COOLING OF PHOTOVOLTAIC PANEL USING WATER-COOLED SYSTEM

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DECLARATION

I hereby declare that this project entitled "Cooling of Photovoltaic Panel Using Water-Cooled System" submitted to Universiti Sains Malaysia is based on my original work except for quotations and citations which have been duly noted by explicit references.

Name: Siew Teng Yi

Date: 27 July 2021

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRAK

Tenaga solar adalah salah satu sumber tenaga yang boleh digunakan untuk memenuhi keperluan sebagai bekalan kuasa yang sedang berkembang di seluruh dunia. Tenaga solar boleh dituai and ditukarkan kepada tenaga elektrik menggunakan panel suria. Secara pratikal, efisiensi panel suria adalah sangat rendah dan ia dijejaskan oleh haba yang terkumpul dalam panel suria yang dipancarkan dari sinaran matahari. Suhu yang tinggi pada panel suria akan menjejaskan kebolehan penukaran tenaga suria oleh panel suria. Walaupun kesan buruk suhu tinggi pada panel suria sudah dikenali, kebanyakan industri tenaga solar tidak menggunakan sebarang mekanisme penyejukan untuk menurunkan suhu pada panel suria dan ia berfungsi dengan tahap efisiensi yang rendah. Ia menghalang lebih banyak tenaga dijanakan oleh panel suria dan menghasilkan faedah ekonomi yang rendah. Dengan mengintegrasikan sistem penyujuk ke panel suria, haba berlebihan boleh dipindahkan dan panel suria boleh dioperasi dalam julat suhu yang lebih rendah. Dalam kajian ini, model sistem penyujuk yang mengandungi tiub kuprum dan panel suria telah disimulasikan dengan ANSYS Fluent 19.2 menggunakan 'Solar Load Model' dan 'Heat Flux' untuk mensimulasikan sinaran matahari Berdasarkan variasi sinaran matahari sehari, kesan daripada suhu dan aliran air telah dikajikan. Suhu permukaan panel suria boleh direndahkan dengan ketara. Tiub penyejuk dengan reka bentuk yang berbeza telah dikajikan dan prestasi yang dihasilkan akan ditunjukkan dalam tesis ini.

ABSTRACT

Solar energy is one of the renewable energy resources that can be utilized to cater for the growing power supply demand worldwide. Solar energy can be harvested and converted into useful electrical energy via solar panel. Practically, the efficiency of solar panel is very low and it is affected by the heat accumulated on solar panel, transmitted through solar radiation. The high temperature on solar panel would affect the solar energy conversion of a solar panel. Despite the adverse effect of high temperature on solar panel, most of solar power industry does not use any cooling mechanisms to reduce the temperature on the solar panel, it is thus performing at low efficiency level. This prevents more energy that can be generated by the solar panel, producing lesser economic benefits. By integrating cooling system into solar panel, the excess heat can be removed and solar panel could operate at lower temperature range. In this study, a model of cooling system consists of copper tube and solar panel is simulated with ANSYS Fluent 19.2 using Solar Load Model and Heat Flux to simulate solar radiation. Based on solar radiation variation in a day, the effects of temperature and flow of water are thus studied. The temperature of the surface of solar panel can be reduced significantly. Different designs of cooling tubes are studied and the resulted performances are presented in this thesis.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Photovoltaic cell which also known as solar cell, absorbs sunlight in the form of electromagnetic radiation and convert it to electrical energy. Photovoltaic cell converts energy by absorbing photons emitted by the sun, the photon will then excite electrons in semiconductor materials that has been doped with either boron or phosphorus. The electron will move between the silicon and thus produce electric current. Generally, the efficiency of photovoltaic cell is around 15%, which can convert ideal sunlight energy of 1000 W/m^2 to 150 W/m^2 usable energy.

Water cooling is a method of heat transfer by removing heat from the system using water as heat transfer medium. Water is often being used because it has high specific heat capacity. Using this method, water flows through heat exchanger on the hot side, then the heated water is transferred to radiator and the heat subsequently released to the environment.

Based on existing literature, the efficiency of photovoltaic cells decreases as the temperature of photovoltaic cells increases. By having water cooling applied on photovoltaic cells, the temperature of photovoltaic cells is expected to decrease which will then increase the efficiency of photovoltaic cells.

Photovoltaic cells usage has been increased by 25% per year and by the end of 2019, the estimated photovoltaic capacity is around 633 GW [1]. In 2019, the electricity generation produced by photovoltaic cells can only meet 3% of electricity demand worldwide [2]. As the price of photovoltaic cells getting lower each year, photovoltaic cells usage will increase, leading to the increase in electrical power from the solar energy.

Currently, a typical solar panel has efficiency of around 15% which means that only 15% of the solar energy exposed to the solar panel is converted into electrical energy. The sun radiates energy with the power of approximately 1000 W/m^2, with efficiency of 15%, the energy generated by solar panel is 150 W/m^2. The rest of the energy is wasted as heat energy and trapped within the solar panel. According to Zaoui et al. [3], the efficiency of solar panel decreases by 0.45% for an increase of 1 °C. Due to that, the performance of solar panel will be affected due to the heat trapped within the solar panel. By decreasing the temperature of solar panel, its efficiency can be increased which will lead to more energy generated by solar panel.

There are several ways to decrease the temperature of photovoltaic cells and one of the methods is using water-cooling mechanism. Water-cooling is a method of heat removal from components, it is commonly used in internal combustion engine, electronics and computers. Water-cooling is chosen because of inexpensiveness of water, higher thermal conductivity in comparison to air and high specific heat capacity among the commonly available liquid. By using water-cooling system together with good thermal interface material, temperature of photovoltaic cells can be decreased to increase the efficiency of solar panel.

1.2 Problem Statement

The sun radiates energy with power of approximately 1000 W/m^2, normal photovoltaic cells have efficiency of 15% which translates to power output of 150W/m^2. Other energy is converted to heat and trapped in the solar panel, thus increasing the temperature of photovoltaic cells. Research shows that the efficiency can be increased by reducing the temperature of the photovoltaic cells. Chilled water could be used to reduce the temperature of photovoltaic cells.

1.3 Objectives

The following objectives of this project are focused in this study to address the issues stated in the problem statements.

- To simulate the solar radiation effect on the solar panel for different time in a day.
- To explore the thermal dissipation for different pipe designs of the water-cooled system on the cooling performance.
- To study the effect of different temperatures and flow rates of water in the water-cooled system on the cooling performance.

1.4 Scope of Research

In this research, a model of solar panel with the size of 1650 mm length by 1000 mm width and cooling pipe is simulated using ANSYS Fluent 19.2. The radiation effect is simulated using Solar Ray Tracing and Heat Flux. The result from the simulation is compared with the reference literature, Liu et al. [4], for validation. The solar irradiation used in the simulation is 1000 W/m^2. The temperature results of radiation effect on solar panel without cooling is simulated and compared with the literature.

For the cooling design, the simulation model is a 3D model that has a rectangular plate as photovoltaic cell and semi cylindrical copper pipe as cooling system. The heat transfer considered comprised of heat conduction and heat convection mechanisms. The models used have different cooling pipe spacing and size to find the optimal heat transfer between solar panel and water. The temperature results of radiation effect on solar panel with cooling is simulated and compared with the literature.

Due to low flow rate and for simplicity, the flow of water is assumed to be laminar. The ambient temperature of the surface of solar panel is 30 °C. The wind speed flowing through solar panel is assumed to be 1 m/s with convection heat transfer coefficient of 10 $W/m^2 K$.

1.5 Thesis Organization

The thesis is organized as follows.

In Chapter 2, the working principle of photovoltaic cell, cooling methods of solar panel and energy balance of solar panel are reviewed.

In Chapter 3, the methodology of this research is described and explained.

In Chapter 4, the results obtained from the simulation are discussed.

In Chapter 5, the conclusion of the research and the scope of future work are listed.

CHAPTER 2

LITERATURE REVIEW

2.1 Photovoltaic cell

Photovoltaic cell is a semiconductor diode that is made of two layered silicon which contains a layer of p-type semiconductor and a layer of n-type semiconductor. Depletion region is formed between the layers as the holes in p-type semiconductor is filled with extra electrons from n-type semiconductor and thus no charge is able to flow through the depletion layer [5].

The photons are absorbed in the depletion layer to excites the electron from valence band to conduction band. Not all photons are able to excites the electron as there is a minimum energy difference between valence band and conduction band which is known as band gap energy. The band gap energy for silicon is 1.11 eV which is small enough to move the electrons simply by shining light on the silicon [6]. The electricity generated is then conducted through copper wires to external load to be used.

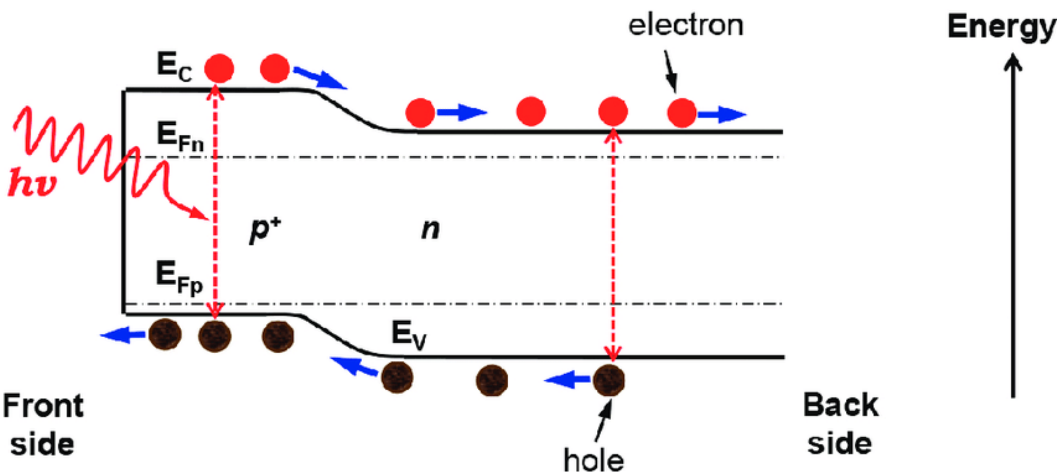

Figure 2.1: Band diagram of solar cell [7].

Existing literatures indicate that temperature would affect the power generated by photovoltaic cell by reducing the band gap. The increase in temperature will cause the atoms to vibrate more and thus increases kinetic energy of the electrons. Lower energy is required to move the electron through the band gap and thus lesser energy is generated [8]. The reduce in power generated can be seen in the voltage drop as temperature increases in Figure 2.2.

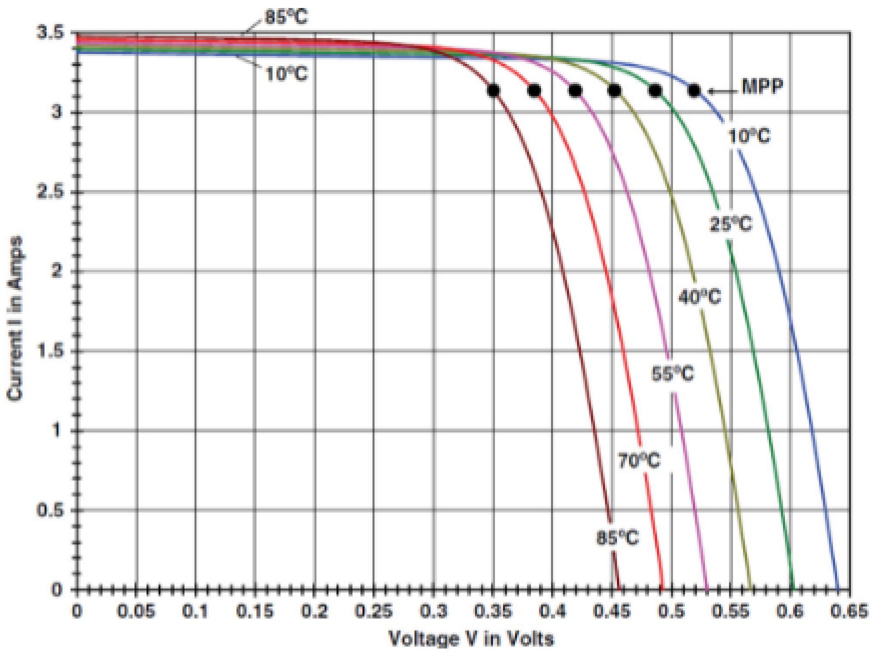

Figure 2.2: Characteristics curve (I-V) for a solar cell with cell temperature as a parameter [9].

2.2 Cooling Methods

Correlation on efficiency of photovoltaic cells and operating temperature is well known, the efficiency of solar panel increases as temperature of photovoltaic cells decreases [10]. Zubeer et al. [11] have compile several cooling techniques of photovoltaic cells which includes air cooling and water cooling. The method of cooling also includes passive cooling and active cooling where passive cooling dissipates heat without consume any energy and active cooling dissipates heat using energy or sometimes known as forced convection.

Grubišić-Čabo et al. [12] discussed several ways of cooling photovoltaic panels, which includes passive cooling, heat pipe cooling, active cooling, nanofluid cooling and thermoelectric cooling. The passive cooling includes air passive cooling and water passive cooling. The air passive cooling is done using aluminium heatsink with thermal grease applied and achieved relative increase in efficiency of 9% whereas water passive cooling is done by submerging the photovoltaic panels in water and achieved relative increase in efficiency of 20% but decrease in solar intensity. Heat pipe cooling uses phase change cooling method with convection of cooling medium. The heat transfer rate is dependent on the size of heat pipe, it could achieve average efficiency increase by 6%, which is quite low. As for active cooling methods, the active air-cooling method has gained about 0.6% total efficiency and active water-cooling method has gained about 2.8% total efficiency which is significant. The nanofluids cooling uses mixture of cooling fluid and solid nanoparticles which made up of metal oxides for example aluminium oxide and copper oxide, with 3.0% wt of particles, total efficiency has increased by 1.5% in comparison to water-cooling. As for thermoelectric cooling, it uses Peltier effect which uses a lot of electrical energy to cool photovoltaic panel which is not viable to increase efficiency of photovoltaic panels.

There are several articles reported the results of air-cooled photovoltaic cells. Popovici et al. [13] shows that air-cooled heat sinks are able to lower the temperature of photovoltaic cells by 10°C and increases the efficiency by 1% or increase power generation by 7.2%. The increase of efficiency is lower than expected, but nevertheless the efficiency increased. Elminshawy et al. [14] use geothermal air-cooling system and is able to decrease the photovoltaic cell's temperature by around 25 °C and increases the efficiency by 3%, equal to the increase of power generation by 14%. Bayrak et al. [15] studied using fin structure with different sizes and lengths, using natural convection to cool photovoltaic panels. The result is not promising as the highest temperature difference between the panel with fins and without fins is 3.39 °C.

As for water-cooled techniques, Castanheira et al. [16] used water sprinkles to spray on top of photovoltaic cells to clean and cool the photovoltaic cells. The results show that this method is capable in reducing the temperature up to 22 °C and increase power generation by 15% but uses 15L of water per hour. Hussien et al. [17] used a heat exchanger system and the system is able to decrease the temperature by 10 °C and increase efficiency by 1.6%, which translates into the increase of power generation by 10%. The system used light bulbs to simulate sunlight and the result obtained is not promising to be applicable in commercial system.

Arcuri et al. [18] studied both air and water-cooled system using cooling duct but different fluids under the photovoltaic panels. The system is able to decrease the temperature of photovoltaic panel by 12 to 15.7 °C and generate 3.35 to 5.75% more energy to be used. According to Zanlorenzi et al. [19], they made prototype cooling system for photovoltaic system which only converts solar energy to usable electrical energy and hybrid module which converts solar energy to usable electrical and thermal energy. The cooling system is able to reduce the average temperature of 8.83 °C and increase the efficiency of photovoltaic panel from 15.1% to 23.5%. If thermal energy is being used, the efficiency is increased to 33.28%.

Abdo et al. [20] studied the usage of saturated activated lumina with saline water to reduce the temperature of photovoltaic panel. Their system is able to reduce the average surface temperature by 13.8 °C and have efficiency improvement of 9.7% compared to system without cooling. Abdo et al. [21] also studied the usage of hydrogel beads to cool solar panel. The system using hydrogen beads to cool solar panel is able to reduce the temperature of solar panel by 9.6 °C and have efficiency improvement of 7.2%.

Koundinya et al. [22] has simulated and completed experimentational study on using Finned Heat Pipe to cool solar panel. From the result, the system is able to reduce temperature of solar panel by 13.8 °C and has improved the efficiency of solar panel by 20.97%. Zhao et al. [23] modified the structure of commercial silicon photovoltaic module to have enhanced radiative cooling. From the result, the cooling capability is not good as it could only reduce the temperature by 1.75 °C which correspond to relative efficiency improvement of 0.79% which is quite low. Khorrami et al. [24] studied the cooling of photovoltaic module using radiation shield which reflects the solar thermal irradiation at band 2 which only heats up the photovoltaic module with different amount of reflections. They are able to reduce the temperature by 6.65 °C and increased the efficiency by 3%.

2.3 Energy Balance

The energy balance equation of the cooling system can be expressed using the Eq. (2.1)

$$P_s = P_r + P_{conv} + P_{rad} + P_w + P_e + \sum mc\frac{\delta T}{\delta t} \qquad (2.1)$$

where P_s is the total solar irradiation, P_r is the reflected radiation, P_{conv} is heat dissipated through convection, P_{rad} is heat dissipated through black body radiation, P_w is heat dissipated through water flow in the pipe and P_e is energy converted into electrical power.

The term on the left hand side in Eq. (2.1) can be expressed as

$$P_s = GA_s \qquad (2.2)$$

where G is solar radiation incident on the surface and A_s is the total surface area,

$$P_s = GA_s\rho_{ref} \qquad (2.3)$$

where ρ_{ref} is reflected radiation fraction,

$$P_{conv} = h_{conv}A_s(T_{panel} - T_{air}) \qquad (2.4)$$

where h_{conv} is coefficient of convective heat transfer, T_{panel} is temperature of solar panel and T_{air} is temperature of air,

$$P_{rad} = \varepsilon F\sigma A_s(T_{panel}^4 - T_{sky}^4) \qquad (2.5)$$

where ε is emissivity of the surface, F is view factors, σ is Stefan-Boltzmann constant,

$$P_s = GA_s\eta_{pv} \qquad (2.6)$$

where η_{pv} is efficiency of photovoltaic panel.

For simplicity, heat dissipated through radiation is not considered in this project.

The overall convective heat transfer coefficient can be determined by combination of natural and forced convection [25]:

$$h_{conv} = \sqrt[3]{h_{natural}^3 + h_{forced}^3} \tag{2.7}$$

The natural convection is caused by the temperature difference of solar panel and air which causes the air to circulate due to different density gradients. In calm weather, the contribution of natural convection becomes significant. According to Bejan et al. [26], natural convection is determined using Eq. (2.8) and (2.9).

$$h_{natural} = \frac{\lambda_a Nu}{L} \tag{2.8}$$

$$\overline{Nu} = 0.14\left[(GrPr)^{\frac{1}{3}} - (Gr_{cr}Pr)^{\frac{1}{3}}\right] + 0.56(Gr_{cr}\,\mathrm{Pr}\cos\theta)^{\frac{1}{4}} \tag{2.9}$$

For forced convection, it occurs due to presence of wind and the formula of convective heat transfer coefficient for forced convection is referred from Sharples et al. [27]

For windward surfaces,

$$h = 3.3w + 6.5 \tag{2.10}$$

For leeward surfaces,

$$h = 2.2w + 8.3 \tag{2.11}$$

where w is wind speed.

CHAPTER 3

METHODOLOGY

3.1 Modelling the Geometry

The model is drawn using SolidWorks. The model is built while referencing to Liu et al.'s model [4], which has layers of photovoltaic module and semi cylindrical cooling pipes which has dimension of 1650 mm x 1000 mm. The semi cylindrical cooling pipes has tube diameter of 35 mm and tube spacing of 50 mm.

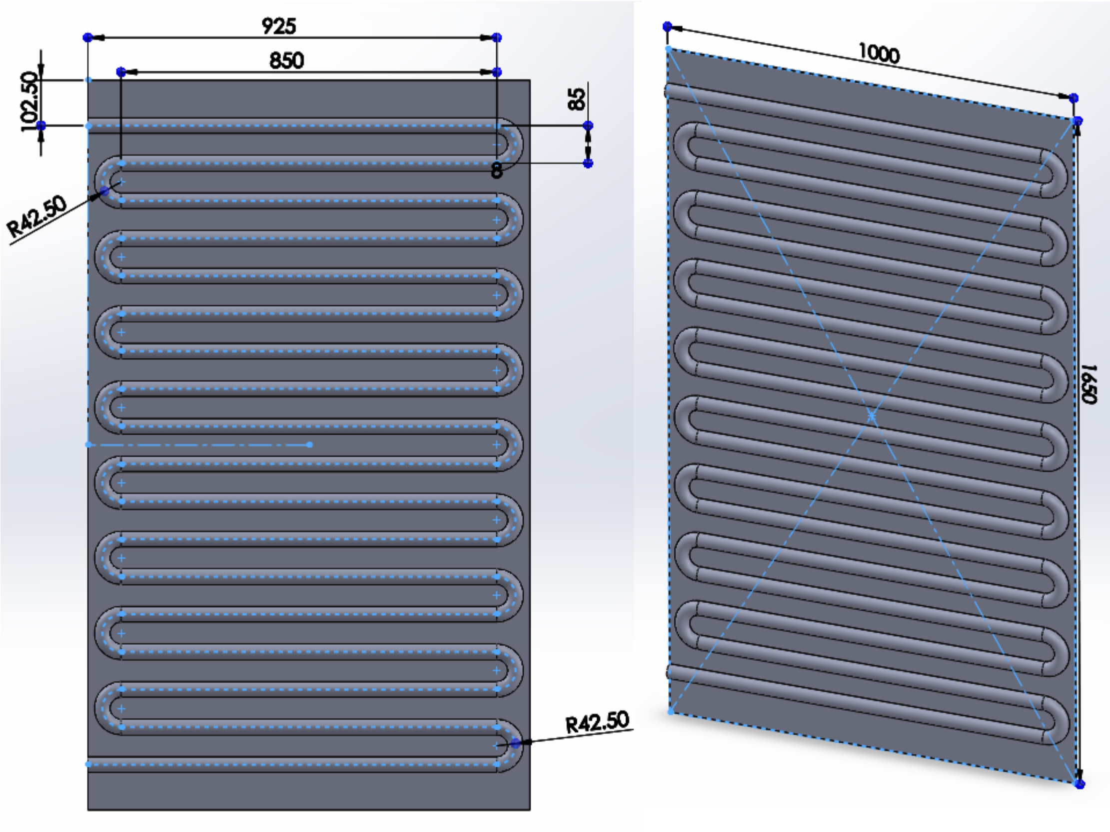

Figure 3.1: Model of cooling system.

It should be ensured that the extrusion of the model has unticked 'Merge result' to has separated layers of photovoltaic module and separated domain for solid and liquid.

The model is then imported into Design Modeler in ANSYS Workbench 19.2. The cooling pipe is switched to be Fluid and renamed.

Two more models with simpler and different design are used to compare to the reference model in Figure 3.1. The models are shown below.

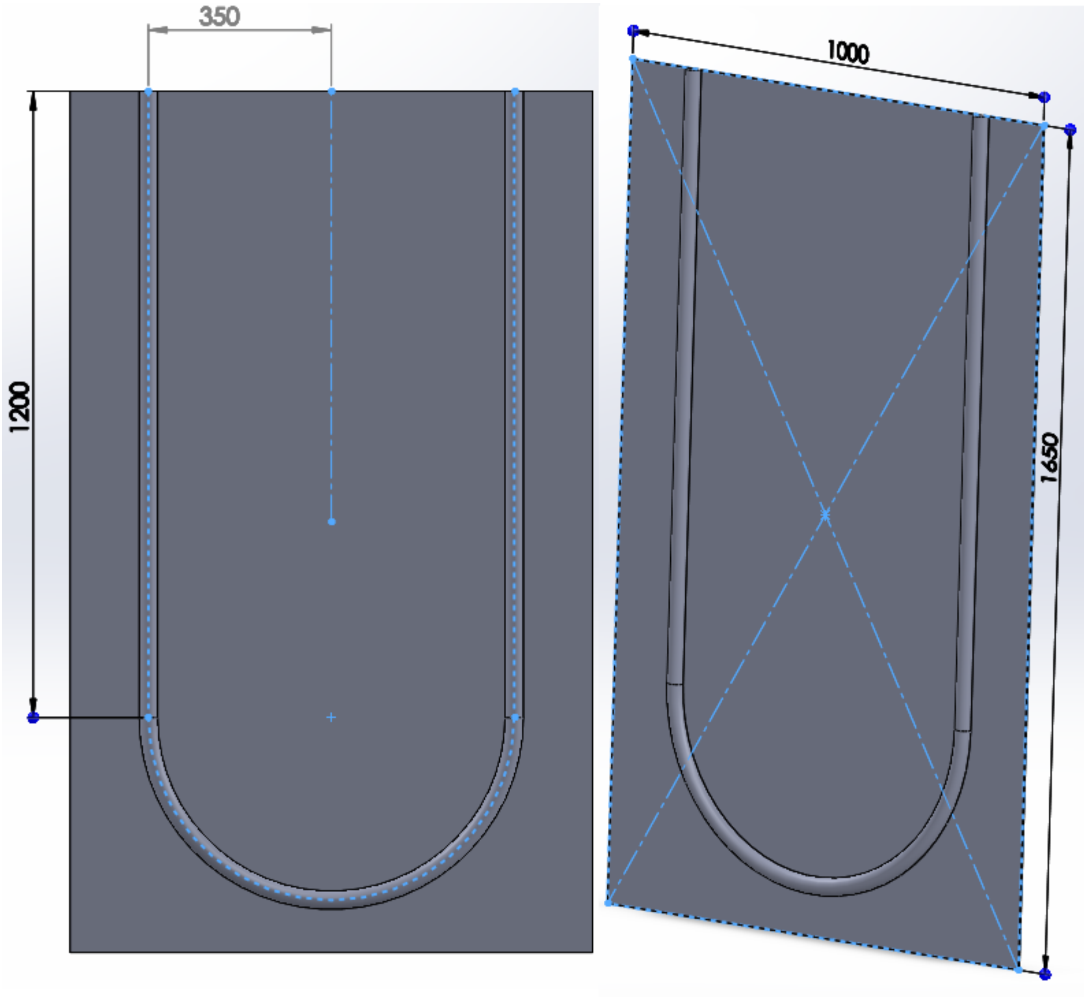

Figure 3.2: Model of cooling system with simple U-tube.

The model in Figure 3.2 has layers of photovoltaic module and semi cylindrical cooling pipes which has dimension of 1650 mm x 1000 mm. The U-tube is a semi cylindrical cooling pipes with tube diameter of 35 mm.

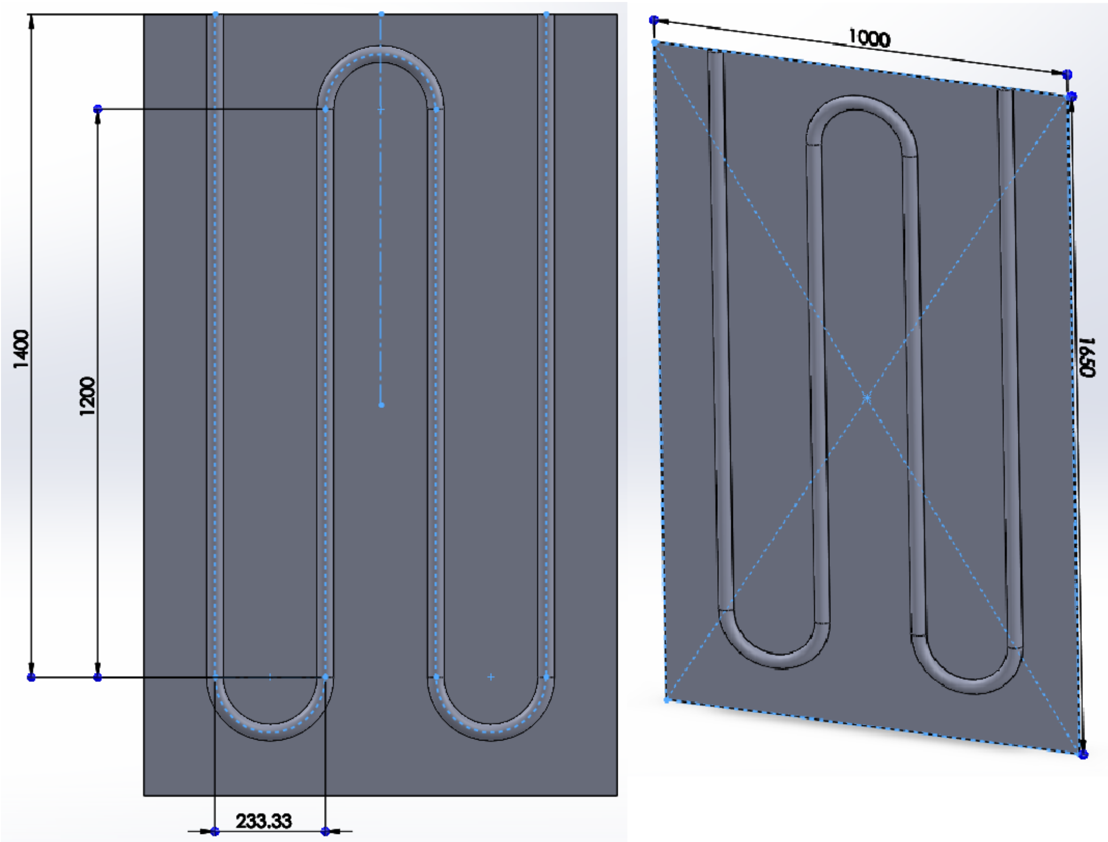

Figure 3.3: Model of cooling system with 4 vertical tubes.

The model in Figure 3.3 has layers of photovoltaic module and semi cylindrical cooling pipes which has dimension of 1650 mm x 1000 mm. The U-tube is a semi cylindrical cooling pipes with tube diameter of 35 mm and spacing of 230 mm.

3.2 Mesh

The meshing process is shown in the Figure 3.4 below. Body sizing is used to mesh the parts into equally sized elements which has the size of 5 mm. Then, the named selections are added to the fluid zone, the solid zone, inlet and outlet of the fluid and the surface to receive solar irradiation.

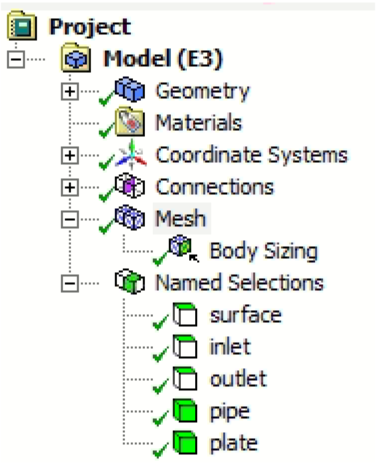

Figure 3.4: Tree outline of mesh.

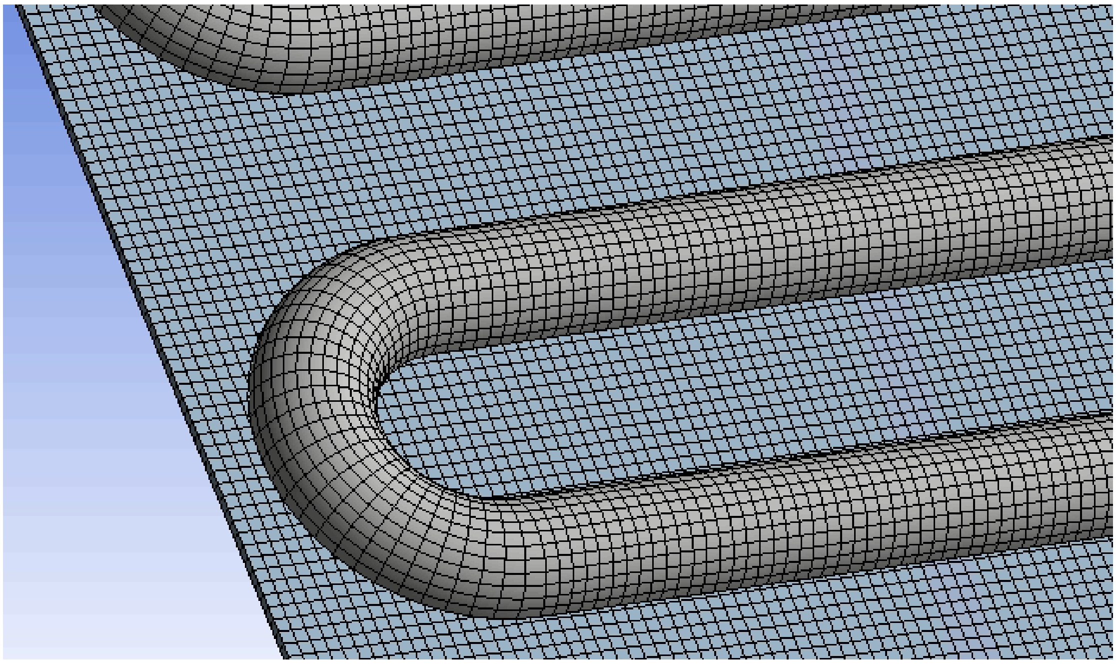

Figure 3.5: Closeup of the mesh.

3.3 Setting up Simulation

3.3.1 Assumption Used

The simulations are set up in ANSYS Fluent 19.2. The assumptions used in the model are as follows:

1. The water flow in the tube is considered laminar and incompressible.

   The thermal properties of materials are shown in

2. Table 3.1 and Table 3.2 below, which is referenced and taken from Liu et al. [4] and Fluent database.
3. The solar irradiation used for validation is assumed to be 1000 W/m^2.
4. The solar irradiation for parametric study is obtained from Solcast [28].
5. The sides of solar panel are insulated and has zero heat loss.
6. The ambient temperature is assumed to be 30 °C.
7. The convection heat transfer coefficient is 10 W/m^{2}K.

Table 3.1: Material properties of fluid.

Material	Water
Density (kg/m^3)	998.2
Specific Heat Capacity (J/kg K)	4182
Thermal Conductivity (W/m K)	0.6
Viscosity (kg/m s)	0.001003

Table 3.2: Material properties of solid.

Material	Copper	Photovoltaic Cell
Density (kg/m^3)	8978	2330
Specific Heat Capacity (J/kg K)	381	677
Thermal Conductivity (W/m K)	387.6	148
Solar absorption coefficient	-	0.7

3.3.2 Boundary Conditions

The boundary conditions are set that the solar irradiation is the heat input and convection of the surface and the water flow carry the heat away from the system. The solar irradiation data is obtained from Solcast [28] for the location at Kuala Lumpur on 15th March 2019. The solar irradiation data is tabulated below. The date of 15th March 2019 is chosen because it is the day where the solar irradiation has the highest value of 1051 W/m^2 of the entire year of 2019.

The inlet of the copper tube was self-defined with the inlet velocity of 0.01 m/s to 0.15 m/s, while inlet temperature ranging between 12 °C and 25 °C. The outlet of the copper tube was set as pressure outlet with the pressure of 0 Pa.

Lastly, the surface of the solar panel was set at convection with the heat transfer coefficient of 10 W/m^2 K. The sides of solar panel were set to have zero heat flux. The thermal interface between solid and fluid region is set as coupled walls.

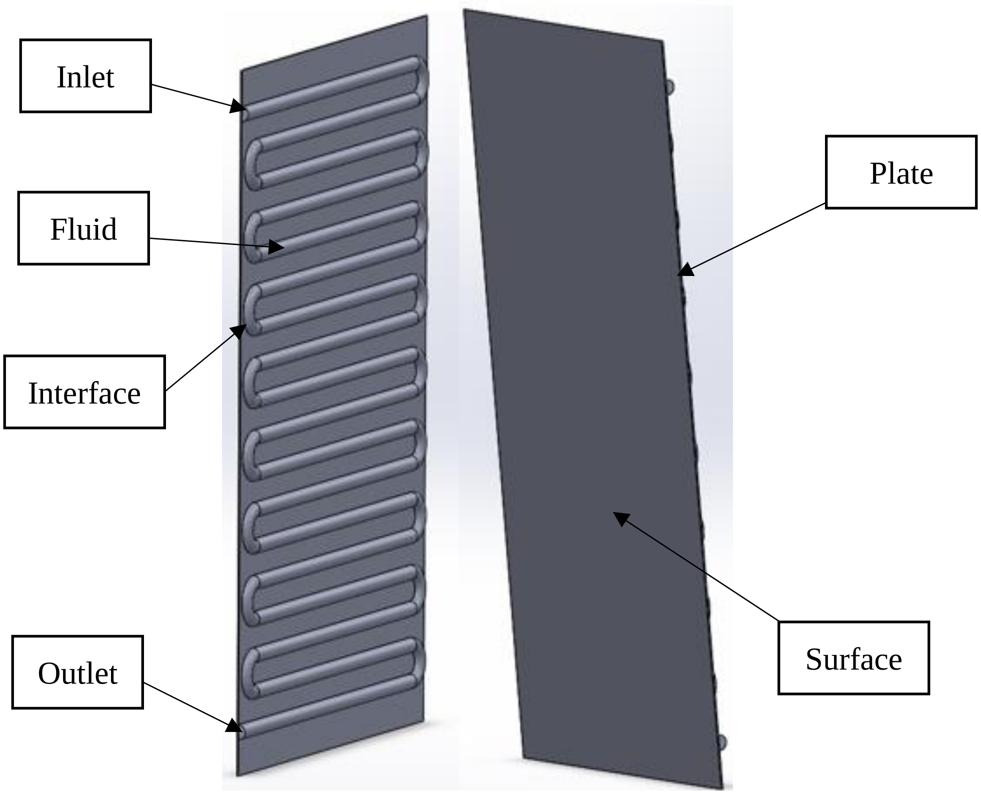

Figure 3.6: Boundary condition settings.

Table 3.3: Description of each boundary condition.

Named Selection	Description
Inlet	Fluid region, water inlet with specified inlet temperature and velocity.
Outlet	Fluid region, water outlet with specified outlet pressure.
Surface	Solid region, solid surface that receives solar irradiation and experience convection. Convection boundary condition: Heat Transfer Coefficient = 10 W/m^2K Free Stream Temperature = 303 K
Interface	Mesh interface, thermally coupled.
Plate	Solid region, thermally coupled with fluid region.
Fluid Region	Fluid region, thermally coupled with plate.

Table 3.4: Solar Irradiation Data of Kuala Lumpur on 19 March 2019.

Time	Solar Irradiation (W/m^2)
7:00	25
8:00	226
9:00	490
10:00	728
11:00	911
12:00	1022
13:00	1051
14:00	992
15:00	859
16:00	647
17:00	253
18:00	100
19:00	8

3.4 Initialization and Calculation

The SIMPLE algorithm is used for the pressure-velocity coupling and second order upwind is used. Hybrid initialization is used. The residuals are considered to converge when it becomes less than 10^{-4}.

The simulation is solved in steady state and the calculation is ran until the residual is converged. The temperature contour of the surface is shown after the simulation and average temperature of the surface is recorded.

3.5 Validation of Result

3.5.1 Result from the Literature

Since there is lack of data of the solar irradiation of the literature, 1000 W/m^2 is used for the simulation to compare with the highest temperature recorded for the surface of photovoltaic panels. The results from literature were digitized using WebPlot Digitizer [29] and the results are shown in

Table 3.5, Table 3.6 and Table 3.7. The trends of the graphs will be observed, compared and matched to their results. Then, the temperature data from simulation is compared to their data with percentage error determined.

Table 3.5: Temperature Result of Tube Spacing digitized from Liu et al [4].

Tube Spacing (mm)	50	100	150	200
Surface Temperature (°C)	24.7	33.4	38.0	40.6

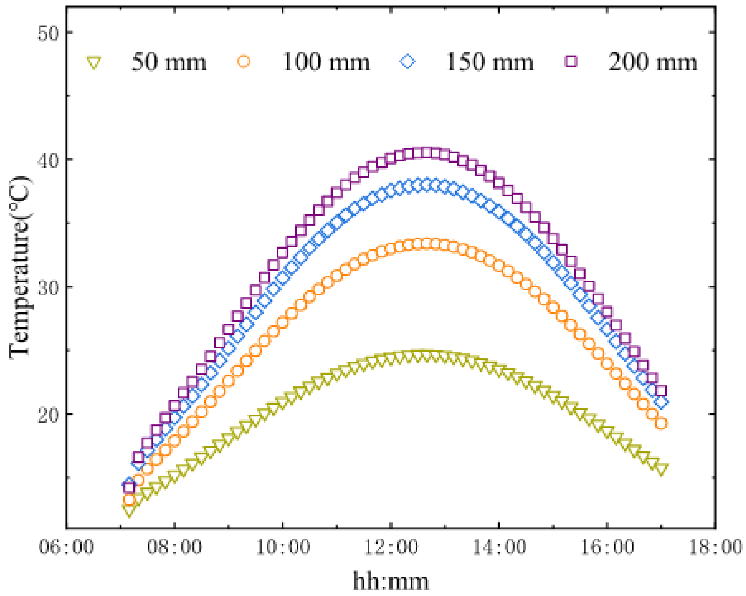

Figure 3.7: The surface temperature at different tube spacings from Liu et al [4].

Table 3.6: Temperature Result of Water Inlet Velocity digitized from Liu et al [4].

Water Inlet Velocity (m/s)	0.01	0.05	0.10	0.15
Surface Temperature (°C)	57.1	32.3	28.5	27.1

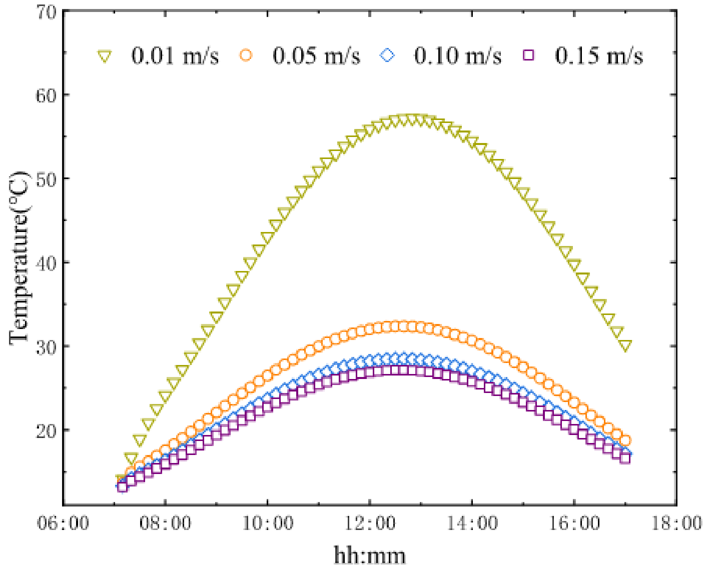

Figure 3.8: The surface temperature at different waterflow velocity from Liu et al [4].

Table 3.7: Temperature Result of Water Inlet Temperature digitized from Liu et al [4].

Water Inlet Temperature (°C)	10	12	14	16
Surface Temperature (°C)	21.1	23.0	24.8	26.6

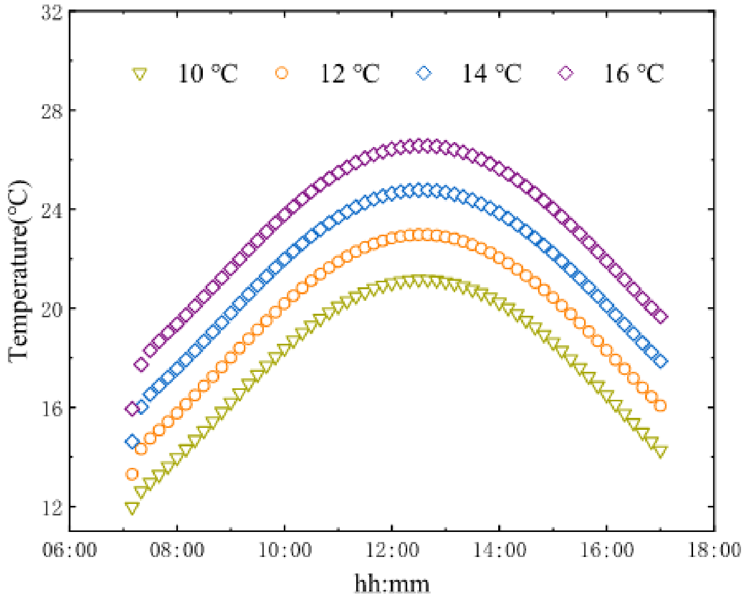

Figure 3.9: The surface temperature at different water inlet temperature from Liu et al [4].

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Validation of Results

4.1.1 Result Comparison with the Literature

Results presented by Liu et al. [4] was taken as the benchmark data for validation because the paper clearly specified the type of cooling tube used, model geometry, boundary conditions and material properties. The literature has detailed simulation details and results but there are some discrepancies in the result. Table 4.1, Table 4.2, Table 4.3, Figure 4.1, Figure 4.2 and Figure 4.3 presented the comparison of the results between literature and simulated result.

From Table 4.1 and Figure 4.1, the lowest difference between literature's temperature and simulated temperature is 0.67 °C with the percentage difference of 1.76% with water inlet velocity of 0.01m/s, the highest difference in temperature is 3.56 °C with the percentage difference of 8.76% with water inlet velocity of 0.05 m/s.

From Table 4.2 and Figure 4.2, the lowest difference between literature's temperature and simulated temperature is 1.40 °C with the percentage difference of 2.45% with tube spacing of 150 mm, the highest difference in temperature is 5.40 °C with the percentage difference of 16.7% with tube spacing of 200 mm.

From Table 4.3 and Figure 4.3, the lowest difference between literature's temperature and simulated temperature is 0.16 °C with the percentage difference of 0.76% with water inlet temperature of 12 °C. Meanwhile, the highest difference in temperature is 0.66 °C with the percentage difference of 2.48% with water inlet temperature of 12 °C.

Results below are the comparison of surface temperature with literature with different tube spacing. The constant parameters are tube diameter of 35 mm, water inlet temperature of 12 °C and water inlet velocity of 0.05 m/s.

Table 4.1: Comparison of surface temperature with literature with different tube spacing.

Tube Spacing (mm)	50	100	150	200
Literature's temperature (°C)	24.70	33.40	38.00	40.60
Simulated temperature (°C)	26.90	31.04	37.33	44.16
Difference (°C)	2.20	2.36	0.67	3.56
Percentage Difference (%)	8.91	7.07	1.76	8.76

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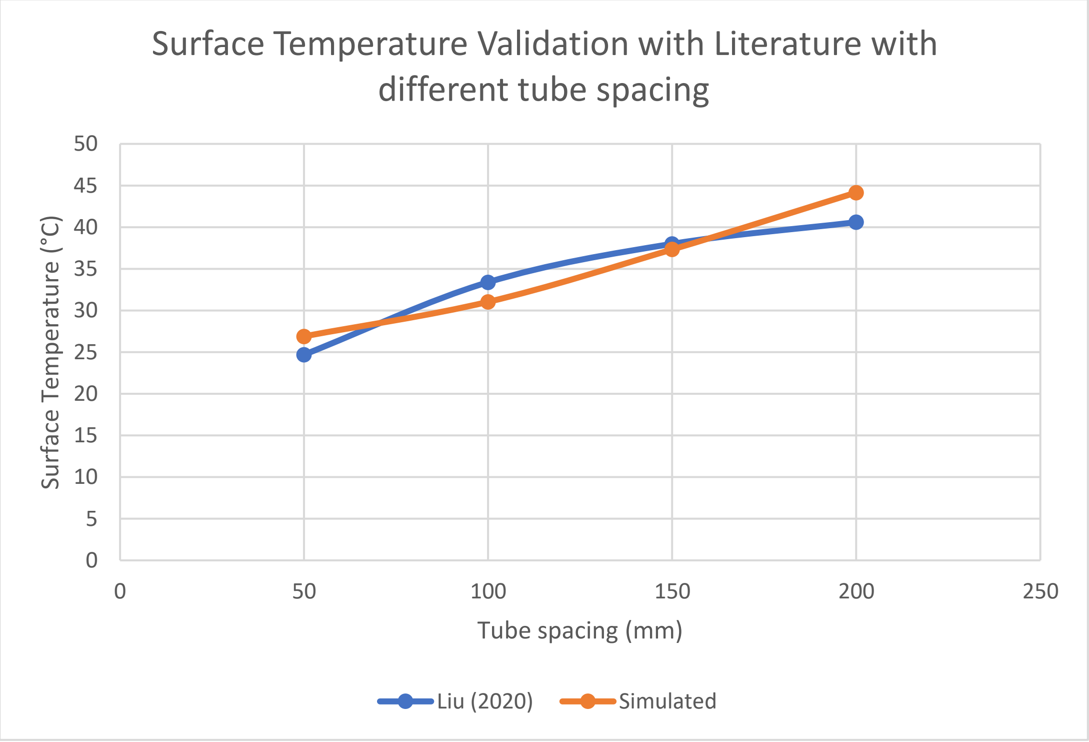

Figure 4.1: Surface temperature validation for different tube spacings.

Results below are the comparison of surface temperature with literature with different water inlet velocities. The constant parameters are tube diameter of 35mm, tube spacing of 50mm and water inlet temperature of 12 °C.

Table 4.2: Comparison of surface temperature with literature with different water inlet velocities.

Water Inlet Velocity (m/s)	0.01	0.05	0.10	0.15
Literature's temperature (°C)	57.10	32.30	28.50	27.10
Simulated temperature (°C)	55.70	26.90	23.26	22.14
Difference (°C)	1.40	5.40	5.24	4.96
Percentage Difference (%)	2.45	16.7	18.4	18.3

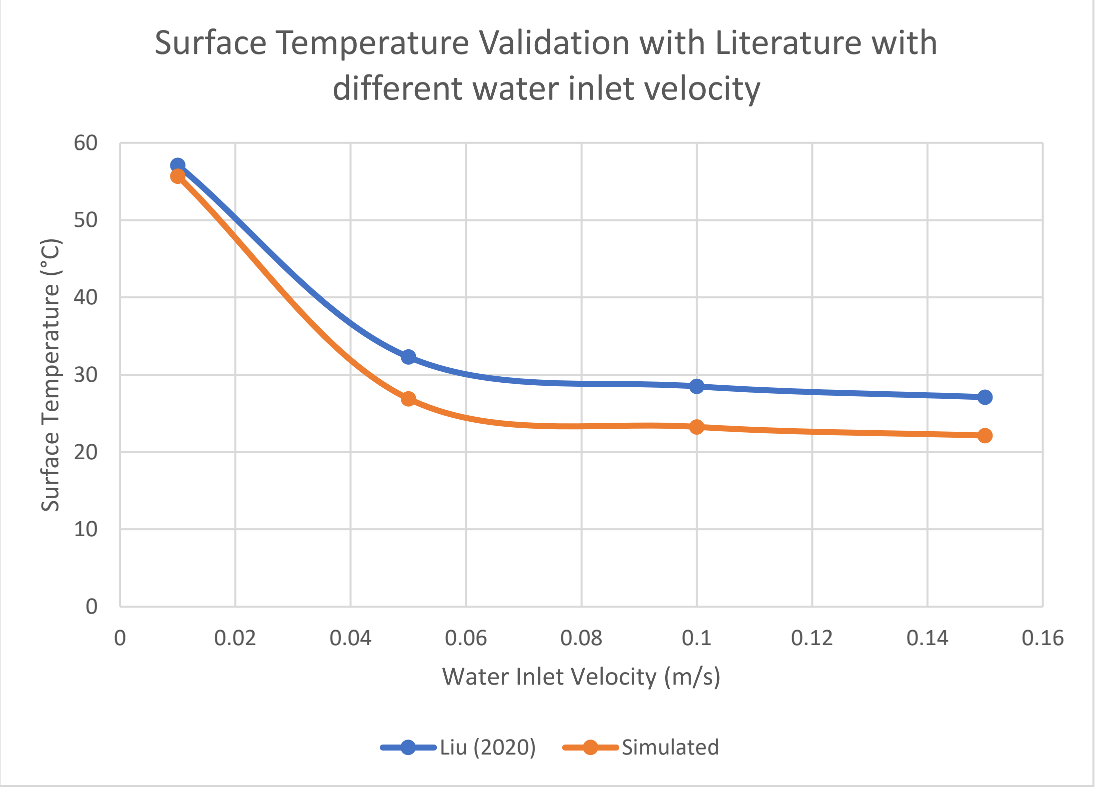

Figure 4.2: Surface temperature validation for different water inlet velocities.