

## 4CBLB00 SOLAR HEAT SYSTEM

### Self-Study Assignment Group 16

SSA No.	Description
3	Modelling Reference System
SSA Owner	
Pranav Joshi	

### Introduction

As understood in the last meeting, the work on the model made of the reference system (Intex Solar Mat) needs to be further detailed and modified.

### Goal

- To continue the modelling work in MATLAB by correcting the time period to 30 minutes (from 24 hours) for the heat storage vessel
- To model heat losses that occur between the storage vessel and solar mat by taking conduction, convection and radiation into account

### Conclusion

- The storage vessel model had been detailed further and compared against experimental data 9
- The heat losses through the first pipe (connecting the storage vessel to the mat, see fig. 10) have been modelled (as shown in fig. 11)

### Recommendations

- The storage vessel model be further detailed to include convective heat losses (since it is an open bucket)
- The rest of the pipes in the system are modelled to take into account the heat lost through them, hence providing a complete model which can be compared with the experimental data

# 1 Elaboration

## 1.1 Understanding The Current Version of The Model

The gitlab project is easy to understand and self-explanatory. Separate files were made for separate parts of the model (as seen in fig. 1), such as a file for the storage vessel, and a separate one for the solar mat.

Name	Size	↑	Date Modified
resources			11/09/2025 2:25
Main.m	1 KB		11/09/2025 2:25
.gitignore	1 KB		11/09/2025 2:25
Solar_Heat_Project.prj	1 KB		11/09/2025 2:25
.gitattributes	1 KB		11/09/2025 2:25
StorageVessel.m	3 KB		11/09/2025 2:25
HeatingMat.m	7 KB		11/09/2025 2:25

Figure 1: Separate files for each sub-system

The heat storage file itself was further understood, by first skimming through it and looking at the graph (as shown in fig. 3a) that it produces when run.

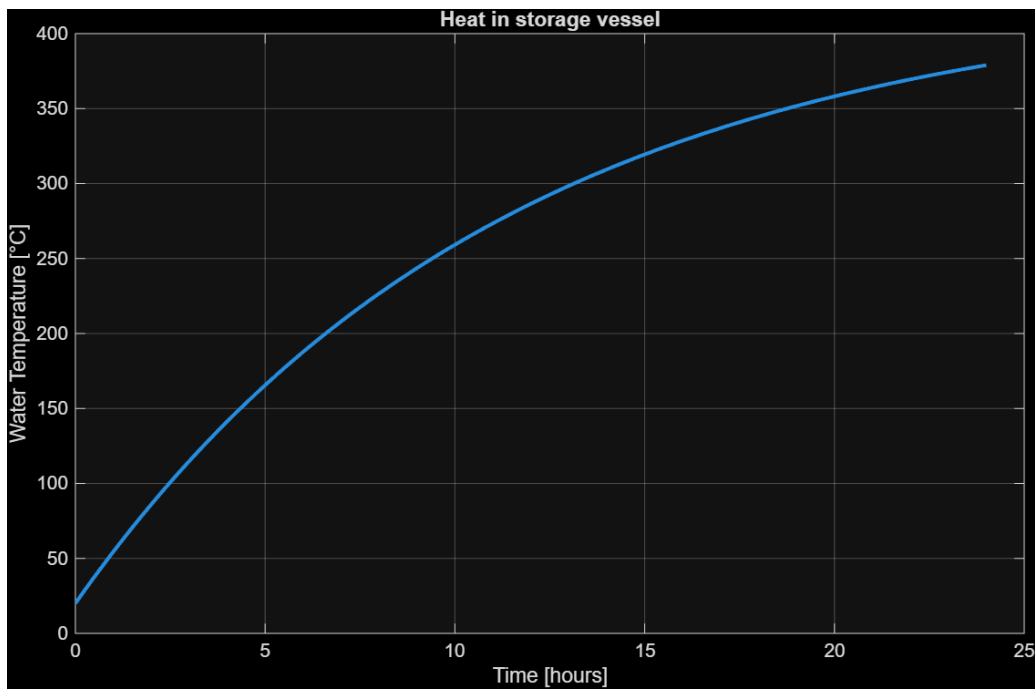


Figure 2: Graph uses a time period of 24 hours and needs to be corrected

This is the first correction that needs to be made in the file, since the test period is 30 minutes. This will help to draw concrete conclusions on the accuracy of the model, when compared with experimental data (since the experimental data is based on heating 2 L of water in 30 mins).

## 1.2 Making Corrections in Storage Vessel File

The correction in the storage vessel file is quite simple, the following piece of code:

```
1 % Simulation time
2 dt = 1; % time step [s]
3 t_end = 24*3600; % 24 hours [s]
4 time = 0:dt:t_end;
```

has been replaced with the following:

```
1 % Simulation time
2 dt = 1; % time step [s]
3 t_end = 30*60; % 30 minutes [s]
4 time = 0:dt:t_end;
```

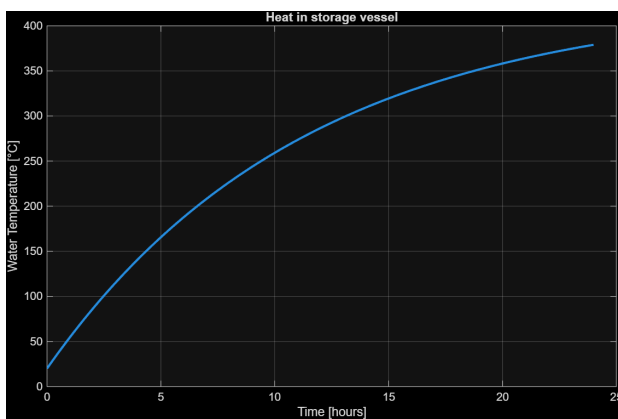
Along with this, the x-scale of the graph was edited to display at a scale of minutes instead of hours by performing the following change in the below code:

```
1 figure;
2 plot(time/3600, T, 'LineWidth', 2);
3 xlabel('Time [hours]');
4 ylabel('Water Temperature [ C ]');
5 title('Heat in storage vessel');
6 grid on;
```

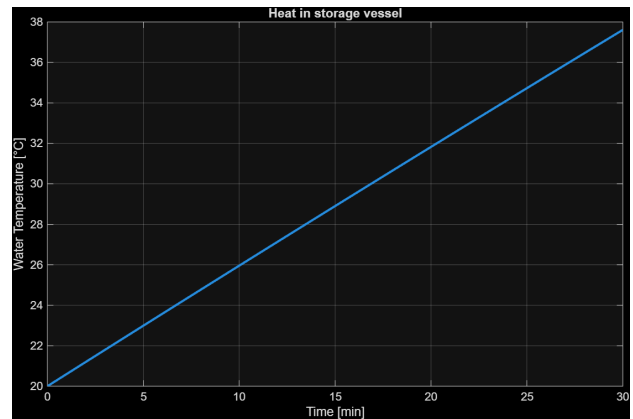
Instead of dividing the time by 3600 (which converts the time array to hours), the time array will now be divided by 60, hence converting seconds to minutes. Furthermore, the x-label has been changed to keep the labels consistent with the x-scale. This is shown below:

```
1 figure;
2 plot(time/60, T, 'LineWidth', 2);
3 xlabel('Time [minutes]');
4 ylabel('Water Temperature [ C ]');
5 title('Heat in storage vessel');
6 grid on;
```

These changes resulted in the following graph:



(a) Before



(b) After Making Changes

Figure 3: Comparison of results before and after making changes.

The most significant changes are the shape of the Temperature against time graph. For the 30 minute time period, the graph is nearly linear and the model predicts a maximum temperature of **37.699 °C** at the end of the 30 minute time period. This data is now compared with the provided experimental data (inlet and outlet temperatures of the solar mat):

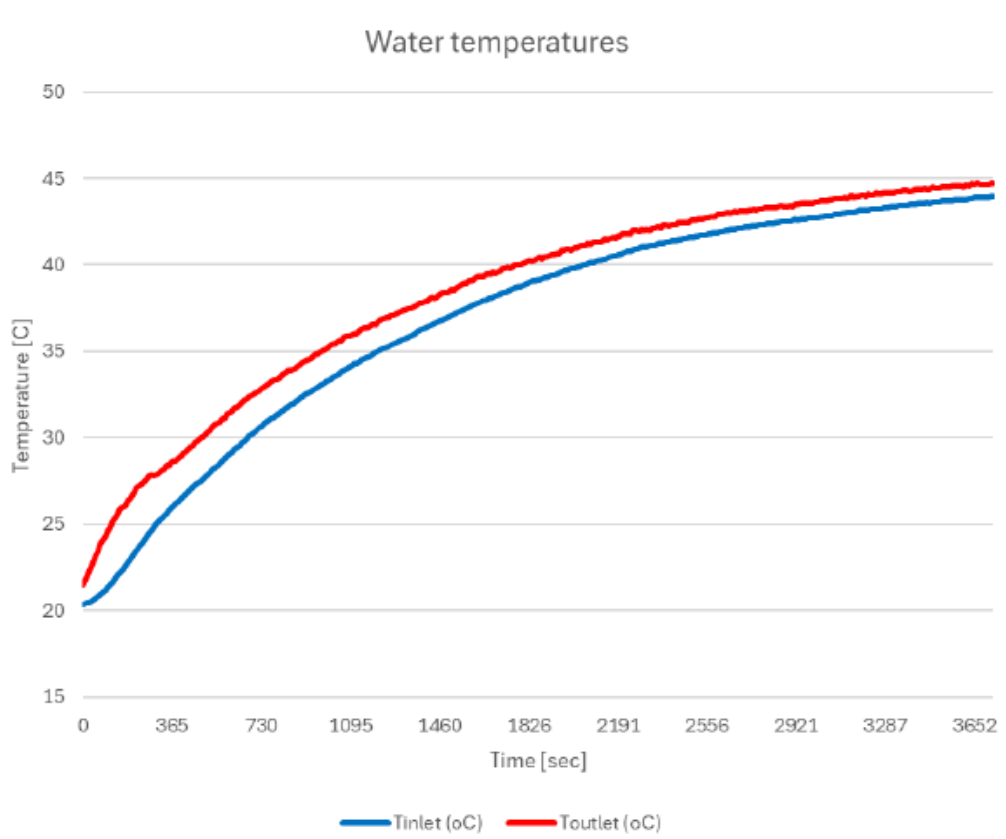


Figure 4: Experimental Data

Although the experimental data doesn't directly reflect the temperatures inside the storage vessel, at the end of the 30 minute time period (1800 s), the temperature of the inlet and storage vessel should be similar or fairly the same, the heat loss in between is neglected for now.

The experimental data indicates that at the end of the 30 minute period, the inlet of the solar mat is at a temperature between 35 and 40 °C. To extract a more detailed number, the excel file provided with the experimental data is looked into.

1	time (sec)	T <sub>inlet</sub> (°C)	T <sub>outlet</sub> (°C)
182	1800	38.81533394	40.08119853

Figure 5: Excel Sheet Data

This data point clearly suggests that at the thirty minute mark, the water entering the system from the storage vessel is 38 °C, which is slightly higher than the modelled 37.699 °C. It is highly unusual that a model under-predicts the temperature using a heat flow model, since it assumes ideal conditions and (hence) tends to over-predict the temperature.

To perform a more detailed comparison, both the experimental as well as model data was plot side by side (as shown in fig. 6).

This was done by using the following blocks of code:

```

1  data = readmatrix('Experimental Data.csv', 'NumHeaderLines', 1);
2  complete_time_data = data(:, 1);
3  complete_Temp_data = data(:, 2);
4  idx = 0;
5
6
7
8

```

```

9     for i = 1:length(complete.time.data)           % Finds the 1800 s
10         if complete.time.data(i) == 1800
11             idx = i;                               % mark as an index
12         end
13     end
14
15     disp(idx)
16     half.time.data = complete.time.data(1:idx); % Slices the time array
17                                           % to only consider first
18                                           % 1800 s of data
19
20     Temp.data = complete.Temp.data(1:idx);         % Corresponding temperature data

```

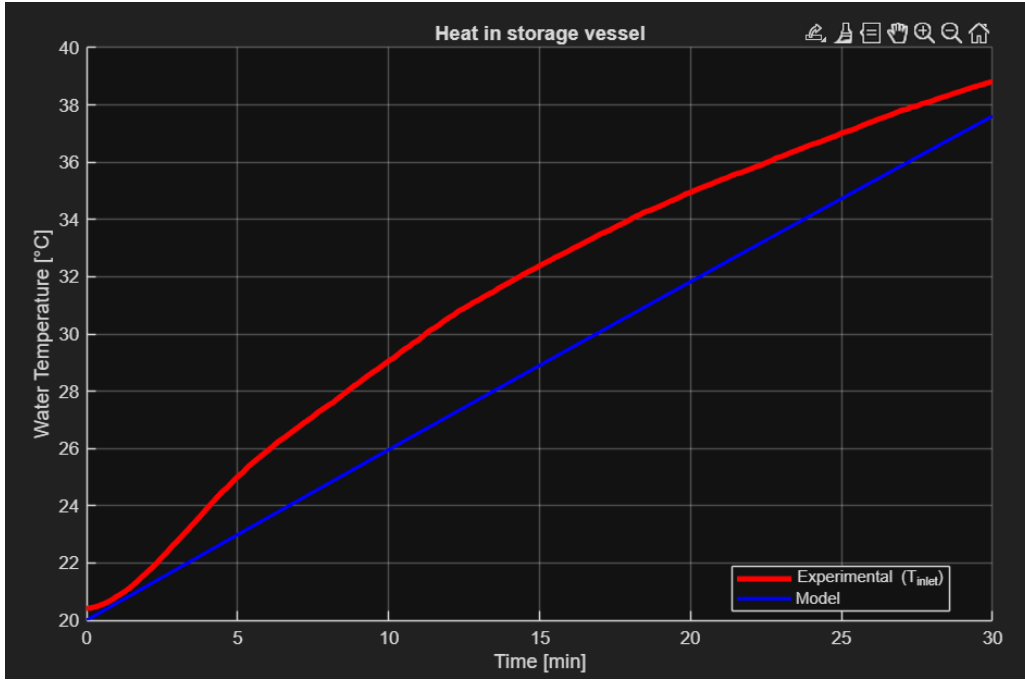


Figure 6: Experimental ( $T_{inlet}$ ) data against model of storage vessel

A clear observation, was that the model grossly under-predicts the temperature of the water in the storage vessel, when it should give a higher temperature than the experimental data because  $T_{inlet}$  is measured after the heat lost between the storage vessel and heating mat. A few potential explanations for this discrepancy is:

- If the solar mat is not perfectly insulated, it may be heating up the inlet and outlet pipes via conduction, hence increasing the temperature of the pipes and causing water to heat up in the pipes (along with the mat). This would explain why the temperature in the storage vessel would be lower than the temperature at the inlet/outlet
- The model underestimates the fraction of water that gets heated up in each cycle, currently the model assumes that 10 percent of the water gets heated up in each cycle, this may need to be changed.

The rest of the parameters are mostly the same between the model and experiment conditions, such as pipe thickness, thermal resistance, and so on.

To gain a better estimation of the fraction of water that is being heated, the following equation can be used to define it:

$$\begin{aligned}
 \text{fraction\_heated} &= \frac{Q_{in}}{m_{total} c_p \Delta T_{heating}} \\
 &= \frac{I A_{mat} \Delta t}{m_{total} c_p \Delta T_{heating}}
 \end{aligned} \tag{1}$$

Here,  $I$  is the irradiance provided by the artificial sun,  $A_{mat}$  is the surface area of the mat,  $\Delta t$  is the time period between two steps in matlab (set to one second),  $m_{total}$  is total mass of water in the system (4 L, or 0.004 m<sup>3</sup>), and  $\Delta T$  is the temperature hike in the water fraction after one cycle. The time taken for a 3.5 L section of water to leave the solar mat can be calculated as first using the provided flow rate of 1.5 L/min:

$$\begin{aligned}
 t &= \frac{V_{water}}{\dot{V}_{water}} \\
 &= \frac{3.5}{1.5} * 60 \\
 &= 140 \text{ s}
 \end{aligned} \tag{2}$$

The temperature hike between the inlet and outlet in a time period of 160 s (according to the experimental data) is roughly 3 °C (as shown in fig. 7 and 8).

time (sec)	$T_{inlet}$ (°C)	$T_{outlet}$ (°C)
140	22.01209694	25.58677314

Figure 7:  $T_{inlet}$  at 140 s

time (sec)	$T_{inlet}$ (°C)	$T_{outlet}$ (°C)
280	24.64497156	27.86077972

Figure 8:  $T_{outlet}$  at 280 s

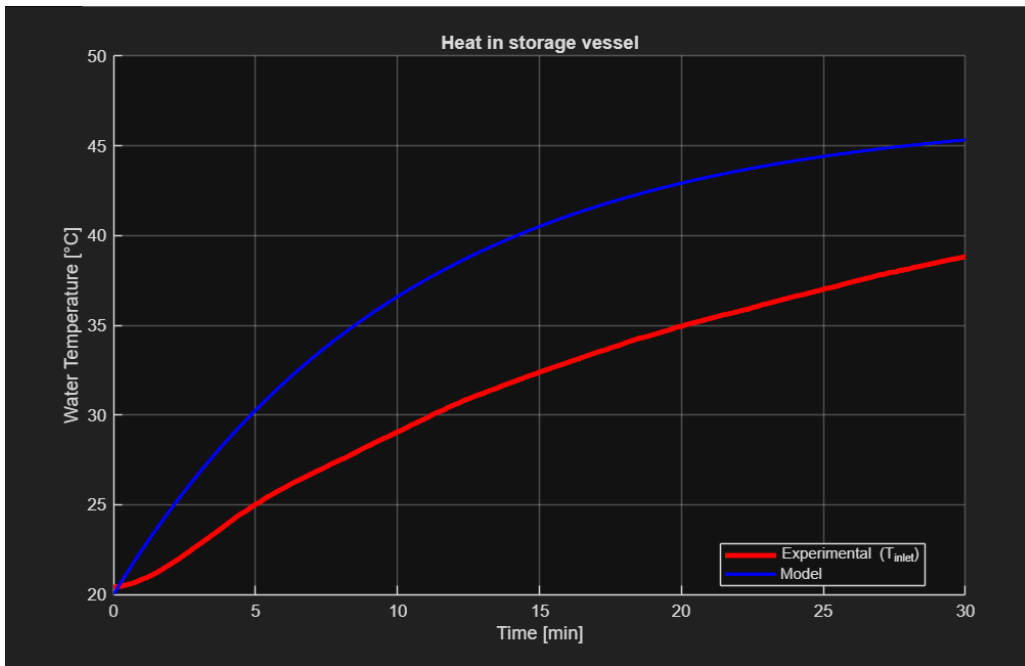
The fraction\_heated becomes:

$$\begin{aligned}
 \text{fraction\_heated} &= \frac{I A_{mat} \Delta t}{m_{total} c_p \Delta T_{heating}} \\
 &= \frac{1000 * 1.44 * 1}{8 * 4184 * 5.7} \\
 &= 0.07
 \end{aligned} \tag{3}$$

Along with this, a few other things also needed to be changed in the code, such as:

- The dimensions and volume of the storage vessel (radius and height)
- The thermal conductivity of polyethylene
- The irradiance of the artificial sun. along with the surface area of the mat needed to be added in as well

After all these changes, the following graph (shown in fig. 9) was retrieved . The shapes of both graphs (model and experimental) match up quite well, which is a good indication. While the model does predict a higher temp. than the experimental data, this is expected, since the model is simple and doesn't consider the heat losses that occur in the pipes between the storage vessel and inlet of the solar mat.

Figure 9: Model vs. Experimental Data ( $T_{inlet}$ )

In the end, the code now looks as follows, in lines 5, 6, 7, 12 and 20 the values of the variables have been changed to match the reference system experimental setup. Along with this lines 15 and 16 are new variables that have been defined to account for the irradiance of the sun and the surface area of the mat. Line 40 has been changed to calculate  $\Delta T_{heating}$  using the fraction\_heated formula that has been used throughout this SSA. Finally, a section has been added (Experimental Data, lines 62 - 80), to extract the experimental data given on canvas and plot it against the model. Everything else remains unchanged in the code.

```

1  % use this file to write the separate code for the storage vessel
2  clear; clc; close all;
3
4  %% Parameters
5  r = 0.265/2;           % vessel radius [m]
6  h = 0.25;             % vessel height [m] needs to be changed
7  r_insulation = 0.002; % insulation thickness [m]
8
9  rho_water = 997;       % [kg/m^3]
10 Specific_heat_capacity_water = 4186; % [J/kgK]
11
12 k_insulation = 0.33;    % thermal conductivity of insulation [W/mK] still needs to be ...
13                       % changed/calculated
14 T_outside = 20;         % temperature outside vessel [ C ]
15
16 Irradiance = 1000;      % irradiance from artificial sun [W/m^2]
17 Mat_surface_area = 1.2*1.2; % surface area of solar mat
18
19 % Simulation time
20 dt = 1;                % time step [s]
21 t_end = 30*60;         % 30 minutes [s]
22 time = 0:dt:t_end;
23
24 %% Initial conditions
25 V = 8*10^(-3);         % volume of storage vessel [m^3]
26 m_total = rho_water * V; % total mass of water [kg]
27 T = zeros(size(time));
28 T(1) = 20;             % initial water temperature [ C ]
29
30 %% Heat loss properties
31 r_outer = r + r_insulation;
32
33 % Surface area including cylindrical side + two flat end caps
34 A_surface = 2*pi*r*h + 2*pi*r^2; % total surface area of a closed cylinder before insulation.
35 A_surface_outer = 2*pi*r_outer*h + 2*pi*r_outer^2; % insulated outer surface
36 R_th = r_insulation / (k_insulation * A_surface_outer); % thermal resistance [K/W]

```

```

37
38 % Heating process
39 fraction.heated = 0.007; % fraction of total mass heated each cycle (needs to be calculated ...
    and changed)
40 ΔT.heating = ...
    Irradiance*Mat.surface.area*1/(rho.water*V*Specific.heat.capacity.water*fraction.heated); ...
    % amount of degrees water heated per cycle [ C ]
41
42
43 %% Time loop
44 for i = 1:length(time)-1
45     % Mass that is heated each cycle
46     m.heated = fraction.heated * m.total;
47
48     % Effective new temperature of the returned heated water
49     T.in = T(i) + ΔT.heating;
50
51     % Mixing of heated water with bulk water
52     T.mix = ( (m.total - m.heated)*T(i) + m.heated*T.in ) / m.total;
53
54     % Heat loss to ambient
55     Q.loss = (T.mix - T.outside) * dt / R.th; % [J]
56     dT.loss = Q.loss / (m.total * Specific.heat.capacity.water);
57
58     % Update temperature
59     T(i+1) = T.mix - dT.loss;
60 end
61
62 % Experimental Data (provided in canvas)
63
64 data = readmatrix('Experimental Data.csv', 'NumHeaderLines', 1);
65 complete.time.data = data(:,1);
66 complete.Temp.data = data(:,2);
67 idx = 0;
68
69 for i = 1:length(complete.time.data) % Finds the 1800 s
70     if complete.time.data(i) == 1800
71         idx = i; % mark as an index
72     end
73 end
74
75 disp(idx)
76 half.time.data = complete.time.data(1:idx); % Slices the time array
77 % to only consider first
78 % 1800 s of data
79
80 Temp.data = complete.Temp.data(1:idx); % Corresponding temperature data
81 %% Plot results
82
83 figure;
84 hold on
85 plot(half.time.data/60, Temp.data, 'r', 'LineWidth', 3); % Experimental Tinlet data
86 plot(time/60, T, 'b', 'LineWidth', 2); % Model
87 xlabel('Time [min]');
88 ylabel('Water Temperature [ C ]');
89 title('Heat in storage vessel');
90 legend('Experimental (T-{inlet})', 'Model', 'Location', 'best');
91 grid on;
92 hold off

```

For now, this model of the storage vessel is deemed accurate enough and the next task (modelling heat losses in the pipes between the inlet/outlet and storage vessel) is focused on.

### 1.3 Modelling Heat Losses Between Storage Vessel and Heating Mat

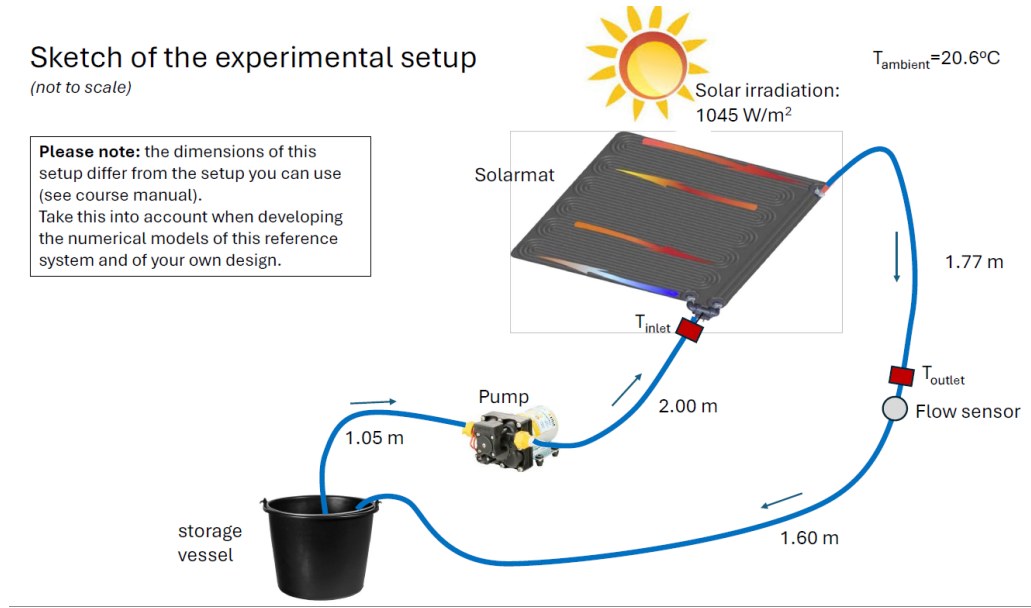


Figure 10: Reference System Diagram

To keep this part of the model simple, the following logic will be used to model these heat losses:

- At each  $dt$  (1 s) the temperature from the storage vessel is extracted and the modelled losses are applied to obtain temperature in the pipe between storage vessel and mat
- The heat lost between the outlet of the mat and the storage vessel requires using the  $T_{outlet}$  data from the heating mat script (which is being worked on by Jasper). This part cannot be done (unfortunately) in this SSA due to time restrictions and MATLAB issues.

The thermal resistance provided by polyurethane (material used to make these pipes, given in experimental data document) is given by the following eqn, (for now it is assumed no heat is lost due to radiation of heat from the pipes, to ease calculations):

$$\begin{aligned}
 R_{pipe} &= R_{conductive} + R_{convective} \\
 &= \frac{\ln\left(\frac{r_{outer}}{r_{inner}}\right)}{2 * \pi * L * k} + \frac{1}{h * A_{surface}} \\
 &= \frac{\ln\left(\frac{6}{6}\right)}{2 * \pi * 3.05 * 0.02} + \frac{1}{20 * 2 * \pi * 6 * 10^{-3} * 3.05} \\
 &= 0.2068 \text{ K/W}
 \end{aligned} \tag{4}$$

Here, outer radius of the pipe is 12 mm, inner radius is 10 mm, the length of the pipe is (1.05+2 m) 3 m, the convective coefficient is that of air and  $k$  of polyurethane is taken to be 0.02 [1].

Using this thermal resistance, the heat loss is calculated as follows:

$$\begin{aligned}
 P_{loss} &= \frac{\Delta T}{R_{pipe}} \\
 &= \frac{T_{InsidePipe} - T_{ambient}}{R_{pipe}}
 \end{aligned} \tag{5}$$

For now it's assumed that  $T_{InsidePipe} = T_{storagevessel}$  to get a preliminary model of the heat losses, this can be further detailed in the future.

This power loss needs to be calculated at each time step ( $dt=1$ ). These equations are implemented in MATLAB as follows:

```

1 %Pipe Losses:
2 % Calculate pipe losses based on temperature difference and thermal resistance
3 R_pipe = 0.2068;           %Thermal resistance of pipe in K/W
4 P_loss = T-20/R_pipe;      % Assuming steady state due to small time interval

```

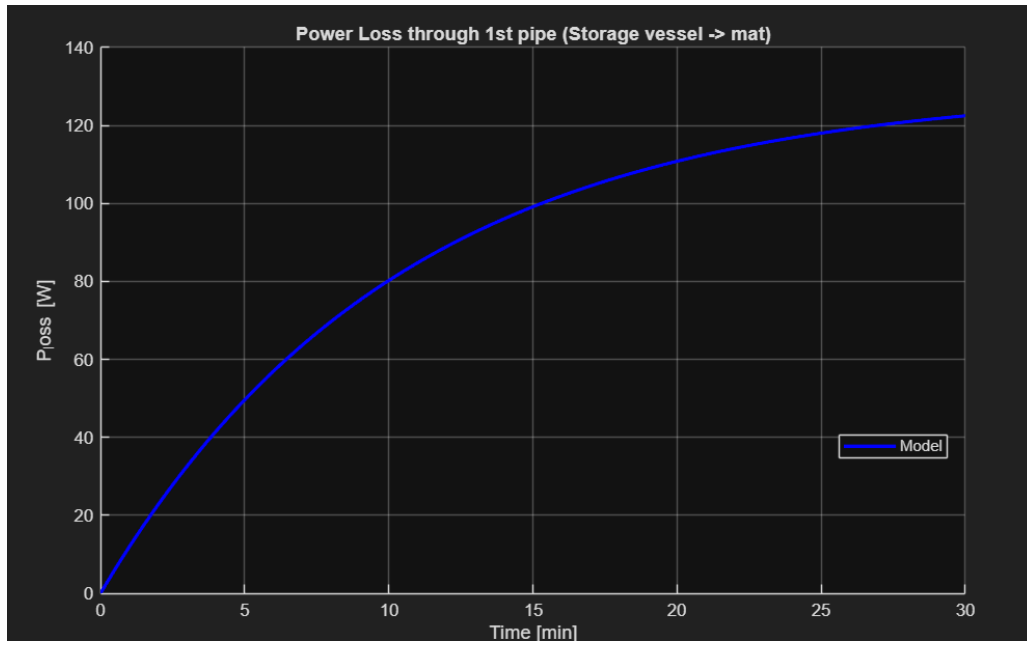


Figure 11: Power Loss through first pipe

In the above graph (fig. 11), the power lost through the first pipe is displayed against time. This model needs further detailing (such as including other parts of the system) to obtain a full picture of the total power lost through the pipes.

Currently this graph cannot be compared with the experimental data, however its shape does seem reasonable, given that as temperature inside the pipe increases, the heat loss should also increase, due to an increasing difference in temperature between the inside of the pipe and the ambient temperature, which is considered to be a constant 20 degrees at this stage.

## Overleaf Link to this SSA

<https://www.overleaf.com/read/mxtycynychzp#53ca0a>

## References

- [1] *Polyurethane Thermal Coeffecients*. URL: <https://pmc.ncbi.nlm.nih.gov/articles/PMC6152006/#:~:text=Typical%20thermal%20conductivity%20values%20for,structures%20%5B2%2C3%5D..> (accessed: 014.09.2025).