.975
400	70	317	309.5	0.489	0.845	3.11E+06	2.2E+06	3.58E+03	7.110
600	70	326	314.0	0.495	0.848	4.67E+06	3.3E+06	3.54E+03	7.931
800	70	333	317.5	0.517	0.859	5.74E+06	4.1E+06	3.62E+03	8.394
1000	70	344	323.0	0.530	0.865	7.19E+06	5.1E+06	3.60E+03	8.938
200	90	308	305.0	0.463	0.832	1.33E+06	9.5E+05	3.48E+03	6.399
400	90	316	309.0	0.473	0.837	2.93E+06	2.1E+06	3.48E+03	7.792
600	90	324	313.0	0.483	0.842	4.34E+06	3.1E+06	3.47E+03	8.599
800	90	332	317.0	0.491	0.846	5.59E+06	4.0E+06	3.45E+03	9.158
1000	90	340	321.0	0.514	0.857	6.69E+06	4.8E+06	3.53E+03	9.581

Appendix A9

Table A9: Result Table for 1500mm Absorber Plate and 4mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	312	307.0	0.403	0.8015	2.15E+06	1.5E+06	3.00E+03	8.579
400	10	324	313.0	0.412	0.8060	4.34E+06	3.1E+06	2.96E+03	10.458
600	10	336	319.0	0.428	0.8140	6.16E+06	4.4E+06	2.97E+03	11.571
800	10	348	325.0	0.436	0.8180	7.66E+06	5.4E+06	2.93E+03	12.338
1000	10	360	331.0	0.440	0.8200	8.90E+06	6.3E+06	2.87E+03	12.894
200	30	309	305.5	0.414	0.8070	1.54E+06	1.1E+06	3.10E+03	7.824
400	30	317	309.5	0.421	0.8105	3.11E+06	2.2E+06	3.08E+03	9.172
600	30	326	314.0	0.433	0.8165	4.67E+06	3.3E+06	3.09E+03	10.290
800	30	334	318.0	0.444	0.8220	5.88E+06	4.2E+06	3.10E+03	10.998
1000	30	343	322.5	0.448	0.8240	7.07E+06	5.0E+06	3.05E+03	11.603
200	50	310	306.0	0.422	0.8110	1.75E+06	1.2E+06	3.15E+03	7.818
400	50	319	310.5	0.437	0.8185	3.48E+06	2.5E+06	3.18E+03	8.705
600	50	329	315.5	0.446	0.8230	5.14E+06	3.7E+06	3.16E+03	9.714
800	50	338	320.0	0.452	0.8260	6.43E+06	4.6E+06	3.12E+03	10.353
1000	50	355	328.5	0.461	0.8305	8.41E+06	6.0E+06	3.04E+03	11.189
200	70	312	307.0	0.415	0.8075	2.15E+06	1.5E+06	3.09E+03	7.630
400	70	324	313.0	0.424	0.8120	4.34E+06	3.1E+06	3.05E+03	7.777
600	70	335	318.5	0.431	0.8155	6.02E+06	4.3E+06	3.00E+03	8.506
800	70	347	324.5	0.449	0.8245	7.55E+06	5.4E+06	3.03E+03	9.061
1000	70	359	330.5	0.450	0.8250	8.80E+06	6.3E+06	2.94E+03	9.462
200	90	308	305.0	0.424	0.8120	1.33E+06	9.5E+05	3.19E+03	6.399
400	90	320	311.0	0.428	0.8140	3.66E+06	2.6E+06	3.11E+03	8.237
600	90	334	318.0	0.436	0.8180	5.88E+06	4.2E+06	3.05E+03	9.276
800	90	340	321.0	0.448	0.8240	6.69E+06	4.8E+06	3.08E+03	9.581
1000	90	352	327.0	0.458	0.8290	8.10E+06	5.7E+06	3.05E+03	10.046

Appendix A10

Table A10: Result Table for 2000mm Absorber Plate and 4mm Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	352	327.0	0.448	0.824	8.10E+06	5.7E+06	2.98E+03	12.540
400	10	364	333.0	0.458	0.829	9.26E+06	6.5E+06	2.95E+03	13.046
600	10	376	339.0	0.468	0.834	1.02E+07	7.1E+06	2.92E+03	13.426
800	10	387	344.5	0.478	0.839	1.09E+07	7.6E+06	2.90E+03	13.692
1000	10	392	347.0	0.488	0.844	1.12E+07	7.8E+06	2.93E+03	13.796
200	30	359	330.5	0.449	0.825	8.80E+06	6.2E+06	2.93E+03	12.854
400	30	368	335.0	0.458	0.829	9.59E+06	6.7E+06	2.92E+03	12.691
600	30	377	339.5	0.468	0.834	1.03E+07	7.2E+06	2.92E+03	12.949
800	30	386	344.0	0.478	0.839	1.08E+07	7.6E+06	2.91E+03	13.157
1000	30	395	348.5	0.488	0.844	1.13E+07	7.9E+06	2.90E+03	13.328
200	50	353	327.5	0.449	0.825	8.20E+06	5.7E+06	2.98E+03	12.120
400	50	366	334.0	0.509	0.855	9.43E+06	6.6E+06	3.26E+03	11.568
600	50	378	340.0	0.519	0.860	1.03E+07	7.2E+06	3.23E+03	11.884
800	50	381	341.5	0.529	0.865	1.05E+07	7.4E+06	3.26E+03	11.950
1000	50	395	348.5	0.539	0.870	1.13E+07	7.9E+06	3.21E+03	12.203
200	70	357	329.5	0.449	0.825	8.61E+06	6.0E+06	2.95E+03	11.268
400	70	363	332.5	0.458	0.829	9.17E+06	6.4E+06	2.96E+03	9.571
600	70	370	336.0	0.468	0.834	9.75E+06	6.8E+06	2.97E+03	9.739
800	70	387	344.5	0.478	0.839	1.09E+07	7.6E+06	2.90E+03	10.051
1000	70	395	348.5	0.488	0.844	1.13E+07	7.9E+06	2.90E+03	10.161
200	90	356	329.0	0.479	0.840	8.51E+06	6.0E+06	3.15E+03	10.171
400	90	363	332.5	0.489	0.845	9.17E+06	6.4E+06	3.16E+03	10.363
600	90	379	340.5	0.499	0.850	1.04E+07	7.3E+06	3.09E+03	10.695
800	90	386	344.0	0.509	0.855	1.08E+07	7.6E+06	3.10E+03	10.804
1000	90	395	348.5	0.519	0.860	1.13E+07	7.9E+06	3.09E+03	10.922

Appendix A11

Table A11: Result Table for 1000mm Absorber Plate with No Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	307	304.5	0.335	0.7675	1.12E+06	7.9E+05	2.53E+03	7.174
400	10	315	308.5	0.345	0.7725	2.74E+06	1.9E+06	2.54E+03	9.175
600	10	322	312.0	0.355	0.7775	4.00E+06	2.8E+06	2.56E+03	10.216
800	10	330	316.0	0.365	0.7825	5.29E+06	3.8E+06	2.58E+03	11.073
1000	10	337	319.5	0.375	0.7875	6.29E+06	4.5E+06	2.60E+03	11.645
200	30	308	305.0	0.349	0.7745	1.33E+06	9.5E+05	2.63E+03	7.520
400	30	317	309.5	0.359	0.7795	3.11E+06	2.2E+06	2.63E+03	9.172
600	30	325	313.5	0.369	0.7845	4.51E+06	3.2E+06	2.64E+03	10.187
800	30	333	317.5	0.379	0.7895	5.74E+06	4.1E+06	2.66E+03	10.921
1000	30	342	322.0	0.389	0.7945	6.95E+06	4.9E+06	2.66E+03	11.544
200	50	308	305.0	0.330	0.7650	1.33E+06	9.5E+05	2.48E+03	7.263
400	50	316	309.0	0.340	0.7700	2.93E+06	2.1E+06	2.50E+03	8.298
600	50	324	313.0	0.350	0.7750	4.34E+06	3.1E+06	2.51E+03	9.261
800	50	333	317.5	0.360	0.7800	5.74E+06	4.1E+06	2.52E+03	10.023
1000	50	341	321.5	0.370	0.7850	6.82E+06	4.8E+06	2.54E+03	10.532
200	70	307	304.5	0.341	0.7705	1.12E+06	7.9E+05	2.57E+03	6.409
400	70	315	308.5	0.351	0.7755	2.74E+06	1.9E+06	2.59E+03	6.873
600	70	322	312.0	0.361	0.7805	4.00E+06	2.8E+06	2.61E+03	7.606
800	70	329	315.5	0.371	0.7855	5.14E+06	3.7E+06	2.63E+03	8.144
1000	70	336	319.0	0.381	0.7905	6.16E+06	4.4E+06	2.65E+03	8.560
200	90	308	305.0	0.343	0.7715	1.33E+06	9.5E+05	2.58E+03	6.399
400	90	315	308.5	0.353	0.7765	2.74E+06	1.9E+06	2.60E+03	7.664
600	90	323	312.5	0.363	0.7815	4.18E+06	3.0E+06	2.62E+03	8.515
800	90	331	316.5	0.373	0.7865	5.44E+06	3.9E+06	2.63E+03	9.097
1000	90	338	320.0	0.383	0.7915	6.43E+06	4.6E+06	2.65E+03	9.484

Appendix A12

Table A12: Result Table for 1500mm Absorber Plate with No Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	308	305.0	0.379	0.7895	1.33E+06	9.5E+05	2.85E+03	7.520
400	10	317	309.5	0.389	0.7945	3.11E+06	2.2E+06	2.85E+03	9.512
600	10	325	313.5	0.399	0.7995	4.51E+06	3.2E+06	2.86E+03	10.570
800	10	333	317.5	0.409	0.8045	5.74E+06	4.1E+06	2.87E+03	11.336
1000	10	341	321.5	0.419	0.8095	6.82E+06	4.8E+06	2.87E+03	11.923
200	30	309	305.5	0.363	0.7815	1.54E+06	1.1E+06	2.72E+03	7.824
400	30	318	310.0	0.373	0.7865	3.30E+06	2.3E+06	2.72E+03	9.321
600	30	327	314.5	0.383	0.7915	4.83E+06	3.4E+06	2.73E+03	10.389
800	30	335	318.5	0.393	0.7965	6.02E+06	4.3E+06	2.74E+03	11.073
1000	30	344	323.0	0.403	0.8015	7.19E+06	5.1E+06	2.74E+03	11.661
200	50	309	305.5	0.379	0.7895	1.54E+06	1.1E+06	2.84E+03	7.555
400	50	318	310.0	0.389	0.7945	3.30E+06	2.3E+06	2.84E+03	8.574
600	50	328	315.0	0.399	0.7995	4.99E+06	3.5E+06	2.84E+03	9.631
800	50	337	319.5	0.409	0.8045	6.29E+06	4.5E+06	2.83E+03	10.291
1000	50	346	324.0	0.419	0.8095	7.43E+06	5.3E+06	2.83E+03	10.797
200	70	309	305.5	0.371	0.7855	1.54E+06	1.1E+06	2.78E+03	6.975
400	70	318	310.0	0.381	0.7905	3.30E+06	2.3E+06	2.78E+03	7.219
600	70	327	314.5	0.391	0.7955	4.83E+06	3.4E+06	2.78E+03	8.004
800	70	336	319.0	0.401	0.8005	6.16E+06	4.4E+06	2.79E+03	8.560
1000	70	346	324.0	0.411	0.8055	7.43E+06	5.3E+06	2.78E+03	9.022
200	90	311	306.5	0.353	0.7765	1.95E+06	1.4E+06	2.63E+03	7.043
400	90	321	311.5	0.363	0.7815	3.83E+06	2.7E+06	2.63E+03	8.334
600	90	332	317.0	0.373	0.7865	5.59E+06	4.0E+06	2.62E+03	9.158
800	90	343	322.5	0.383	0.7915	7.07E+06	5.0E+06	2.61E+03	9.712
1000	90	353	327.5	0.393	0.7965	8.20E+06	5.8E+06	2.61E+03	10.080

Appendix A13

Table A13: Result Table for 2000mm Absorber Plate with No Pin

Solar Input (W/m2)	Angle (degree)	T outlet (K)	T film (K)	V outlet (m/s)	V mean (m/s)	Grashorf Number	Rayleigh number	Reynolds Number	Nusselt Number (Harrolds)
200	10	331	316.5	0.322	0.761	5.44E+06	3.9E+06	2.27E+03	11.162
400	10	341	321.5	0.332	0.766	6.82E+06	4.8E+06	2.28E+03	11.923
600	10	352	327.0	0.342	0.771	8.10E+06	5.7E+06	2.28E+03	12.540
800	10	362	332.0	0.352	0.776	9.08E+06	6.4E+06	2.28E+03	12.972
1000	10	372	337.0	0.362	0.781	9.90E+06	6.9E+06	2.28E+03	13.310
200	30	321	311.5	0.329	0.7645	3.83E+06	2.7E+06	2.38E+03	10.089
400	30	331	316.5	0.339	0.7695	5.44E+06	3.9E+06	2.39E+03	10.754
600	30	342	322.0	0.349	0.7745	6.95E+06	4.9E+06	2.39E+03	11.544
800	30	353	327.5	0.359	0.7795	8.20E+06	5.7E+06	2.38E+03	12.120
1000	30	363	332.5	0.369	0.7845	9.17E+06	6.4E+06	2.38E+03	12.524
200	50	317	309.5	0.397	0.7985	3.11E+06	2.2E+06	2.91E+03	9.172
400	50	325	313.5	0.407	0.8035	4.51E+06	3.2E+06	2.92E+03	9.359
600	50	332	317.0	0.417	0.8085	5.59E+06	4.0E+06	2.93E+03	9.947
800	50	349	325.5	0.427	0.8135	7.77E+06	5.4E+06	2.86E+03	10.938
1000	50	356	329.0	0.437	0.8185	8.51E+06	6.0E+06	2.88E+03	11.227
200	70	320	311.0	0.395	0.7975	3.66E+06	2.6E+06	2.87E+03	8.826
400	70	329	315.5	0.405	0.8025	5.14E+06	3.7E+06	2.87E+03	8.144
600	70	341	321.5	0.415	0.8075	6.82E+06	4.8E+06	2.84E+03	8.807
800	70	349	325.5	0.425	0.8125	7.77E+06	5.4E+06	2.85E+03	9.136
1000	70	362	332.0	0.435	0.8175	9.08E+06	6.4E+06	2.82E+03	9.545
200	90	325	313.5	0.417	0.8085	4.51E+06	3.2E+06	2.99E+03	8.679
400	90	330	316.0	0.427	0.8135	5.29E+06	3.8E+06	3.02E+03	9.034
600	90	345	323.5	0.437	0.8185	7.31E+06	5.1E+06	2.96E+03	9.792
800	90	350	326.0	0.447	0.8235	7.88E+06	5.5E+06	2.99E+03	9.979
1000	90	355	328.5	0.457	0.8285	8.41E+06	5.9E+06	3.02E+03	10.141

Appendix A14

Table A14: Result of Nusselt number with Different Correlations

<table>
<tr><th colspan="8">Length:2000mm Pin:2mm</th></tr>
<tr><th>Insolation (W/m2)</th><th>Angle (degree)</th><th>Rayleigh number</th><th>Reynolds Number</th><th>Nusselt Number (Harrolds)</th><th>Nusselt Number (Dittus-Boeter)</th><th>Nusselt Number (Sieder-Tater)</th><th>Nusselt Number (Gnielski)</th></tr>
<tr><td>200</td><td>50</td><td>4.3E+06</td><td>3.44E+03</td><td>11.128</td><td>13.524</td><td>16.489</td><td>9.415</td></tr>
<tr><td>400</td><td>50</td><td>5.0E+06</td><td>3.19E+03</td><td>10.608</td><td>12.732</td><td>15.711</td><td>8.665</td></tr>
<tr><td>600</td><td>50</td><td>4.5E+06</td><td>2.93E+03</td><td>10.316</td><td>11.920</td><td>14.888</td><td>7.882</td></tr>
<tr><td>800</td><td>50</td><td>4.7E+06</td><td>2.74E+03</td><td>10.463</td><td>11.297</td><td>14.266</td><td>7.269</td></tr>
<tr><td>1000</td><td>50</td><td>4.6E+06</td><td>2.57E+03</td><td>10.351</td><td>10.732</td><td>13.701</td><td>6.705</td></tr>
<tr><th colspan="8">Length:200mm Pin:3mm</th></tr>
<tr><th>Insolation (W/m2)</th><th>Angle (degree)</th><th>Rayleigh number</th><th>Reynolds Number</th><th>Nusselt Number (Harrolds)</th><th>Nusselt Number (Dittus-Boeter)</th><th>Nusselt Number (Sieder-Tater)</th><th>Nusselt Number (Gnielski)</th></tr>
<tr><td>200</td><td>50</td><td>5.0E+06</td><td>3.11E+03</td><td>11.603</td><td>12.502</td><td>15.278</td><td>8.444</td></tr>
<tr><td>400</td><td>50</td><td>6.0E+06</td><td>3.08E+03</td><td>11.189</td><td>12.394</td><td>15.215</td><td>8.341</td></tr>
<tr><td>600</td><td>50</td><td>6.3E+06</td><td>3.11E+03</td><td>11.375</td><td>12.477</td><td>15.344</td><td>8.420</td></tr>
<tr><td>800</td><td>50</td><td>6.9E+06</td><td>3.09E+03</td><td>11.683</td><td>12.421</td><td>15.332</td><td>8.366</td></tr>
<tr><td>1000</td><td>50</td><td>7.6E+06</td><td>3.05E+03</td><td>11.992</td><td>12.293</td><td>15.245</td><td>8.243</td></tr>
<tr><th colspan="8">Length:2000mm Pin:4mm</th></tr>
<tr><th>Insolation (W/m2)</th><th>Angle (degree)</th><th>Rayleigh number</th><th>Reynolds Number</th><th>Nusselt Number (Harrolds)</th><th>Nusselt Number (Dittus-Boeter)</th><th>Nusselt Number (Sieder-Tater)</th><th>Nusselt Number (Gnielski)</th></tr>
<tr><td>200</td><td>50</td><td>5.7E+06</td><td>2.98E+03</td><td>12.120</td><td>11.995</td><td>14.728</td><td>7.907</td></tr>
<tr><td>400</td><td>50</td><td>6.6E+06</td><td>3.26E+03</td><td>11.568</td><td>12.903</td><td>15.919</td><td>8.772</td></tr>
<tr><td>600</td><td>50</td><td>7.2E+06</td><td>3.23E+03</td><td>11.884</td><td>12.784</td><td>15.841</td><td>8.659</td></tr>
<tr><td>800</td><td>50</td><td>7.4E+06</td><td>3.26E+03</td><td>11.950</td><td>12.901</td><td>16.004</td><td>8.771</td></tr>
<tr><td>1000</td><td>50</td><td>7.9E+06</td><td>3.21E+03</td><td>12.203</td><td>12.727</td><td>15.867</td><td>8.606</td></tr>
<tr><th colspan="8">Length:2000 mm No Pin</th></tr>
<tr><th>Insolation (W/m2)</th><th>Angle (degree)</th><th>Rayleigh number</th><th>Reynolds Number</th><th>Nusselt Number (Harrolds)</th><th>Nusselt Number (Dittus-Boeter)</th><th>Nusselt Number (Sieder-Tater)</th><th>Nusselt Number (Gnielski)</th></tr>
<tr><td>200</td><td>50</td><td>2.2E+06</td><td>2.91E+03</td><td>9.172</td><td>11.836</td><td>14.319</td><td>7.800</td></tr>
<tr><td>400</td><td>50</td><td>3.2E+06</td><td>2.92E+03</td><td>9.359</td><td>11.858</td><td>14.391</td><td>7.821</td></tr>
<tr><td>600</td><td>50</td><td>4.0E+06</td><td>2.93E+03</td><td>9.947</td><td>11.901</td><td>14.483</td><td>7.863</td></tr>
<tr><td>800</td><td>50</td><td>5.4E+06</td><td>2.86E+03</td><td>10.938</td><td>11.623</td><td>14.250</td><td>7.548</td></tr>
<tr><td>1000</td><td>50</td><td>6.0E+06</td><td>2.88E+03</td><td>11.227</td><td>11.661</td><td>14.335</td><td>7.585</td></tr>
</table>