STUDY ON PCM STORAGE PARAMETER TO INCREASE HEAT STORAGE CAPACITY

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***Abstract*—85.5% of total world energy consumption in 2016 come from fossil fuels and much more efforts need to be done to reduce our current dependencies on fossil fuels. Using solar thermal energy to heat domestic hot water is one of numerous researches that have high potential and that lead us towards the correct direction in shifting to renewable energy source. This study presents a numerical parametric study of a solar thermal evacuated system using phase change material (PCM). Laminar water flow as heat transfer fluid (HTF) and natural convection were considered for the numerical simulation. The current research studies, take different design parameters into consideration. For design parameters, the effects of length and diameter of the PCM container on PCM heat storage capacity are studied. As for operating parameters such as the water mass flow rate inside the PCM tube, heat flux absorbed from the sun exposure and the inlet water temperature were remained constant. Results show that, increasing tube diameter give 11.6% more impact on PCM heat storage capacity compare to increasing tube length.**

Keywords—

PCM	***Phase Change Material***
HTF	***Heat Transfer Fluid***
β	***Thermal expansion coefficient***
C	***Mushy zone constant***
cp	***Specific heat of Phase Change Material***
H	***Enthalpy***
k	***Thermal conductivity***
L	***Latent heat of fusion***
P	***Pressure***
Q,q	***Heat flux***
T	***Temperature***
$\vec{g}$	***Gravity Acceleration Vector***
$\vec{v}$	***Velocity Vector***
γ	***Liquid Fraction***
η	***Absorption Efficiency***
ρ	***Density of Phase Change Material***
μ	***Dynamic Viscosity***

I. INTRODUCTION

From British Petroleum (BP) Statistical Review of World Energy 2017, as of 2016, total world energy consumption is 13276.3 million tonnes oil equivalent (MTOE) [1]. From the total energy consumed, 85.5% of it come from fossil fuels, 6.86% from hydro-electricity, 4.46% come from nuclear energy and 3.16% from renewable energy. Even though the percentage of energy consumed from fossil fuels reduced from 86.0% in 2015, more efforts still needed to be done in order reduce the emission of greenhouse gas to the environment and to directly respond to the global climate change threat.

Currently, numerous projects and researches have been done to reduce the world dependent on fossil fuels energy and indirectly increase our world dependencies on renewable energy. One notable research intensively studied, is on the solar thermal energy application using phase change materials (PCM).

Since solar thermal energy applications depend on the sun exposure, which is highly time-dependent and unpredictable (due to weather), the efficiency of the solar thermal energy systems relies immensely on the efficiency of solar thermal energy storage technology. The usage of PCM in solar thermal energy system offers high product reliability since, PCM offers high heat storage capacity per volume or mass [2]. This translate to higher output water temperature stability and slower temperature decrease inside the water storage tanks.

The research done is an attempt to study the effect of design PCM tube design and system operating parameter on its thermal storage capacity. Numerical simulations are done using a Fluent CFD Software under ANSYS Workbench version 17.2.

II. PHYSICAL AND NUMERICAL MODELS

A. Physical Model

Figure 2.1 shows the physical configuration of the solar thermal energy storage with PCM for U-tube design. The PCM tube is exposed to light source (sun). In order to ensure equal distribution of the solar energy transmission on the surface of the PCM tube and to eliminate energy loss from convection to the environment, the PCM tube is enveloped with a vacuum tube of ceramic glass. The vacuum tube heat absorption efficiency, η is rated at 83%.

The PCM outer container is made of copper tube with 38.1mm in diameter and 0.6mm in thickness. For U-tube design, the tube is made of copper tube with 6.35mm inside diameter and 9.53mm outside diameter. In this research, water is used as heat transfer fluid. Water from storage tank is circulated inside these tubes.

The PCM material used is based on RT82, a commercial material from Rubitherm GmbH, Germany. The PCM is filled in between the copper tube and the PCM container. The thermo-physical properties can be found in Table 2 1 below.

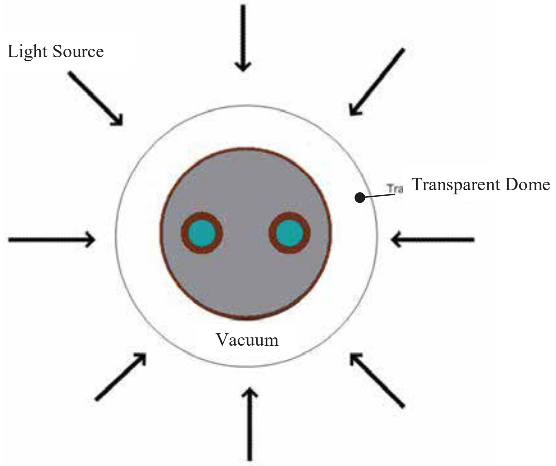

Figure 2.1: Physical Configuration of Solar Thermal Energy Storage using PCM Tube

TABLE 2-1 THERMO-PHYSICAL PROPERTIES OF THE PCM (RT 82)

Property	RT82
Density of PCM, solid,ρs (kg/m^3)	950
Density of PCM, liquid, ρl (kg/m^3)	770
Specific heat of PCM, cpl (J/kg. K)	2000
Latent heat of fusion, L (J/kg)	176000
Melting temperature, Tm (°C)	78-82
Thermal conductivity, k (W/m.K)	0.2
Thermal expansion coefficient (1/K)	0.001
Dynamic Viscosity, μ (kg/m.s)	0.03499

Sources Rubitherm GmbH, 2011 Available from: /http://www.rubitherm.de/

B. Numerical Simulations

For this research studies, numerical simulations were done using computational fluid dynamic (CFD) commercial software Fluent under ANSYS workbench version 17.2.

1. Governing Equations

The effect of natural convection during solidification and liquidation of PCM is buoyancy-driven flows. Therefore, a Boussinesq approximation model is considered to calculate the density variations of the PCM, ρ based its temperature.

Boussinesq Approximation Model:

$$\rho=\rho_{ref}\,(1-\beta(T-T_{ref}\,)) \qquad (1)$$

Where ρ_{ref}, is the reference density at reference temperature, T_{ref}, β is the thermal expansion coefficient, and T is the current PCM temperature.

Additionally, based on the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) standard 93-2010 [3], for this research application, the operating water inlet velocity per tube is from 0.007 ms^{-1} to 0.014 ms^{-1} which correspond to Reynolds number of 44 to 177. Thus, from the Reynolds number, it is safe to conclude that the flow inside the tube is purely laminar and that the viscous dissipation is negligible.

Accordingly, the governing equations used to model the fluid flow and heat transfer inside the solar thermal energy storage system using PCM are:

Continuity Equations:

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho.\vec{v}) = 0 \qquad (2)$$

Momentum Equations:

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla.(\rho.\vec{v}\vec{v}) = -\nabla \mathrm{p} + \nabla.(\bar{\bar{\tau}}) - \rho\vec{g} \qquad (3)$$

With, Cauchy stress tensor,

$$\bar{\bar{\tau}} = \mu\left[(\nabla\vec{v} + \nabla\vec{v}^T) - \frac{2}{3}\nabla.\vec{v}I\right] \qquad (4)$$

Energy Equations:

$$\frac{\partial(\rho H)}{\partial t} + \nabla.(\rho\vec{v}H) = \nabla.(k\Delta T) + S \qquad (5)$$

Where ρ is the fluid density, $\vec{v}$ is the fluid velocity, p is the pressure, g is the gravity acceleration, μ is the dynamic viscosity, I is the identity matrix, H is the enthalpy, k is the thermal conductivity and S is the energy source term.

Enthalpy, H can be further defined as sum of the sensible enthalpy, h and the latent heat, ΔH:

$$H = h + \Delta H \qquad (6)$$

$$\text{with } \mathrm{h} = h_{ref} + \int_{T_{ref}}^{T} c_p\, \Delta T \qquad (7)$$

Where h_{ref} is the reference enthalpy at reference temperature,T_{ref}, c_p is the specific heat capacity and latent heat, ΔH can be defined in term of latent heat of the material, L as:

$$\Delta H = \gamma L \qquad (8)$$

with liquid fraction, γ can be defined as:

$$\gamma = \begin{cases} 0 & if \quad T < T_s \\ 1 & if \quad T > T_l \\ (T-T_s)/(T_l-T_s) & if \quad T_l > T > T_s \end{cases} \qquad (9)$$

The latent heat content is 0 when the PCM material is 100% solid ($T < T_s$) and 1 when the material is 100% liquid ($T > T_l$). When the material temperature is in between the solidus and liquids temperature, the value of latent heat is proportional to the liquid fraction ratio.

In ANSYS Fluent, the enthalpy-porosity technique treats the mushy region (partially solidified region) as porous medium. The porosity in each cell is set equal to the liquid fraction, γ in that cell [4]. Thus, the source term, S in eq. (5) take the following form:

$$S_i = C\,(1-\gamma)^2 \frac{u_i}{\gamma^3+\epsilon} \qquad (10)$$

where $\frac{C\,(1-\gamma)^2}{\gamma^3+\epsilon}$ is the porosity function defined by Brent et al. [5] to make the momentum equations mimic Carmane Kozeny equations for flow in porous media with C is a constant reflect of the mushy zone morphology. This constant varies between

10^4 and 10^7. As per suggested by Ye et al [6], a value of 10^5 is taken for the mushy zone constant C.

2. Boundary Conditions

In ANSYS Fluent, during charging process, the both the PCM inside the container and the water circulating inside copper tube are initialized with ambient temperature of 300K. Whereas during discharging process, PCM are superheat in liquid state at an initial temperature of 363K whereas circulated water is initialized with ambient temperature of 300K.

In order to simulate the heat absorbed from sun radiation, a heat flux thermal boundary condition with 0.6mm thickness is applied at the outer surface of the PCM container. Thermal coupled boundary conditions are applied on interfaces between the PCM and the inner copper tube as well as the interfaces between the inner copper tube and the circulated water. For these studies, energy absorbed by PCM is transferred to the circulated water with no heat loss to the outside ambient.

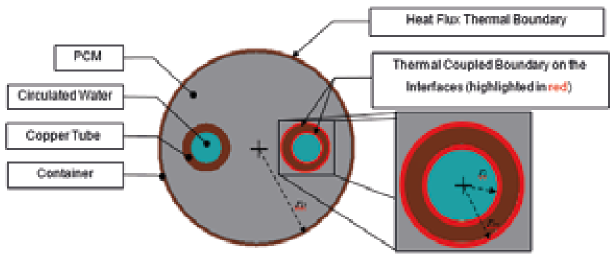

Figure 2.2: Boundary Conditions

These boundary conditions translate are per below:

Heat flux thermal boundary at the outer surface of PCM container gives,

at $r = r_O$,

heat flux absorbed by the system, $q = Q \cdot \eta$ (11)

Where Q is the amount of heat reached to the system per unit of time and η is the heat absorption efficiency of the vacuum tube.

Thermal coupled boundary on the interfaces (highlighted in red) gives,

at $r = r_m$, $T_{PCM} = T_{Copper\ Tube}$ (12)

at $r = r_i$, $T_{Copper\ Tube} = T_{Water}$ (13)

3. Numerical Methodology

A commercial computational software, ANSYS Fluent 17.2 is used to simulate the solidification and melting of the PCM for these research. Three dimensions of the PCM solar thermal evacuated tube were drawn using ANSYS Design Modeler and meshed using ANSYS Meshing. Hexahedral mesh were generated for the circulated water body, whereas a combination of tetrahedral and pyramid meshes were generated for the copper tube and PCM zone with prism meshes used near the boundary layer using inflation method. Then, the mesh were imported to Fluent solver for case setup. Here, cell zones and boundary layers were defined to their respective materials properties and boundary conditions as per mentioned in chapter I and II above.

The semi-implicit pressure-linked equation (SIMPLE) was used for the pressure correction [7]. As for the spatial discretization, for pressure correction equation, the pressure staggering option (PRESTO) scheme is used whereas Quadratic upwind differencing (QUICK) was used to solve the momentum and energy equations. The least squares cell based is opted to solve the gradients involved in the spatial equations. The under-relaxation factor for pressure, momentum, energy and liquid fraction update are 0.3, 0.7, 1 and 0.9 respectively [8]. Predetermined convergence criteria is set to 10^{-6} for energy equation and 10^{-3} for other variables.

III. Experimental Verification And Validation

A. Experimental Apparatus and Procedure

An experimental apparatus of the solar thermal evacuated system using actual size model of PCM tube was fabricated to validate the numerical simulation of the PCM solidification and melting process. Figure 3.1 shows a schematic diagram of the experimental apparatus which includes the solar thermal evacuated tube, flow meter, thermocouples, heat exchanger, water storage tank, water circulation pump and a data acquisition system. In this apparatus, a closed water circulation system is used with a flow meter to monitor the mass flow rate of the water in circulation and it is controlled using the flow regulating valve situated downstream to the solar thermal evacuated tube. The inlet water temperature and outlet water temperature are both captured by the two thermocouples situated the entrance and exit of the solar thermal evacuated tube. A pyranometer is also mounted alongside the apparatus to measure the solar radiation flux (in watts per square meter) from a field of view of 180°.

Figure 3.2 shows the position of thermocouples the inside the PCM to capture the local temperature variation inside each the solar thermal evacuated tube. The position of thermocouples is spaced 400mm apart to well capture the temperature distributions of the PCM inside the solar thermal evacuated tube.

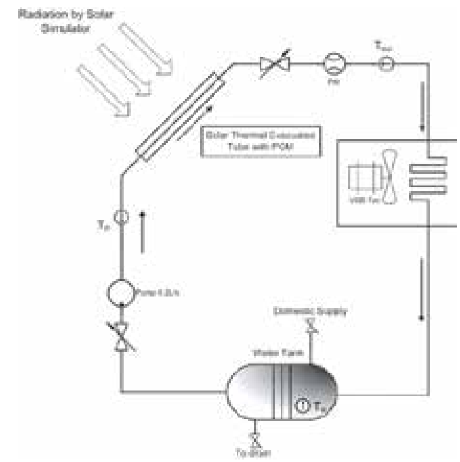

Figure 3.1: Experimental Solar Thermal Evacuated Tube with PCM Schematic Diagram.

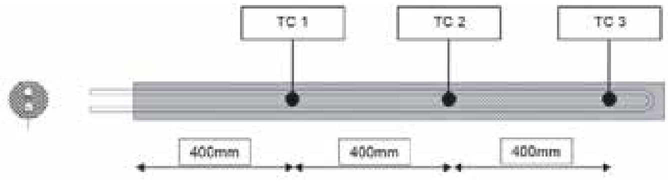

Figure 3.2: Thermocouple (TC) Sensor Positions inside Solar Thermal Evacuated Tube with PCM.

B. *Validation of Numerical Model*

Prior to the numerical parametric study of the PCM solidification & melting in solar thermal evacuated system, a model validation was done to ensure that the estimations and assumptions made in the numerical model were correct [9]. Actual field heat flux data captured by pyranometer during the experimental proceeding, were imported to ANSYS Fluent. Data from pyranometer were linked to the numerical model heat flux thermal boundary conditions using transient profile data. Validation were done based on the different mass flow rates. Figure 3.3 shows a comparison results between the data collected experimentally and numerically of the temporal progression of water outlet temperature and the PCM temperature taken from thermocouple TC1. Although there is an under prediction of the thermocouple TC 1 temperature values once the PCM fully melted, generally, the results show a good accordance between both the experimental and numerical data. With the NRMS error values calculated, results obtained shows only 3.03% error for the thermocouple temperature. Conclusion can be made that the numerical model estimations and assumptions used were correct to simulate the actual field results. Thus, for the parametric research of the solar thermal energy storage using PCM tube, only numerical studies were done.

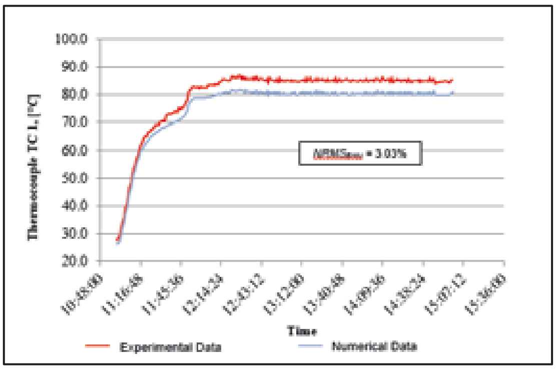

Figure 3.3: Experimental and Numerical Comparison of Thermocouple TC 1 Temperature Results. (Mass flow rate of 2.217 x 10^{-4} kg/s)

IV. Parametric Results And Discussion

For the parametric studies on design parameters of the solar thermal evacuated, two design parameters were taken into considerations which are the length and diameter of the PCM tube. A minimum and maximum range of each parameter were predefined as per Table 4 1.

Parametric studies was done using design of experiment (DOE) method. Central composite design (CCD) with face centered design type was used. Using CCD design method, nine design points were generated based on the minimum and maximum values of each design parameters. These nine generated design points are presented as per diagram in figure 4.1.

TABLE 4.1: Minimum and Maximum Value of Design Parameters.

Parameter	Designation	min	average	max
length [mm]	P1	1250	1750	2250
diameter [mm]	P2	32.1	38.1	44.1

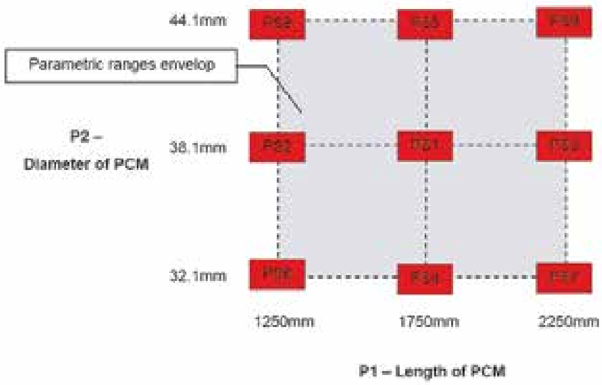

Figure 4.1: Design Points generated from CCD Design Method.

A. *The Effect of PCM Tube Length*

Parametric studies was done to check the effect of PCM tube length to the discharging process of the solar thermal evacuated tube system. The studies were done using a constant water mass flow rate of 4.434 x 10^{-4} kgs-1 and an initial water inlet temperature of 299K (26°C). For comparison purposes, graphs presented in figure 4.2 and 4.3 are for PCM tube with the same diameter of 38.1mm which correspond to design point PS2, PS1 and PS3 respectively.

Figure 4.2 shows the volume average of PCM melting faction inside the solar thermal evacuated tube for design point PS2, PS1 and PS3 which correspond PCM tube length to 1250mm, 1750mm and 2250mm. Since numerically it is hard to differentiate a very small number such as 10^{-2} and the value of absolute zero, a lower threshold was introduced which is the time required to reach 0.05 melting fraction, t_0.05MF. Simulated results shows that design PS2, PS1 and PS3 required 3180s, 3870s and 4670s respectively. In other words, the longer PCM tube length, t_0.05MF is higher. This is mainly due to the increase of PCM mass which is directly proportional to the tube length.

Based on previous results that indicate total PCM mass plays an important roles in providing better discharging thermal performance, thus, it is obvious that a new criteria independent to the PCM mass needed to be introduced. For that, the total specific energy storage criteria, which is the total energy stored by the PCM per kilogram of PCM, was calculated for each design point. Duration to reach 10% of its initial total specific energy stored, t_(10%TSES) was taken as a threshold for this criteria.

As presented in figure 4.3, tube design PS2 required t_(10%TSES) equal to 3396s compared to 4958s and 6053s for tube design PS1 and PS3 respectively. This imply that longer PCM tube design, it have not only higher capacity to store more energy, but also it take longer duration to deplete its energy storage while still maintaining high water outlet temperature i.e. higher $t_{10\%TSES}$.

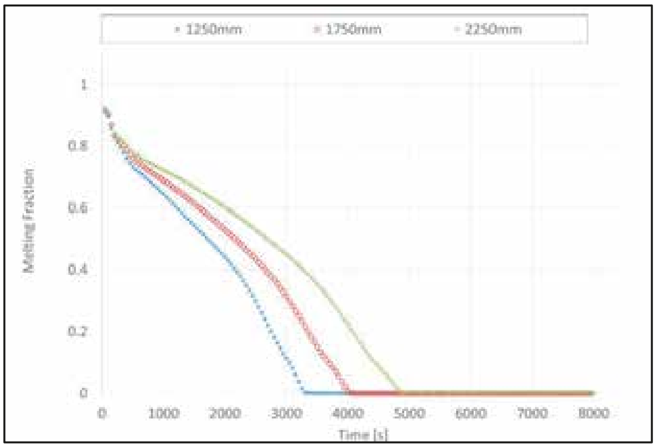

Figure 4.2: Effect of Length of PCM tube to Melting Fraction.

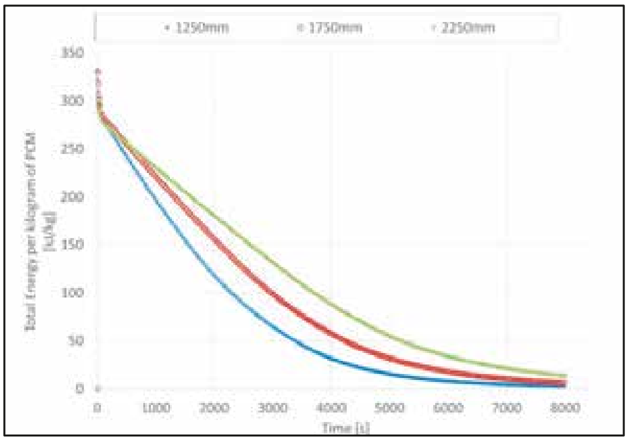

Figure 4.3: Total Specific Energy Storage Comparison for Different Tube Length.

B. The Effect of PCM Tube Diameter

Additional parametric studies was also done to check the effect of PCM tube diameter to the discharging process of the solar thermal evacuated tube system. Here, for comparison purposes, the length of PCM tube is fixed with a value of 1750mm.Graphs presented in figure 4.4 and 4.5 are for PCM tube corresponding to design point PS4, PS1 and PS5 with a tube diameter of 32.1mm, 38.1mm and 44.1mm respectively.

Figure 4.4 shows the volume average of PCM melting faction inside the solar thermal evacuated tube for design point PS4, PS1 and PS5 which correspond PCM tube diameter to 32.1mm, 38.1mm and 44.1mm. Results shows that t_0.05MF for PS4, PS1 and PS5 are respectively 2590s, 3870s and 5340s. Tube design PS5 have higher t_0.05MF due to its high PCM mass of 1.866kg compared to 0.898kg and 1.344kg for PS4 and PS1.

As discussed in chapter IV.A, same observation can be seen, where PCM tube discharging thermal performance are highly dictated by the mass of PCM. Thus, total energy stored per kilogram of PCM, t_(10%TSES) were calculated and plotted as per shown in figure 4.5. t_(10%TSES) obtained for PS5 is the highest with 6808s compared to 4958s for PS1 and 3451s for PS4. This implied that the larger the diameter of the PCM tube, it is able to withstand longer duration to deplete its energy storage while still maintaining longer high water outlet temperature.

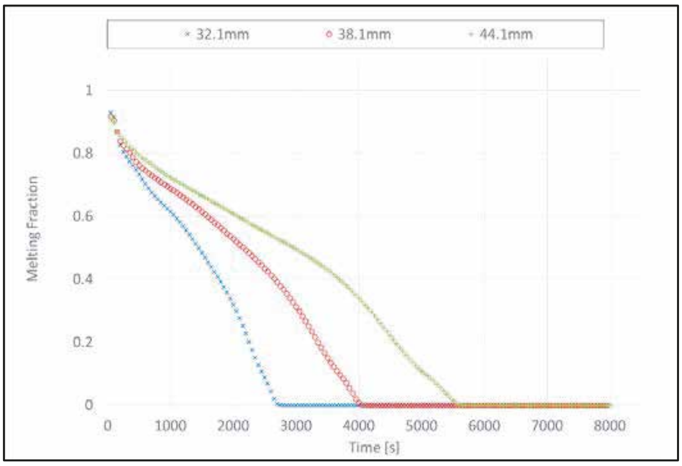

Figure 4.4: Effect of Diameter of PCM tube to Melting Fraction.

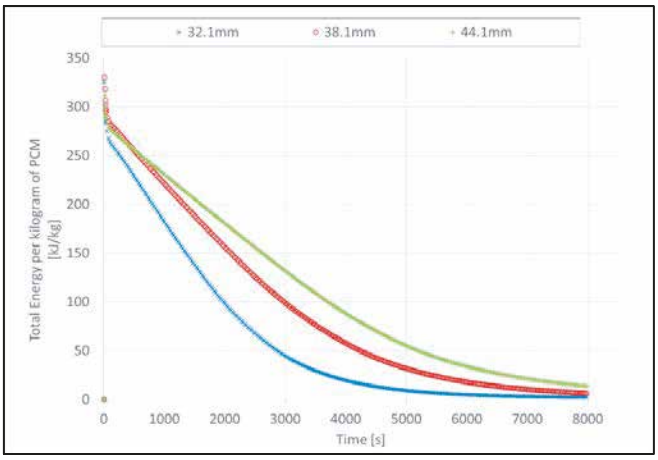

Figure 4.5: Total Specific Energy Storage Comparison for Different Tube Diameter.

C. Parametric Sensitivities

As results in chapter indicated, 4.1 and 4.2, both parameter studied, PCM tube length and PCM tube diameter are directly proportional to the discharging thermal performance of the PCM tube as solar thermal energy storage. Thus, parametric sensitivities or also known as impact factor is studied to identify which one of these two parameters have the highest impact towards a better discharging thermal performance in the solar thermal energy storage using PCM tube.

For that, comparison needed to be made for each of the tube design, PS1 to PS9. Figure 4.6 shows the total specific energy comparison between all the design points. It can be note that the tube design PS6 with a tube diameter of 32.1mm and tube length of 1250mm required the shortest time to reach 10% of total specific energy stored, $t_{10\%TSES}$ whereas, tube design PS9 with the tube diameter of 44.1mm and tube length of 2250mm have the longest $t_{10\%TSES}$. Summarize tables of PCM tube intrinsic properties and simulation results for each design points, PS1 to PS9 were presented in table 6 1 and table 6 2 in the appendix.

Comparing PS8, PS7 and PS1, all these three designs have similar PCM mass of 1.333kg, 1.155kg and 1.344kg respectively with PS8 have the biggest tube diameter and shorter length, PS7 have the longest tube length and smallest diameter, and PS1 are in the middle for both tube diameter and tube length. From the $t_{10\%TSES}$ plotted in figure 4.6, it can be noted that, tube design PS8 give the longest $t_{10\%TSES}$ at 5449s compared to 4213s for PS7 and 4958s for PS1. This shows that PCM tube diameter have higher impact on the discharging thermal performance. In order words, for the same PCM mass and volume, by changing the diameter, it have more impact on the time required to reach 10% of total specific energy stored than by changing the tube length.

These findings can also be directly linked to the sensitivity value of each design parameter. Sensitivity value shows the impact factor each input parameter, here, the PCM tube length and PCM tube diameter towards the output parameter, time required to reach 10% of total specific energy, $t_{10\%TSES}$. Generally, sensitivity is driven by the amount by which the output parameter varies across the variation range of an input parameter [4]. These statistical sensitivities are based on the Spearman-Rank Order Correlation.

For this parametric research studies, sensitivity of changing the tube diameter towards the time required to reach 10% of total specific energy, $t_{10\%TSES}$ is 55.8% compared to 44.2% for tube length (refer figure 4.7). This conclude that tube diameter have 11.6% higher impact on the value of $t_{10\%TSES}$) compared to tube length. In other words, higher discharging thermal performance are better on bigger PCM tubes with bigger diameter.

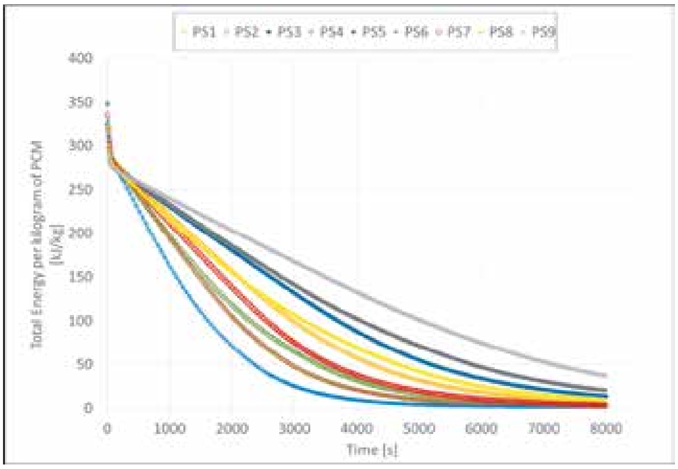

Figure 4.6: Total Specific Energy Storage Comparison for Different Design Points.

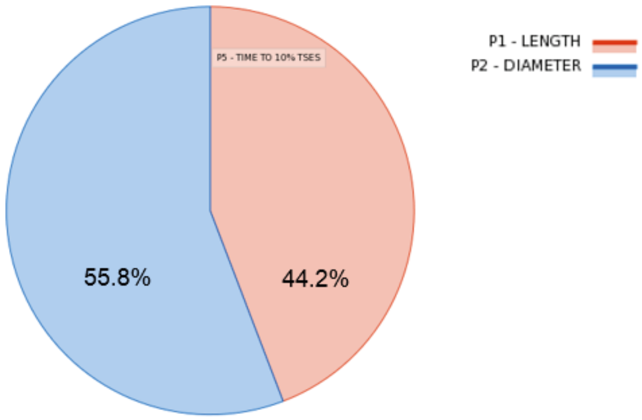

Figure 4.7: Sensitivity of Each Design Parameter toward Time Required to Reach 10% of Total Specific Energy Storage.

V. CONCLUSION

Numerical investigation of the effect of the PCM tube length and tube diameter of the solar thermal evacuated system were studied. Results shown that the time required to reach 10% of initial energy stored increase with tube length and tube diameter with the later have higher impact on the time measured. Sensitivity of changing the tube diameter towards the time required to reach 10% of initial total specific energy is 55.8% compared to 44.2% if tube length is varied. This signify that in order to increase the discharging thermal performance of the solar thermal energy storage using PCM tube, increasing its diameter give 11.6% more impact factor than increasing the tube length.

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