Passive Radiative Cooling Technology for Energy Efficient Buildings

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Abstract:

With a steady growth of cooling demand in buildings, the cooling efficiency for the HVAC system has been drawing concern among the public. Through passive radiative cooling (PRC), an object is cooled by naturally emitting thermal infra-red radiation to the outer space within the atmospheric window, which is between 8-13 μm. It consumes very low, or even no energy to cool an object, it has a huge potential to be integrated with HVAC buildings, water-cooling plants or photovoltaic cells, in order to achieve a more desirable cooling capacity. In this paper, the design on how the PRC panel was integrated with discrete systems was being proposed, where their cooling performances would be evaluated respectively. Moreover, a real-life model had been fabricated and was used to compare with the flow analysis simulation. It was found that the night-time cooling effect is stronger than day-time cooling effect. In addition, with trivial or even no external power supply, the PRC technology should be a promising technology to achieve a significant cooling effect in the future.

Keywords:

Passive radiative cooling, heat exchanger, HVAC, cooling capacity, flow simulation

1. Introduction

In the contemporary society, there is an unprecedented demand for energy consumption because of revolutionizing technology, population growth and industrial development. [1] According to the Electrical and Mechanical Services Department, air-conditioning accounted for 18% of total energy consumption in Hong Kong in 2018, which constituted the largest sector among different energy purposes. Given that situation, the government is actively advocating the concept of “Green Buildings”, in which buildings are designed with different environmentally-friendly features for the sake of higher energy efficiency, while not sacrificing thermal comfort. Recently, passive radiative cooling (PRC)technology is getting promoted across the city. Through passive radiative cooling, an object is cooled by naturally emitting thermal infra-red radiation to the outer space through the atmospheric window, which is between 8-13 micrometer [2]. Since it conducts very low, or even no energy to cool on object, it has a huge potential to be integrated with HVAC buildings, water-cooling plants or photovoltaic cells, in order to achieve a more desirable cooling capacity. In this report, the cooling capacity of a PRC panel will be discussed by placing it on top of a heat exchanger under an exposed environment for 24 hours.

2. Objective

PRC technology has numerous possible applications through embedding it into different systems. To investigate the cooling capacity of the PRC panel, an experiment has been conducted and subsequent results help to explain it. In this experiment, a dynamic water-based cooling system model is set up for the experiment.

Before getting into the mechanism of the dynamic water-based cooling system model, it is imperative to understand the mediums of heat transfer. [3] Heat can be transferred under three circumstances, which are conduction, convection and radiation. In conduction, a substance's energy is transferred from the more energetic particles to the adjacent less energetic particles through oscillation between particles. In convection, a substance's energy is transferred between a solid surface and the adjacent liquid or gas in motion, which involves the combined effects of conduction and fluid motion. In radiation, a substance's energy is transferred by emitting electromagnetic waves from it.

For conduction, the formula can be expressed as follow:

$$\dot{\mathrm{Q}} = \mathrm{kA}\frac{T_1 - T_2}{x} \tag{1}$$

where $\dot{\mathrm{Q}}$ is the power with unit in W, k is the thermal conductivity with unit in $\frac{\mathrm{W}}{m \cdot K}$, A is the contact area with unit in m^2, T_1 is the surface temperature of medium one with unit in K, T_2 is the surface temperature of medium two with unit in K, x is the distance between two mediums with unit in m.

For convection, the formula can be calculated by:

$$\dot{\mathrm{Q}} = \mathrm{hA}_s(T_s - T_\infty) \tag{2}$$

where $\dot{\mathrm{Q}}$ is the power with unit in W, h is the convective heat transfer coefficient with unit in $\frac{\mathrm{W}}{m^2 \cdot K}$, A_s is the surface area with unit in m^2, T_s is the surface temperature with unit in K, T_∞ is the surrounding temperature with unit in K.

For radiation, the following formula can be utilized:

$$\dot{\mathrm{Q}} = \varepsilon\sigma_s \mathrm{A}_s {\mathrm{T}_s}^4 \tag{3}$$

where $\dot{\mathrm{Q}}$ is the power with unit in W, ε is the emissivity between 0 and 1, σ_s is the Stefan-Boltzmann constant with value $5.67 \times 10^{-8} \frac{W}{m^2 \cdot K^4}$, A_s is the surface area with unit in m^2, T_s is the absolute temperature with unit in K.

Moreover, since the system is water-based with different elevations involved, to study the relationships between pressure, speed and height, Bernoulli's equation is applicable owing to the conservation of energy. Bernoulli's equation can be expressed by:

$$\mathrm{P}_1 + \frac{1}{2}\rho {\mathrm{v}_1}^2 + \rho g \mathrm{h}_1 = \mathrm{P}_2 + \frac{1}{2}\rho {\mathrm{v}_2}^2 + \rho g \mathrm{h}_2 \tag{4}$$

where P is the pressure with unit in Pa, ρ is the density of fluid with unit in $\frac{kg}{m^3}$, v is the speed with unit in ms^{-1}, g is the gravitational force with value $9.81\mathrm{ms}^{-2}$, h is the height with unit in m.

The paper's objective is to evaluate the performance of PRC panel in both software simulation and laboratory's experiment. Different performance criteria including temperature difference, cooling capacity, and heat loss would be measured. For software simulation, it would be aided by the SolidWorks software to perform all the drawings, assembly, flow simulation and result analysis. For the laboratory's experiment, a 1:1 model would be fabricated. All the processes including design, material procurement, model assembly, laboratory-testing, data-logging and result analysis would be participated. Having accomplished both software simulation and laboratory's experiment, their results would be compared and difference between two respective performance criteria would be discussed.

3. Investigative Methodology

3.1 SolidWorks Model Mechanism

The design of the dynamic water-based cooling system model could be shown in the Figure 1.

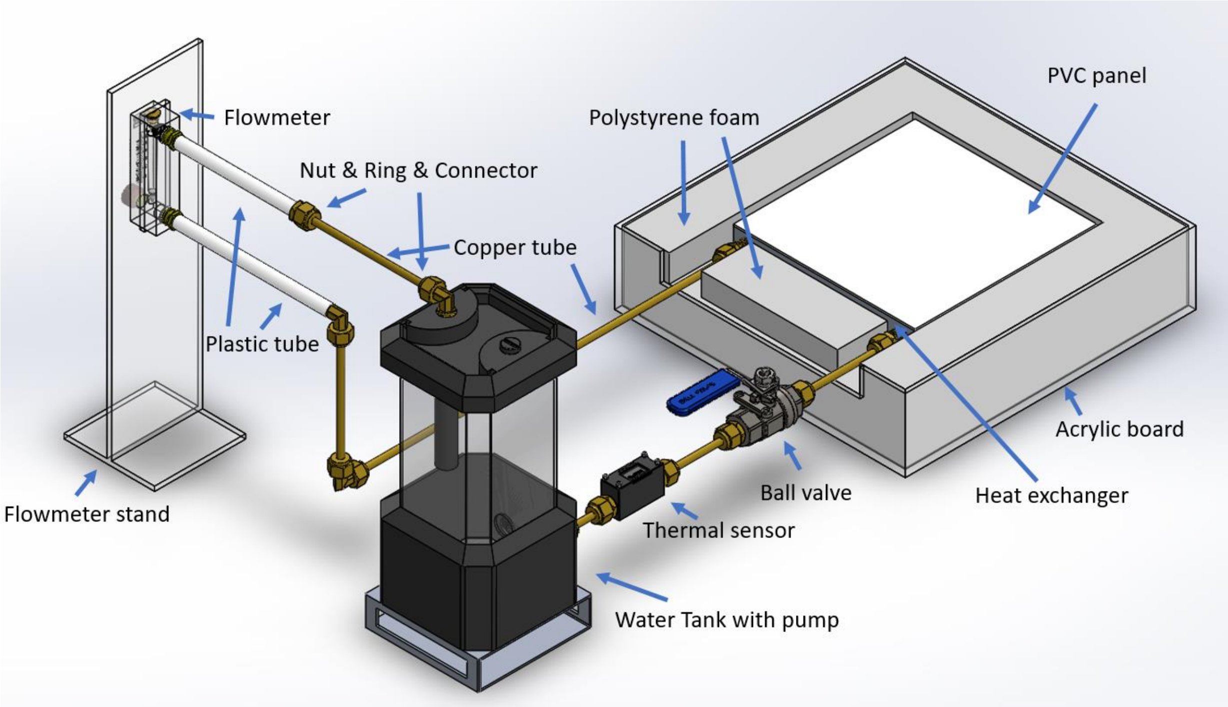


Figure 1: The overview of the dynamic water-based cooling system model

Figure 1 shows the overview of the dynamic water-based cooling system model, which was produced by SolidWorks. The general working mechanism has the following procedures: Firstly, distilled water is poured into the water tank together with pump. After the lid has been covered, power is switched on. Then, water starts flowing through the flowmeter, heat exchanger, ball valve, thermal sensor and at last flows back to the water tank. It is considered as one complete cycle. During the process, water's flow rate can be measured by flowmeter, whereas water's temperature can be measured by thermal sensor. The system will be operating for 24 hours, and the temperature change between inlet and outlet during the period will be recorded by Excel. Moreover, the system will be placed under an exposed sunlight environment for the sake of optimal experimental conditions. The performance between the system with PVC panel and the system without PVC panel will be compared. It is expected that the system with PVC panel will record a slightly higher temperature reduction between inlet and outlet, when compared with the system without PVC panel.

The material list of SolidWorks assembly is generated in Table 1, in which there are 15 components in total.

Material/Component	Piece(s)/Size
Water tank with pump	1 piece
Copper tube	1000mm length in total
Nut	12 pieces
Ring	12 pieces
Straight socket connector	8 pieces
90°-curved socket connector	2 pieces
Flowmeter	1 piece
Flowmeter stand	1 piece
Plastic tube	300mm length in total
PVC Panel	200mm x 200mm x 2mm
Heat exchanger	200mm x 200mm x 25mm
Acrylic board	4 pieces of 330mm x 80mm x 4mm
Polystyrene foam	320mm x 320mm x 75mm
Ball valve	1 piece
Thermal sensor	1 piece

Table 1: Material list for SolidWorks model assembly

3.2 Model Actualization

Having the model constructed in the SolidWorks, the model actualization was in the pipeline. On the first day of model actualization, there was a big obstacle, which was the size-fitting problem. Since plumbing accessories have different dimensions across them, it seemed that adaptors were required to connect them together. For example, the nuts were in the size of G1/2, which was about 20mm in diameter, while the vertical socket connectors were in the size of G1/4, which was about 12mm in diameter. This problem can be shown in Figure 2.

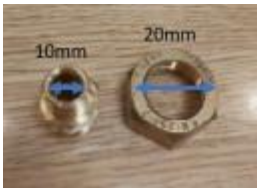


Figure 2: Inconsistent size-fitting between plumbing accessories

On the second day of model actualization, the consistent size of plumbing accessories had been delivered, so the team could start our model fabrication. Acrylic board was cut into specified dimension with a laser-cutting machine located in the laboratory. Also, polystyrene foam was also cut into specified dimension with a cutter. Moreover, copper tube was cut into different sessions with a copper tube cutter. In addition, some of the components were connected, while the core structure was assembled as well. The process went smoothly, and everything was on schedule. Figure 3 summarized the second day of work.

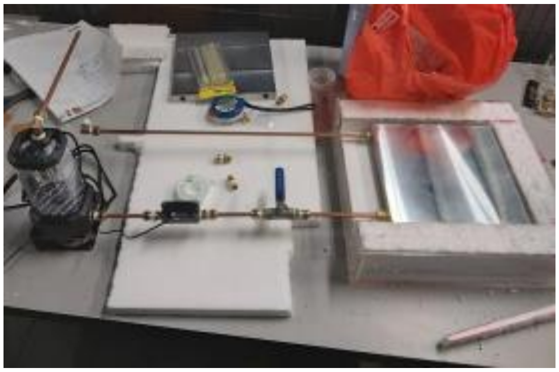
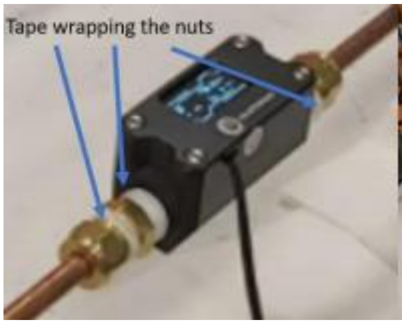


Figure 3: Summarization of second day of work

On the third day of model actualization, there was another concern, which was the water leakage concern. In the SolidWorks model assembly, all the dimensions were well-specified and therefore this concern had not been considered. To address the issue, the team used polytetrafluoroethylene tape to wrap around the copper tube and nuts so as to prevent water leakage from joints. Figure 4 shows how the joints were wrapped by the tape. Other than that, the team had connected the remaining sessions of the whole model. It was expected that the model could be finished within three days. Figure 5 summarized the third day of work.



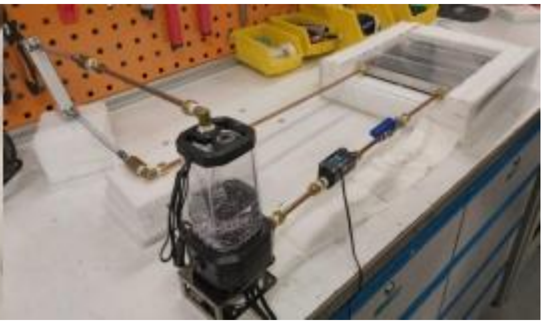


Figure 4: Tape wrapping

Figure 5: Summarization of third day of work

On the fourth day of model actualization, the team would like to build up a flowmeter stand for the flowmeter. As observed in Figure 5, the flowmeter was supported by piles of polystyrene foams, it is desirable to have a more solidified measure to support the flowmeter. Therefore, the remaining acrylic board materials were used to fabricate the flowmeter stand. Other than that, there was water leakage problem again due to a loosen connection. Hence, the team connected some parts of components again to improve the whole model. Figure 6 summarized the fourth day of work.

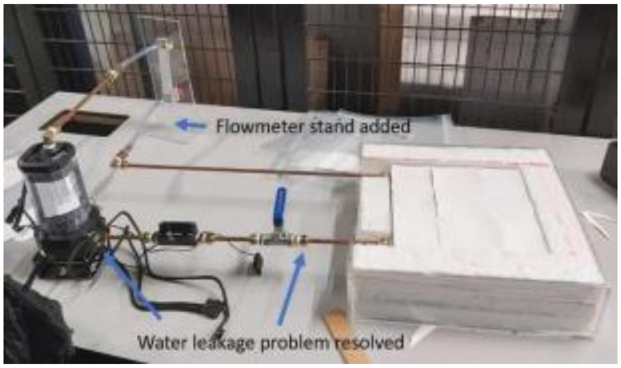


Figure 6: Summarization of fourth day of work

The fifth day of model actualization marked the end of model actualization. In order to fabricate a more pragmatic and comprehensive model, the team decided to wrap the model with aluminum foil and polystyrene foam so that a better thermal insulation could be achieved. They could block heat transfer by the means of conduction and radiation under an exposed sunny-day environment, where solar radiation could be very high. More than that, instead of measuring the water temperature by thermal sensor, another pair of wires were used, to measure the water inlet and outlet temperature. On 30th April 2021 at around 21:00, the team had finished the experiment's set-up and just needed to wait for 24 hours to log data. Figure 7 summarized the final model actualization. Figure 8 was used to compare the SolidWorks Model Design with the model actualization in real life.

Figure 7: Final model actualization

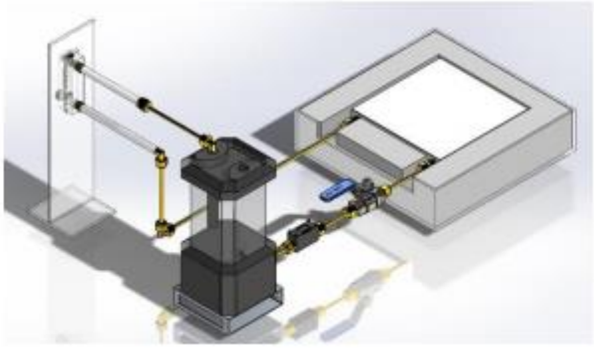
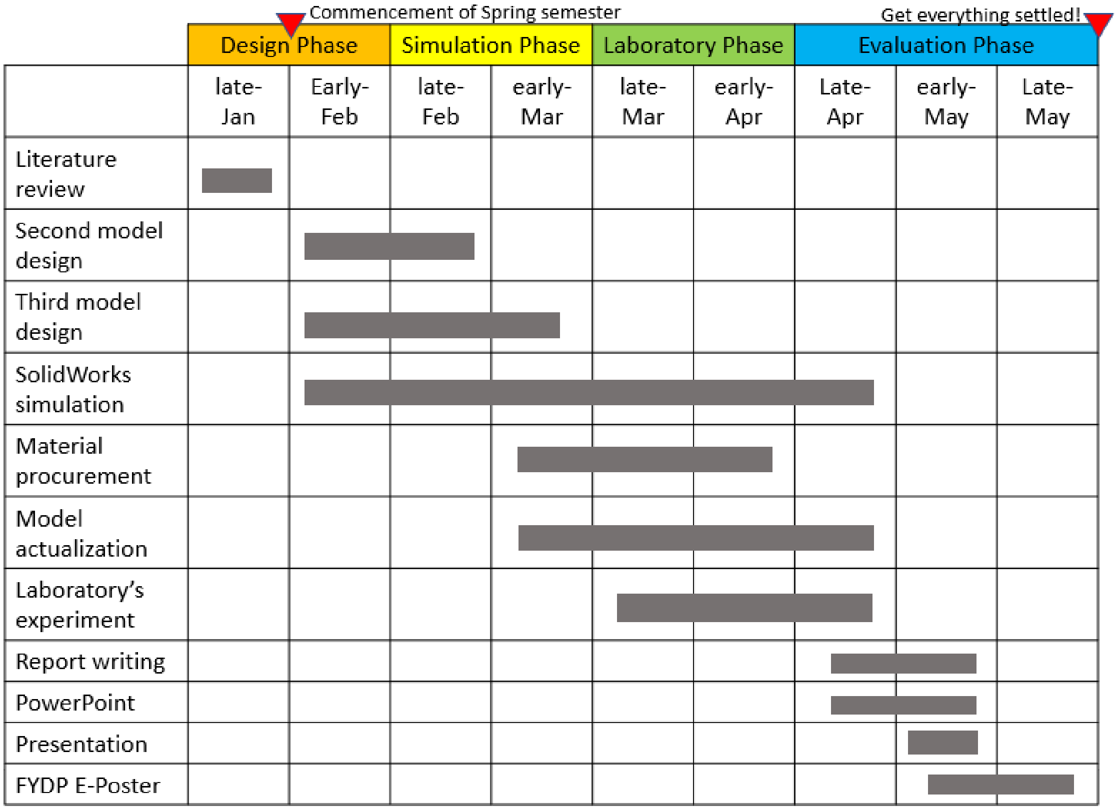


Figure 8: SolidWorks model simulation

4. Project Schedule



Commencement of Spring semester

Get everything settled!

	Design Phase		Simulation Phase		Laboratory Phase		Evaluation Phase		
	late-Jan	Early-Feb	late-Feb	early-Mar	late-Mar	early-Apr	Late-Apr	early-May	Late-May
Literature review	■								
Second model design		■	■						
Third model design		■	■	■					
SolidWorks simulation		■	■	■	■	■	■		
Material procurement				■	■	■			
Model actualization				■	■	■	■		
Laboratory's experiment					■	■	■		
Report writing							■	■	
PowerPoint							■	■	
Presentation								■	
FYDP E-Poster								■	■

Table 2: Gantt-Chart for the project schedule

5. Results and Discussions

5.1 Flow Simulation in SolidWorks

Having the model meshed, the flow simulation can start running for the result. In the ideal case, apart from the PRC panel, all components' exposed surfaces are well-insulated. Therefore, there will not be any interaction between outer environment and the system itself. In the preliminary set-up, the analysis type is set to be internal flow analysis with cavities that without flow conditions excluded. The surrounding environment's temperature and pressure are set to be 298K and 100,000Pa respectively. For the enclosed surface part, as expected, water will flow through the water tank with pump, copper tube, plastic tube, flowmeter, the core structure, ball valve, thermal sensor and at last back to the water tank with pump. Figure 9 shows how water will be looped inside the system. The light-blue color illustrates the contained volume within the system.

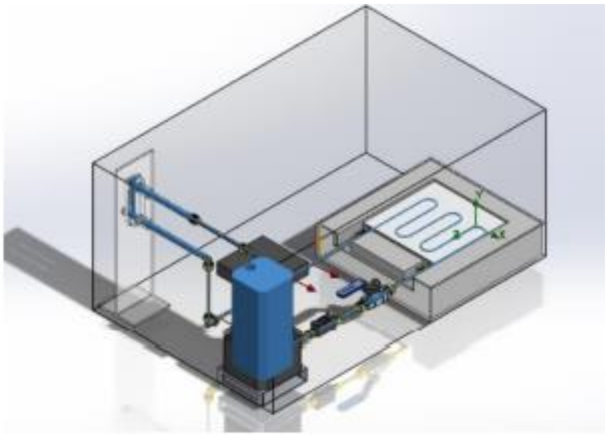


Figure 9: Enclosed system represented in light-blue color

Figure 10 shows the surface plot of temperature distribution along the system. As observed in Figure 10, the closer the component is to the pump, the higher the component's temperature is. At both water inlet and outlet position, they have a similar temperature level, which is about 297K. The performance of PRC panel seems to be not very promising. To be more explicit, the cut plot along the cross-section area can show the maximum temperature and minimum temperature as well. In Figure 11, it shows the cut plot along water inlet and water outlet position. Unexpectedly, the water inlet position has a higher temperature than the water outlet position, which are 297.99K and 298.80K respectively.

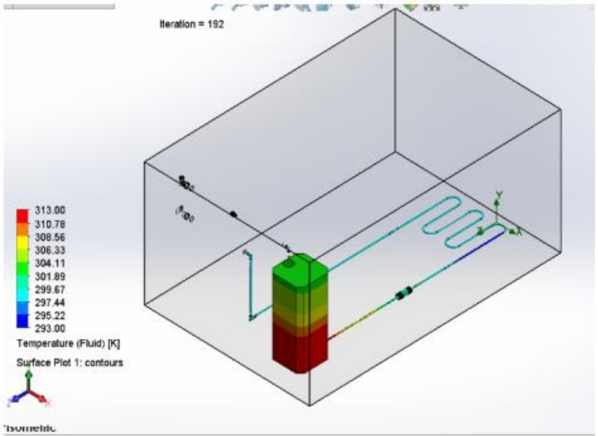


Figure 10: Surface plot of model's temperature

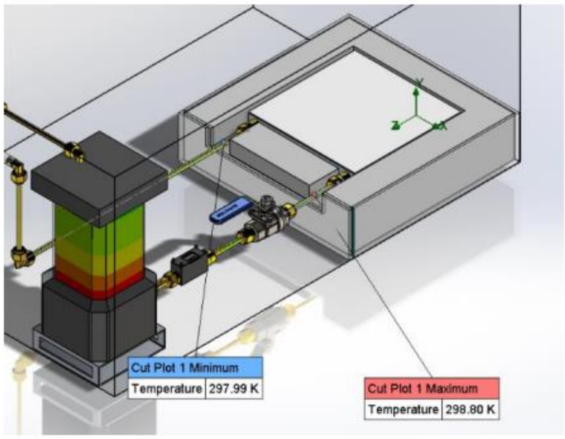


Figure 11: Cut plot of model's temperature

5.2 Flow in Actualization

In the experiment, the water inlet temperature and outlet temperature were recorded respectively. In Figure 12, it shows the temperature variation against time during the experiment. From the graph, it is observed that inlet temperature and outlet temperature have a positive relation with ambient temperature. Their temperatures were higher in daytime, whereas their temperatures were lower in nighttime. In addition, the water outlet temperature is always lower than the water inlet temperature. It is testimony to the cooling performance of PRC panel. On average, there were a temperature reduction in 4°C. The lower the temperature is, the more efficient the PRC panel was. However, their temperatures were still higher than the ambient temperature, which was a strange phenomenon.

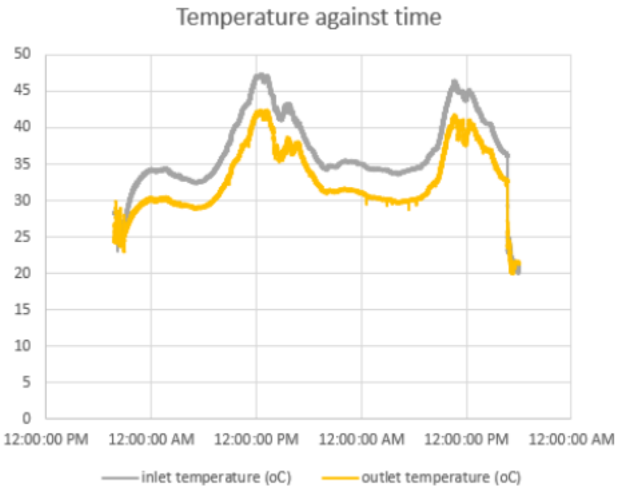


Figure 12: Plotting of inlet and outlet temperature against time

Moreover, Figure 13 shows the plot of ambient temperature and solar radiation against time. There is not a concrete correlation between them. Nonetheless, the highest ambient temperature recorded was about 36.8°C, whereas the highest inlet temperature and highest outlet temperature were 47.2°C and 42.3°C respectively. Logically, it should not be happening. There must be some errors involved in the experiment.

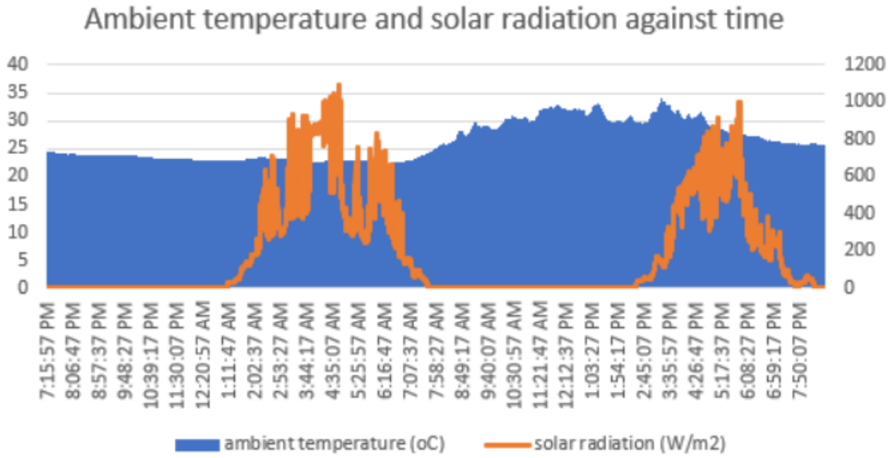


Figure 13: Plotting of ambient temperature and solar radiation against time

5.3 Explanation for Flow Simulation in SolidWorks and Flow in Actualization

In flow simulation in SolidWorks model, it was found that the outlet temperature is higher than the inlet temperature. Instead of resorting the reason to the inefficiency of the PRC panel, it is more about the extra heat supplied by the water tank with pump. [4] Since water pump produces energy while operating, and this energy is transferred to the surrounding components through conduction in copper tube. Theoretically, the close the position it is to the water pump, the higher the temperature the component has. Similarly, in model actualization, because the water pump produces an excessive amount of heat, rather than cooling the whole system, the whole system is heated up by the water pump, resulting into a temperature that is higher than the ambient temperature. To alleviate the problem, the result suggests that the system can seek a water pump that has a lower power, which also has sufficient power to pump water. Moreover, the surface area of PRC panel can be increased. In the model actualization, it is observed that the water outlet temperature is lower than the water inlet temperature. It is testament to the observable cooling performance of PRC panel.

6. Conclusion

In conclusion, despite the mediocre performance of the experiment, the efficiency of the PRC panel is still noticeable. In order to have a better demonstration, it is suggested that the surface area of PRC panel can be increased so that more area can be used for the cooling purpose. Moreover, it might not be necessary to connect a water pump with it because of the excessive heat produced by it. In the design, there is a 1:1 model from model actualization to SolidWorks drawing and Assembly. Most of the parts have been precisely drawn, apart from some delicate plumbing accessories such as nuts and threads, which leads to the gap between components. The team would express the SolidWorks model as a satisfactory one since it is embedded with all the components with detailed specifications. When it comes to the SolidWorks flow simulation, because of the complex dimensions drawn in assembly, some minor features have to be adjusted for the sake of enclosed volume. This might hinder the accuracy of the model simulation. Nonetheless, the general promising outcomes are still achievable

7. References

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