Momentum Transfer and Mechanical Operations Lab

Transient Heat Conduction

9th September, 2024

Team: MTMO 2

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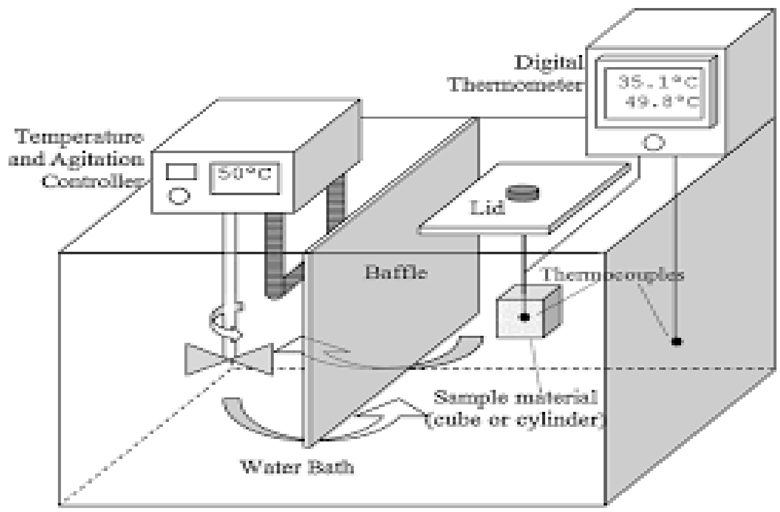
1 Abstract with Graphics

The transient heat conduction experiment investigates the behaviour of heat transfer in different geometries and mediums, particularly focusing on comparing the rates of heating and cooling and calculating the heat transfer coefficients for air and water. The experiment also explores the impact of material properties, such as thermal conductivity, on heat transfer efficiency.

In this experiment, we investigated the transient heat conduction in metallic objects of spherical and cylindrical shapes. The experiment was conducted using a water bath, thermometer, water heater, metallic sphere, metallic cylinder, thermocouples, indicator, and stopwatch. The heating cycle involved immersing the metallic object in a water bath at 100°C and measuring the temperature at various depths using thermocouples at intervals of 10 seconds. The cooling cycle was performed by removing the object from the water bath and placing them in ambient air, with temperature measurements taken at increasing intervals of 30 seconds. By monitoring temperature changes during both heating and cooling, the experiment allows for the calculation of heat transfer coefficients, which provide insights into the convective heat transfer behaviour of air and water.



Results from the experiment are compared with theoretical models, such as the lumped system analysis and Biot number calculations, to validate the observed data. The heat transfer coefficients for both mediums are computed using the Biot number, and results show a strong correlation between theoretical predictions and experimental data. The experiment provides valuable insights into how material properties and geometry influence transient heat conduction and helps predict how systems will respond to temperature changes over time.

2 Aim

- To compare the rate of heating and cooling and calculate the heat transfer coefficients of air and water using three different shapes.
- To monitor the variation of temperature with time for all heating and cooling systems.
- To understand the effect of material of construction in heat transfer.

3 Background and Motivation

Heat conduction is a fundamental concept in thermal science, playing a critical role in various industries, from electronics to manufacturing. In many real-world applications, the temperature of an object does not remain constant but varies over time, making transient heat conduction an important area of study. Unlike steady-state conditions, where temperature gradients are stable, transient heat conduction addresses the dynamic nature of temperature change in response to time-dependent thermal inputs or outputs.

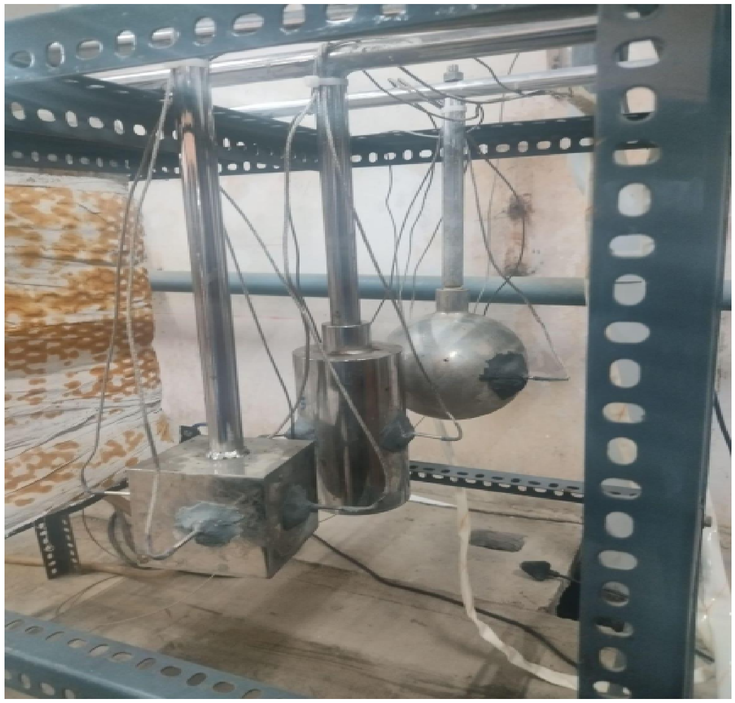


Figure 1: Metallic Objects used for this experiment

For Chemical Engineers, understanding transient heat conduction is crucial when designing systems that involve heating or cooling of materials, such as reactors, heat exchangers, or even cooling mechanisms in electronic devices. Materials of different shapes, sizes, and compositions exhibit varying thermal behaviors under transient conditions, affecting their response to heat and the efficiency of thermal processes.

The motivation behind this experiment stems from the need to evaluate how different geometries (cylindrical and spherical objects) and materials interact with their surrounding environment, such as air and water, during heat transfer processes. By monitoring temperature changes over time, this study aims to improve the understanding of the heat transfer coefficients for various shapes and mediums. This insight is vital for optimizing industrial operations and ensuring the safe and efficient design of thermal systems.

4 Materials and Methods

4.1 Apparatus & Materials Required

Water Bath, Thermometer, Water Heater, Metallic Sphere, Metallic Cylinder, Thermocouples, Temperature Indicator, Stopwatch.

4.2 Experimental Setup Description

The experimental setup is shown in figure 2, which consists of two parts, which are for sphere and cylinder, that are performed separately.

Figure 2: The Complete set-up for the Heat Transfer Experiment

- **Water Bath Setup:** A water bath is used to heat water to the desired temperature of 100°C. The water is heated using a water heater, and the temperature of the water is monitored using a thermometer to ensure precise control.
- **Metallic Samples:** Two metallic objects are used for the experiment: a metallic sphere and a metallic cylinder. These objects are immersed in the water bath for heating and exposed to ambient air for the cooling process.
- **Temperature Indicator:** A temperature indicator is used to read and display the temperatures recorded by the thermocouples in real-time.
- **Stopwatch:** A stopwatch is used to time the heating and cooling cycles. Temperature readings are taken at regular intervals, starting at 10-second intervals during heating and cooling, with larger intervals during cooling as the temperature decreases.

4.3 Procedure

4.3.1 Heating Cycle:

- Heat water in a water bath using a water heater, and monitor the temperature with a thermometer until it reaches 100°C.
- Submerge the cylinder into the water bath and initiate the stopwatch. Measure the temperatures at three specific points using thermocouples: T_1 (15 mm from the surface), T_2 (25 mm from the surface), and T_3 (35 mm from the surface).
- Record the temperature readings of T_1, T_2, and T_3 at 10-second intervals.
- Continue recording data until all thermocouples reach a stable temperature of 100°C.
- Repeat the same procedure for a sphere, with thermocouples positioned at 20 mm, 40 mm, and 60 mm from the surface.

4.3.2 Cooling Cycle:

- Remove the cylinder from the water bath and place it in ambient air.
- Immediately start the stopwatch and measure the temperatures at T_1, T_2, and T_3.
- Record the temperature readings at 30-second intervals.
- Continue the measurements until the temperature at all points drops to room temperature. (though because of time limit upto 65°C values were tabulated).

Repeat the same process for the sphere too.

5 Observation Tables

The tabulations include the observed data from each of the sub-experiments and are tabulated in order in the **Appendix** section.

For reference, the following ordering is followed:

- Automatic tabulation of *heating of cylinder* is shown in figure 9.
- Automatic tabulation of *cooling of cylinder* is shown in figures 10 & 11.
- Automatic tabulation of *heating of sphere* is in figure 12.
- Automatic tabulation of *cooling of sphere* is shown in figures 13, 14 & 15.
- Manual tabulation of *heating of cylinder* is shown in figure 16.

- Manual tabulation of *cooling of cylinder* is shown in figures 16 & 17.
- Manual tabulation of *heating of sphere* is in figure 17.
- Manual tabulation of *cooling of sphere* is shown in figure 18.

Now for each of the sub-parts of the whole experiment the following results are obtained and all the related script files are uploaded in GitHub repository mentioned in the **Appendix** section.

6 Results & Calculations

6.1 Steel Sphere

In the case of a sphere, we will be using Spherical Coordinate system to derive our equation for heat transfer. Assuming transient case ($\partial/\partial t \neq 0$) and ignoring effects of radiation and in absence of source for heat generation, we can write the energy balance equation as :

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) \tag{1}$$

The initial conditions is :

$$At\ t = 0\ sec\ \rightarrow T = T_i \tag{2}$$

And the boundary conditions are:

$$\left(\frac{\partial T}{\partial r} \right)_{r=0} = 0 \tag{3}$$

$$\left(-k \cdot \frac{\partial T}{\partial r} \right)_{r=R} = h(T - T_{Surr}) + \epsilon \cdot \sigma \left(T^4 - T_{Surr}^4 \right) \tag{4}$$

This is obtained by equating the conduction with convection and radiation heat transfer at the sphere surface. In the case of heating, the effect of forced convection dominates the effect of radiation, and as such the radiation term can be omitted unlike in case of cooling.

For the case of Heating : $T_i = 309.983\ K$, $T_\infty = 373.150\ K$
For the case of Cooling : $T_i = 373.150\ K$, $T_\infty = 344.617\ K$

The properties of Steel Sphere were taken to be as follows :
R (radius) = 0.05945 m
$k = 50.2\ W/m \cdot K$
$\rho = 7900\ kg/m^3$
$C_p = 490\ J/kg \cdot K$

Value of Biot's Number (Bi) :

$$Heating \ : \ Bi = \frac{hR}{k} = 32.2110 \tag{5}$$

$$Cooling \ : \ Bi = \frac{hR}{k} = 0.029742 \tag{6}$$

Values of Fourier number (Fo) :

$$t = 10 \ sec \ : \ Fo = \frac{\alpha t}{R^2} = 0.03669 \tag{7}$$

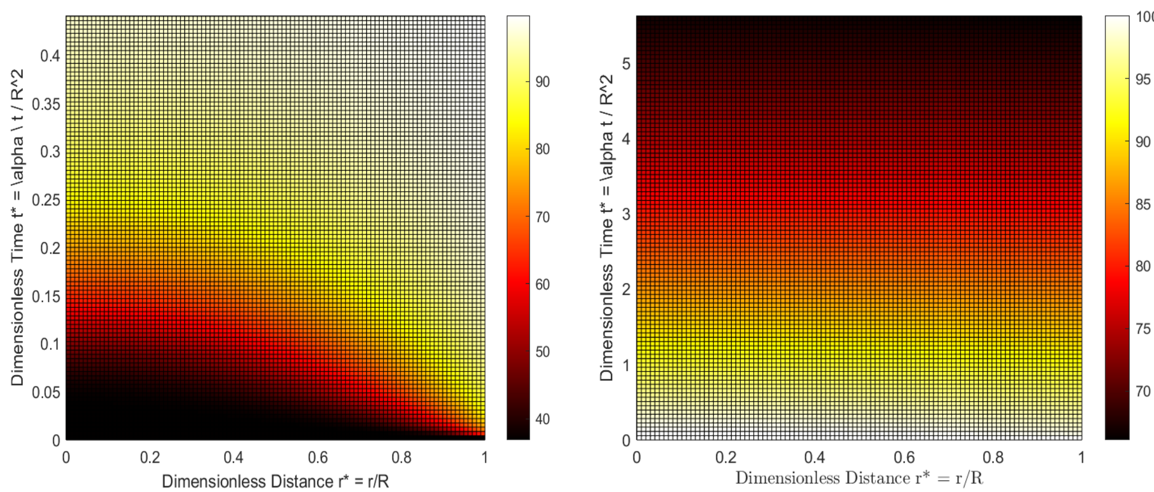
$$t = 30 \ sec \ : \ Fo = \frac{\alpha t}{R^2} = 0.1101 \tag{8}$$

The value of convection coefficients (h) were calculated from data as:

$$Water \ : \ h = 8778.647 \ W/m^2 \cdot K \tag{9}$$

$$Air \ : \ h = 25.1142 \ W/m^2 \cdot K \tag{10}$$

The results from solving PDEs are as follows (shwon in figures 3a & 3b) :

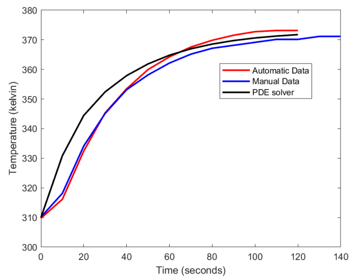


(a) Numerical Solution of PDE (Heating)

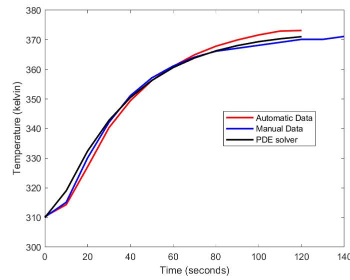
(b) Numerical Solution of PDE (Cooling)

Figure 3: Numerical Solutions - Mesh-Grid Values

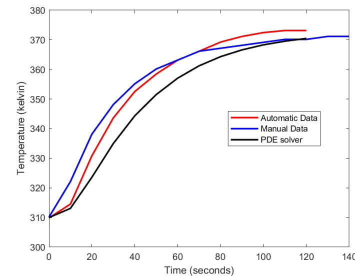
The comparisons of theoretical data and experimental data are given by the following plots which are the heating (figures 4) and cooling (figures 5) therms:



(a) Thermocouple 1
Closest to Surface (Heating)

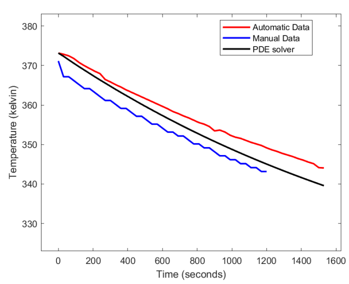


(b) Thermocouple 2
In Between (Heating)

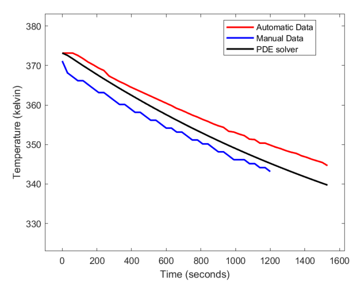


(c) Thermocouple 3
Closest to Center (Heating)

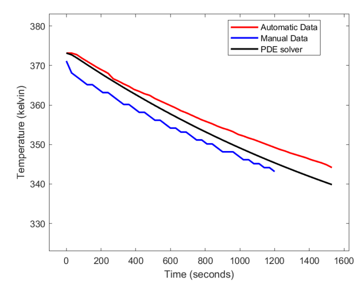
Figure 4: Heating Therms for Sphere



(a) Thermocouple 1
Closest to Surface (Cooling)



(b) Thermocouple 2
In Between (Cooling)



(c) Thermocouple 3
Closest to Center (Cooling)

Figure 5: Cooling Therms for Sphere

6.2 Steel Cylinder

In the case of a cylinder, we will be using Cylindrical Coordinate system to derive our equation for heat transfer. Assuming transient case ($\partial/\partial t \neq 0$) and 1-dimensional case (only r direction), we can write the energy balance equation as :

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \tag{11}$$

The initial conditions is :

$$At\ t = 0\ sec\ \rightarrow T = T_i \tag{12}$$

And the boundary conditions are:

$$\left(\frac{\partial T}{\partial r} \right)_{r=0} = 0 \tag{13}$$

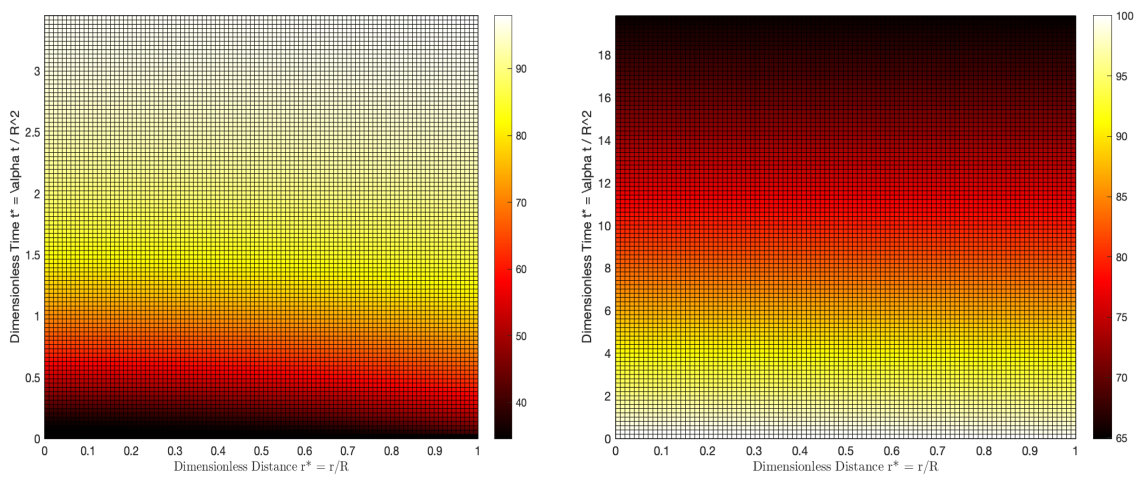
$$\left(-k \cdot \frac{\partial T}{\partial r} \right)_{r=R} = h(T - T_{Surr}) + \epsilon \cdot \sigma \left(T^4 - T_{Surr}^4 \right) \tag{14}$$

This is obtained by equating the conduction with convection and radiation heat transfer at the sphere surface. In the case of heating, the effect of forced convection dominates the effect of radiation, and as such the radiation term can be omitted unlike in case of cooling.

For the case of Heating : $T_i = 307.75\ K$, $T_\infty = 373.15\ K$
For the case of Cooling : $T_i = 373.15\ K$, $T_\infty = 303.45\ K$

The properties of Steel Cylinder were taken to be as follows :
$R = 0.0368$ m
$k = 50.2\ W/m \cdot K$
$\rho = 7900\ kg/m^3$
$C_p = 490\ J/kg \cdot K$

The results from solving PDEs are as follows (shwon in figures 6a & 6b) :



(a) Numerical Solution of PDE (Heating)

(b) Numerical Solution of PDE (Cooling)

Figure 6: Numerical Solutions - Mesh-Grid Values

Value of Biot's Number (Bi) :

$$Heating\ :\ Bi = \frac{hR}{k} = 0.5525 \tag{15}$$

$$Cooling\ :\ Bi = \frac{hR}{k} = 0.0118 \tag{16}$$

Values of Fourier number (Fo) :

$$t = 10\ sec\ :\ Fo = \frac{\alpha t}{R^2} = 0.0958 \tag{17}$$

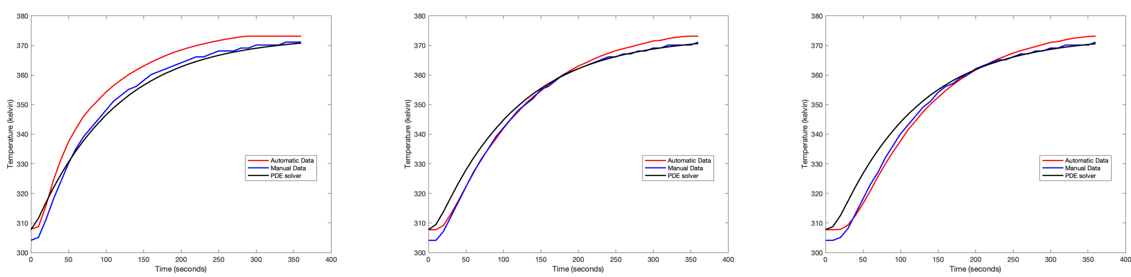
$$t = 30\ sec\ :\ Fo = \frac{\alpha t}{R^2} = 0.2874 \tag{18}$$

The value of convection coefficients (h) were calculated from data as:

$$Water\ :\ h = 753.8782\ W/m^2 \cdot K \tag{19}$$

$$Air\ :\ h = 16.1028\ W/m^2 \cdot K \tag{20}$$

The comparisons of theoretical data and experimental data are given by the following plots which are the heating (figures 7) and cooling (figures 8) therms:



(a) Thermocouple 1 Closest to Surface (Heating)

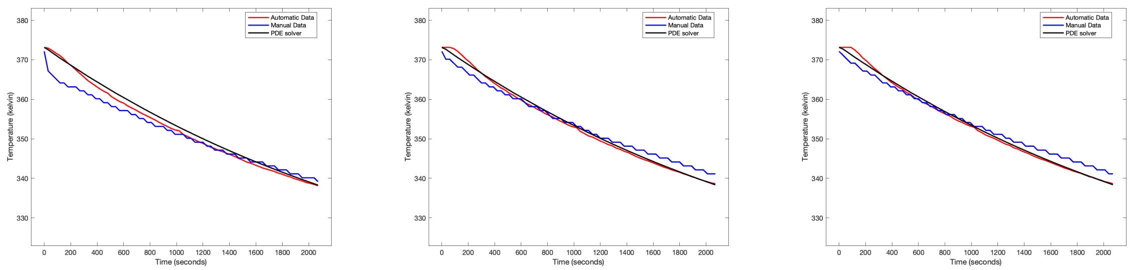
(b) Thermocouple 2 In Between (Heating)

(c) Thermocouple 3 Closest to Center (Heating)

Figure 7: Heating Therms for Cylinder

7 Conclusions and Remarks

- From the numerical solutions obtained from MATLAB codes, we can observe that the cooling cases occur as lumped system (Bi $<$ 0.1). The heating cases, however, are NOT lumped systems, as Bi $=$ 32.2 for Sphere and Bi $=$ 0.55 for Cylinder.
- The heating and cooling in Cylinder takes a larger amount of time to reach steady-state when compared to the case of Sphere.
- For the case of Steel Sphere, the value of h comes out to be around 8778.6 $W/m^2 \cdot K$ for water and 33.45 $W/m^2 \cdot K$ for air, which is close to the values given in literature.



(a) Thermocouple 1
Closest to Surface (Cooling)

(b) Thermocouple 2
In Between (Cooling)

(c) Thermocouple 3
Closest to Center (Cooling)

Figure 8: Cooling Therms for Cylinder

- However, for the case of Steel Cylinder, the value of h comes out to be around 753.9 $W/m^2 \cdot K$ for water and 16.11 $W/m^2 \cdot K$ for air. The value of h for air is acceptable, however, the value for water has a very high amount of error in it.
- It is also noticed, that the innermost thermocouple in case of Sphere gives higher values than the middle and outer thermocouples in case of heating, even though this disagrees with the numerical solution obtained from solving PDEs.

8 Error Analysis

Least Count of Vernier Calliper $\equiv \Delta r = 0.02$ mm
Least Count of Stopwatch $\equiv \Delta t = 0.01$ sec
Error in Temperature measurement (Automatic) $\equiv \Delta T = 0.1$ K
Error in Temperature measurement (Manual) $\equiv \Delta T = 1$ K
Error in calculating convection coefficient (h) :

$$\frac{\Delta h}{h} = \frac{\Delta r}{R} + \frac{\Delta t}{t} + \left(\frac{1}{Bi \cdot Fo}\right)\frac{\Delta T}{T} \tag{21}$$

8.1 Sources of Error

- Malfunction in thermocouples or wires connecting the thermocouple to measurement equipment.
- Ignoring effect of conduction to the rod holding the steel sphere or cylinder in place.
- Ignoring the z-direction in the case of Steel Cylinder, causing major changes in the solution given by PDEs.

- Error due to human stimulus, like mistakenly touching the system, causing the surface temperature to fluctuate.

9 Precautions

- When handling heated water, exercise caution to prevent splashes or spills, as these may result in burns.
- Ensure the experiment is conducted in a well-ventilated environment to prevent the buildup of fumes or excessive heat, particularly when using heating equipment.
- It is crucial to maintain uniformity in the heating and cooling sources to prevent the formation of hot spots or inconsistencies in temperature distribution.
- Ensure that thermocouples or temperature sensors are securely and correctly attached to the surfaces being measured, as this is essential for obtaining accurate readings.
- Verify that the materials utilized in the experiment are non-reactive with water or air when exposed to heat, as such reactions could compromise both safety and the integrity of the results.
- Avoid overheating or over-cooling the objects beyond their material limits, as this may result in damage or erroneous data.

10 Thought Question / Open-Ended

Q. Imagine a spacecraft designed to travel to a distant planet with extreme temperature variations between its sun-facing and dark sides. The spacecraft's thermal protection system includes a multi-layer insulation material designed to manage these temperature extremes.

Given the spacecraft's cylindrical shape, the insulation's material properties (thermal conductivity, thickness), and the temperature difference between the sun-facing and dark sides, how would you use Fourier's law of heat conduction to optimize the insulation design? Specifically, how would you calculate the optimal thickness of the insulation layers to ensure that the internal temperature of the spacecraft remains within a safe range, and what factors would influence your design choices?

A. This case is slightly different from our previous case study in the fact that the object of interest is not the cylinder itself, but its covering. as such, we can assume that our system is a hollow cylinder of insulation material (similar to a pipe), of some thickness d, conductivity k, density ρ and specific heat C_p.

Next we will consider the orientation of our system. To make calculations a little simpler, we can make three assumptions :

- The thickness of hollow cylinder d is much smaller than the diameter of the cylinder D, or, $d << D$. This makes it possible to change our perspective from a hollow cylinder to a thin slab.
- The diameter of the cylinder is much smaller than the length of the cylinder, or, $D < L$. This makes it possible to ignore the effects of top and bottom surface area.
- The orientation of the cylinder is such that the temperature is same throughout the length of the cylinder, or, T is independent of z.

Now that the assumptions have been made, we can create a new partial differential equation to explain our system. We can cut the hollow pipe in the z-direction, and flatten it to a thin slab of thickness d, where, x goes from 0 to πD, y goes from 0 to d and z goes from 0 to L.
The main equation is :

$$\rho C_p \frac{\partial T}{\partial t} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \tag{22}$$

The initial conditions is :

$$At\ t = 0\ sec\ \rightarrow T = T_i \tag{23}$$

And the boundary conditions are:

$$for\ y = 0\ and\ x \in (\pi D/4, 3\pi D/4)\ : T = T_{HIGH} \tag{24}$$

$$for\ y = 0\ and\ x \notin (\pi D/4, 3\pi D/4)\ : T = T_{LOW} \tag{25}$$

$$for\ y = d\ : T = T_o + error\ \forall\ x \tag{26}$$

$$(T)_{x=0} = (T)_{x=\pi D}\ \forall\ y \tag{27}$$

Solving this system of equations should give us our required answer.

11 Acknowledgements

We as a group contributed our respective parts into completing the above report on Transient Heat Conduction.

In terms of specifications, Rapolu Paranay Reddy helped with “Apparatus & Materials"; “Experimental Setup Description" part of the report. Atharva Sunilkumar Ghodke contributed in “Procedure" & “Precaution" parts. Anomol Upadhyay delivered the content for “Aim (Objective)"; “Background & Motivation" along with Lakkireddy Vishnu Vardhan Reddy helping in “Abstract” part of the report and rest of all the parts are done & organized by Deepanjhan Das (general editor) & Aayush Bhakna (proof reader).

Regarding AI transcript for the open-ended thought question asked, we didn’t use ChatGpt for our thought question. It was more confusing and so we, after discussing the scenario and after reading some related papers, we wrote as per our understanding. Therefore no such transcript is provided in the **Appendix** section.

And at last but not the least, we specially thank the respective TA for this experiment Mr. Shailesh bhaiya for his kind help and to let us have a thorough understanding of the whole process and the concept. We thank all the course instructors for their effective control and high co-operation as per the need.

References

- Properties of steel (ρ, C_p and k) were taken from the book 'University physics' by Francis W. Sears, Mark W. Zemansky, Hugh D. Young. (7th ed.)
  * Can be easily verified from internet as well *

- Conductivity of different materials was referenced from this webpage :
  http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/thrcn.html

- The general equation for heat transfer by conduction (transient) was derived using methods taught by Prof Renganathan in CH2014 course (Heat & Mass Transfer).

- The numerical solution of PDEs was calculated in MATLAB using techniques taught by Prof Renganathan in CH5140 course (Process Modelling, Simulation and Analysis).

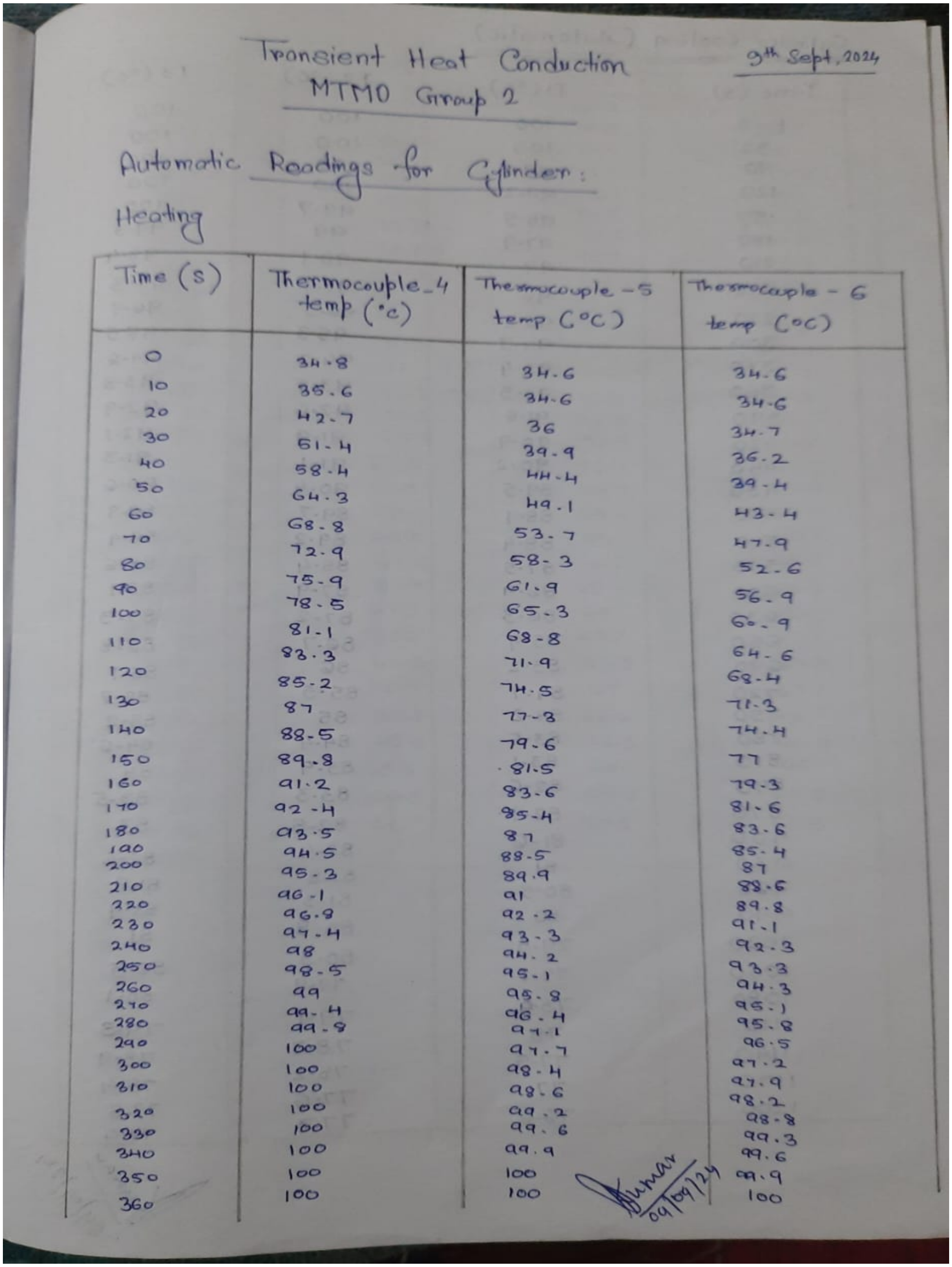
- Another book, ‘Process Dynamics’ by Bequette B Wayne was also referenced to learn about the PDE solver ‘pdepe’ available in MATLAB.

- The MATLAB codes are available in the GitHub repository provided below in the Appendix.

Appendix

Lab Data: All the experimental observations with each of the sub-parts of the main experiment that was performed and tabulated during the laboratory session are included in order in the following (in figures 9, 10, 11, 12, 13, 14, 15, 16, 17, 18).

Reference to all the contents: The official GitHub repository which contains all the related data and coded scripts for calculations is also provided below: https://github.com/deep183Das/CH3510_MTMO_Lab_Group_2/tree/main/Experiment_5. One can easily refer to all the related lab resources from this GitHub repository from where screenshots of few instances are shown in the above figures, in in this report.



Transient Heat Conduction
MTMO Group 2

9th Sept, 2024

Automatic Readings for Cylinder:

Heating

Time (s)	Thermocouple_4 temp (°c)	Thermocouple – 5 temp (°C)	Thermocouple – 6 temp (°C)
0	34.8	34.6	34.6
10	35.6	34.6	34.6
20	42.7	36	34.7
30	51.4	39.9	36.2
40	58.4	44.4	39.4
50	64.3	49.1	43.4
60	68.8	53.7	47.9
70	72.9	58.3	52.6
80	75.9	61.9	56.9
90	78.5	65.3	60.9
100	81.1	68.8	64.6
110	83.3	71.9	68.4
120	85.2	74.5	71.3
130	87	77.3	74.4
140	88.5	79.6	77
150	89.8	81.5	79.3
160	91.2	83.6	81.6
170	92.4	85.4	83.6
180	93.5	87	85.4
190	94.5	88.5	87
200	95.3	89.9	88.6
210	96.1	91	89.8
220	96.8	92.2	91.1
230	97.4	93.3	92.3
240	98	94.2	93.3
250	98.5	95.1	94.3
260	99	95.8	95.1
270	99.4	96.4	95.8
280	99.8	97.1	96.5
290	100	97.7	97.2
300	100	98.4	97.9
310	100	98.6	98.2
320	100	99.2	98.8
330	100	99.6	99.3
340	100	99.9	99.6
350	100	100	99.9
360	100	100	100

Kumar 09/09/24

Figure 9: Data for Heating of Cylinder (automatic)

Cylinder Cooling (Automatic)

Time (s)	T1 (°c)	T2 (°c)	T3 (°c)
t = 0	100	100	100
30	100	100	100
90	99.8	100	100
120	99.2	100	100
150	98.5	99.7	100
180	97.9	99	99.3
210	97	98.1	98.4
240	96	97.1	97.3
270	95.2	96.3	96.5
300	94.3	95.3	95.5
330	93.4	94.3	94.6
360	92.5	93.5	93.8
390	91.6	92.6	92.9
420	90.9	91.9	92.1
450	90.2	91.1	91.3
480	89.5	90.4	90.6
510	88.9	89.7	89.9
540	88.4	89.2	89.4
570	87.5	88.4	88.6
600	86.9	87.9	88.1
630	86.3	87.2	87.3
660	85.9	86.7	86.8
690	85.2	86	86.1
720	84.7	85.5	85.7
750	84.2	85	85.2
780	83.6	84.4	84.6
810	83.1	83.9	84
840	82.6	83.3	83.5
870	82.1	82.8	83
900	81.6	82.4	82.6
930	81	81.8	81.9
960	80.5	81.3	81.4
990	80	80.8	81
1020	79.5	80.3	80.5
1050	79.1	79.9	80.1
1080	78.9	79.7	79.8
1110	78	78.7	78.9
1140	77.5	78.2	78.4
1170	77	77.6	77.8
1200	76.6	77.3	77.4

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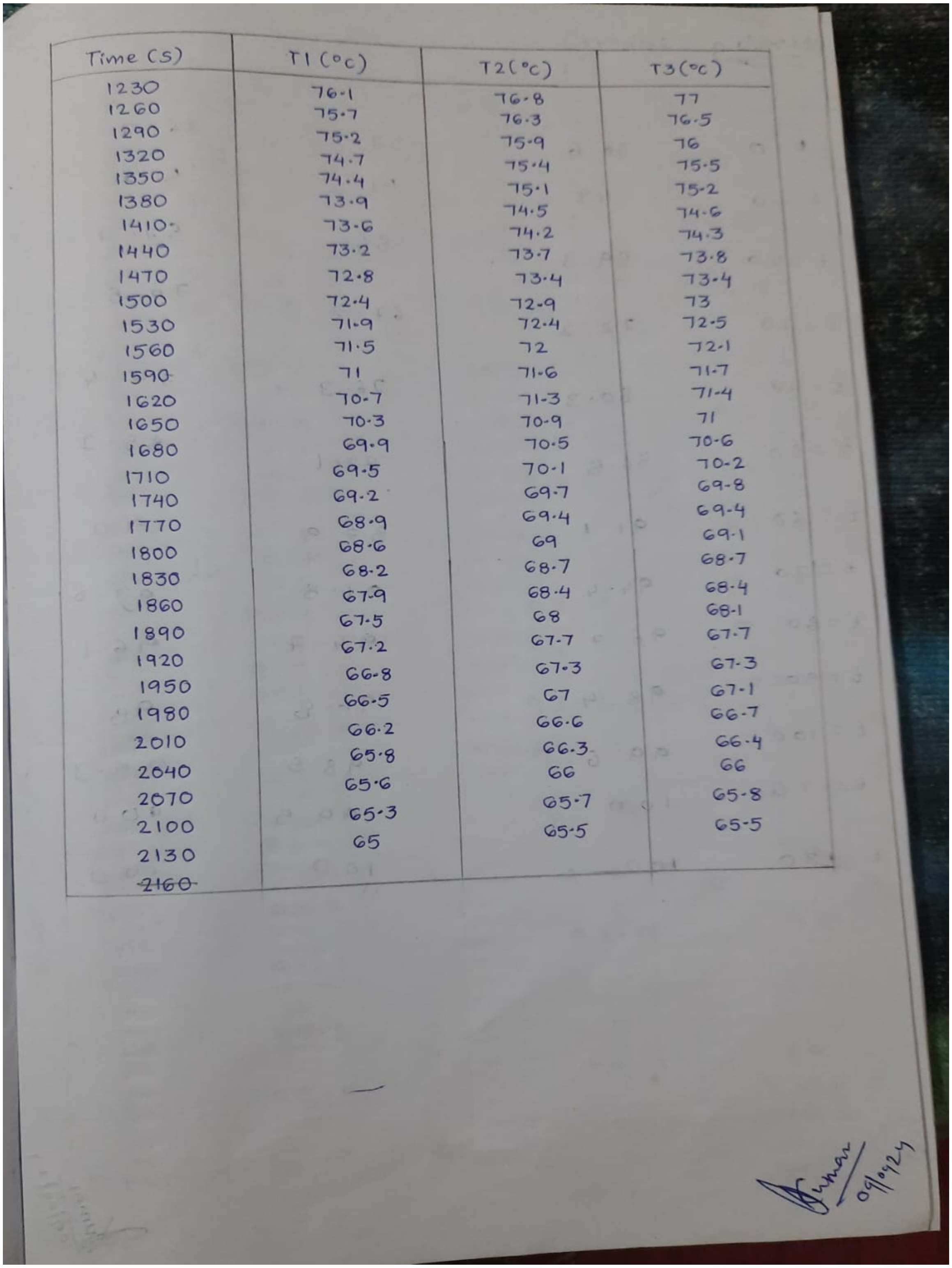
Figure 10: Data for Cooling of Cylinder (automatic) - 1



Time (s)	T1 (°c)	T2(°c)	T3(°c)
1230	76.1	76.8	77
1260	75.7	76.3	76.5
1290	75.2	75.9	76
1320	74.7	75.4	75.5
1350	74.4	75.1	75.2
1380	73.9	74.5	74.6
1410	73.6	74.2	74.3
1440	73.2	73.7	73.8
1470	72.8	73.4	73.4
1500	72.4	72.9	73
1530	71.9	72.4	72.5
1560	71.5	72	72.1
1590	71	71.6	71.7
1620	70.7	71.3	71.4
1650	70.3	70.9	71
1680	69.9	70.5	70.6
1710	69.5	70.1	70.2
1740	69.2	69.7	69.8
1770	68.9	69.4	69.4
1800	68.6	69	69.1
1830	68.2	68.7	68.7
1860	67.9	68.4	68.4
1890	67.5	68	68.1
1920	67.2	67.7	67.7
1950	66.8	67.3	67.3
1980	66.5	67	67.1
2010	66.2	66.6	66.7
2040	65.8	66.3	66.4
2070	65.6	66	66
2100	65.3	65.7	65.8
2130	65	65.5	65.5
~~2160~~			

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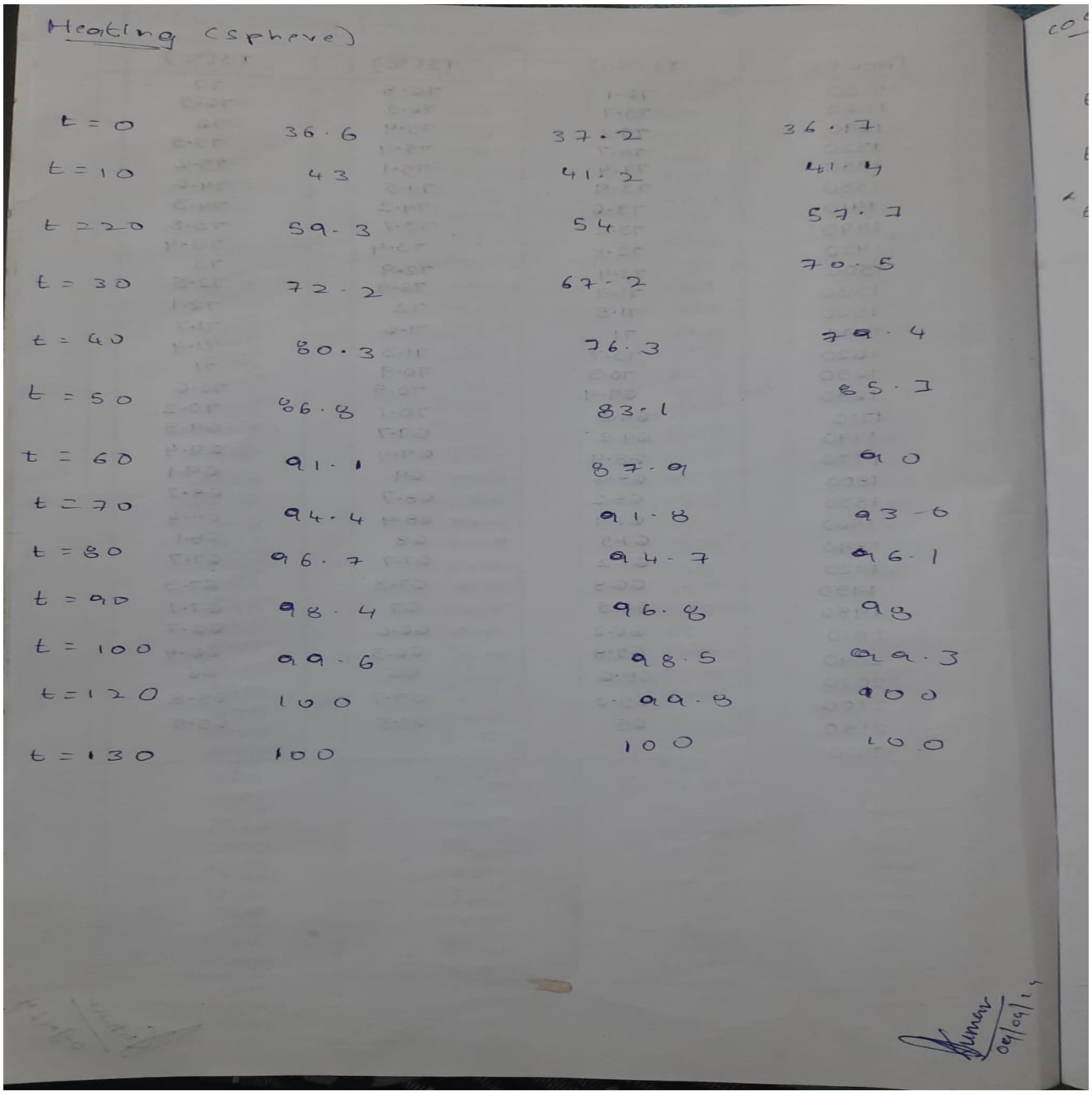
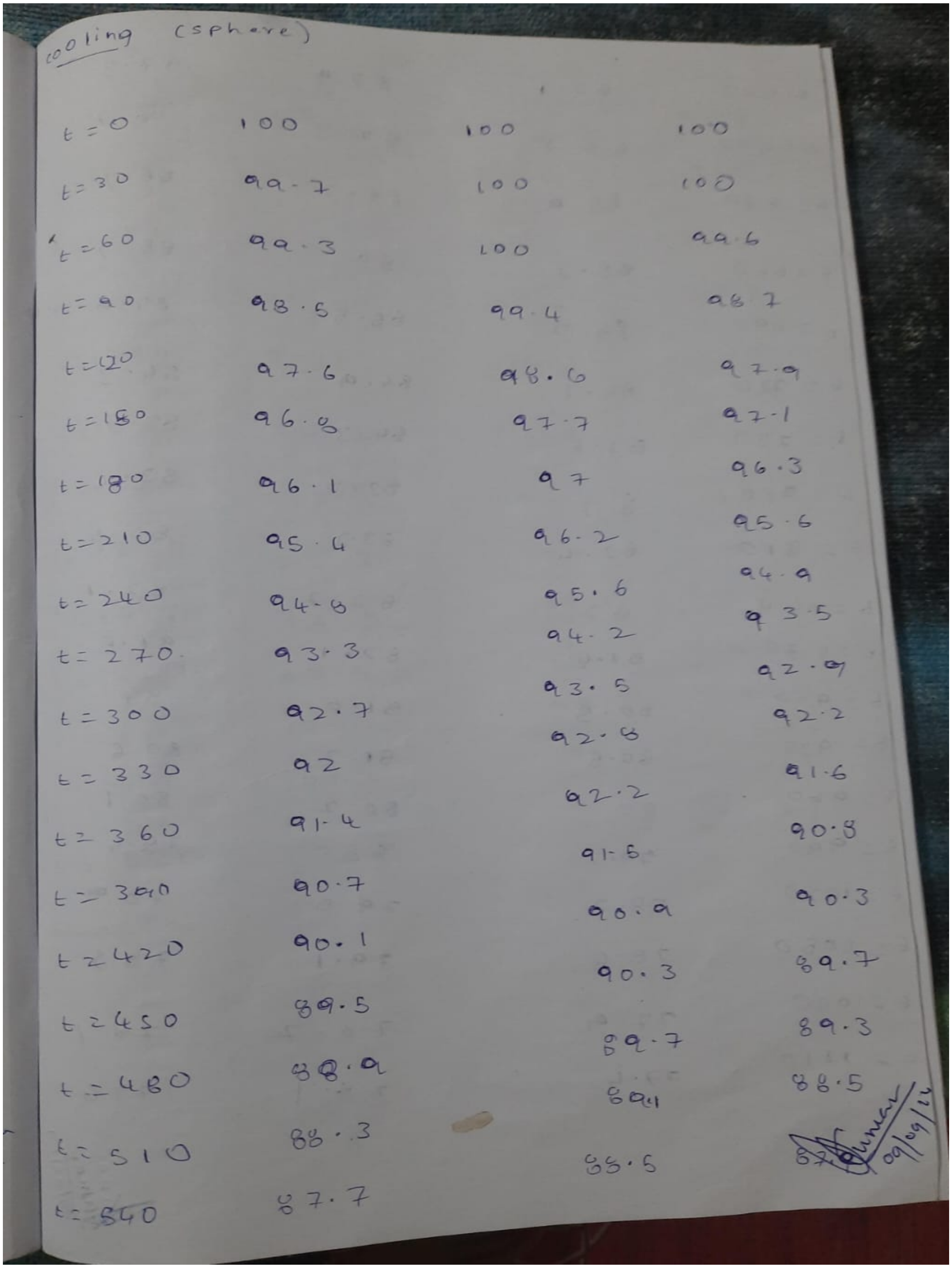
Figure 11: Data for Cooling of Cylinder (automatic) - 2



Heating (sphere)

t = 0	36.6	37.2	36.17
t = 10	43	41.2	41.4
t = 20	59.3	54	57.7
t = 30	72.2	67.2	70.5
t = 40	80.3	76.3	79.4
t = 50	86.8	83.1	85.7
t = 60	91.1	87.9	90
t = 70	94.4	91.8	93.6
t = 80	96.7	94.7	96.1
t = 90	98.4	96.8	98
t = 100	99.6	98.5	99.3
t = 120	100	99.8	100
t = 130	100	100	100

Figure 12: Data for Heating of Sphere (automatic)



cooling (sphere)

t=0	100	100	100
t=30	99.7	100	100
t=60	99.3	100	99.6
t=90	98.5	99.4	98.7
t=120	97.6	98.6	97.9
t=150	96.8	97.7	97.1
t=180	96.1	97	96.3
t=210	95.4	96.2	95.6
t=240	94.8	95.6	94.9
t=270	93.3	94.2	93.5
t=300	92.7	93.5	92.9
t=330	92	92.8	92.2
t=360	91.4	92.2	91.6
t=390	90.7	91.5	90.8
t=420	90.1	90.9	90.3
t=450	89.5	90.3	89.7
t=480	88.9	89.1	89.3
t=510	88.3	88.5	88.5
t=540	87.7		87[illegible]

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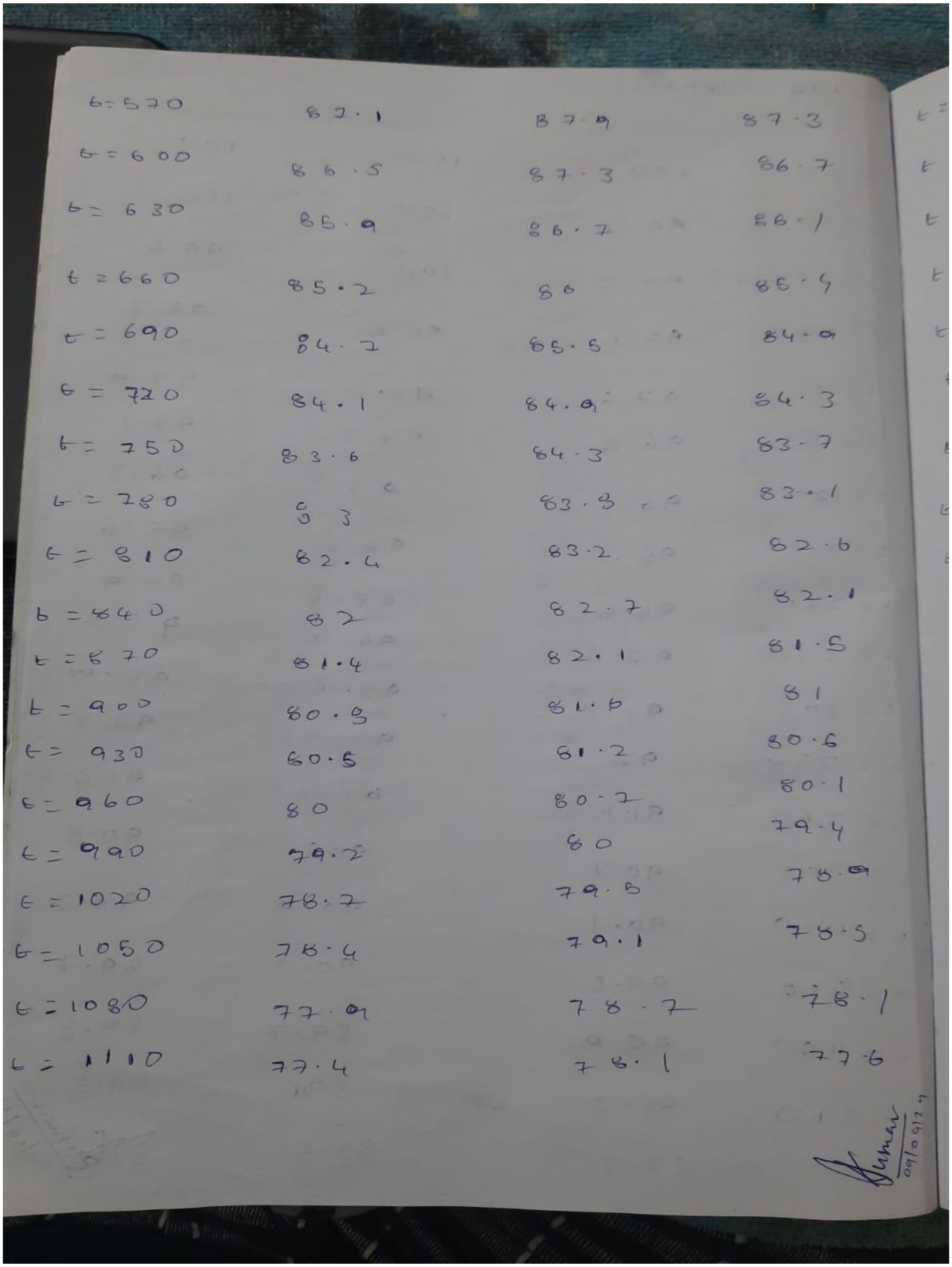
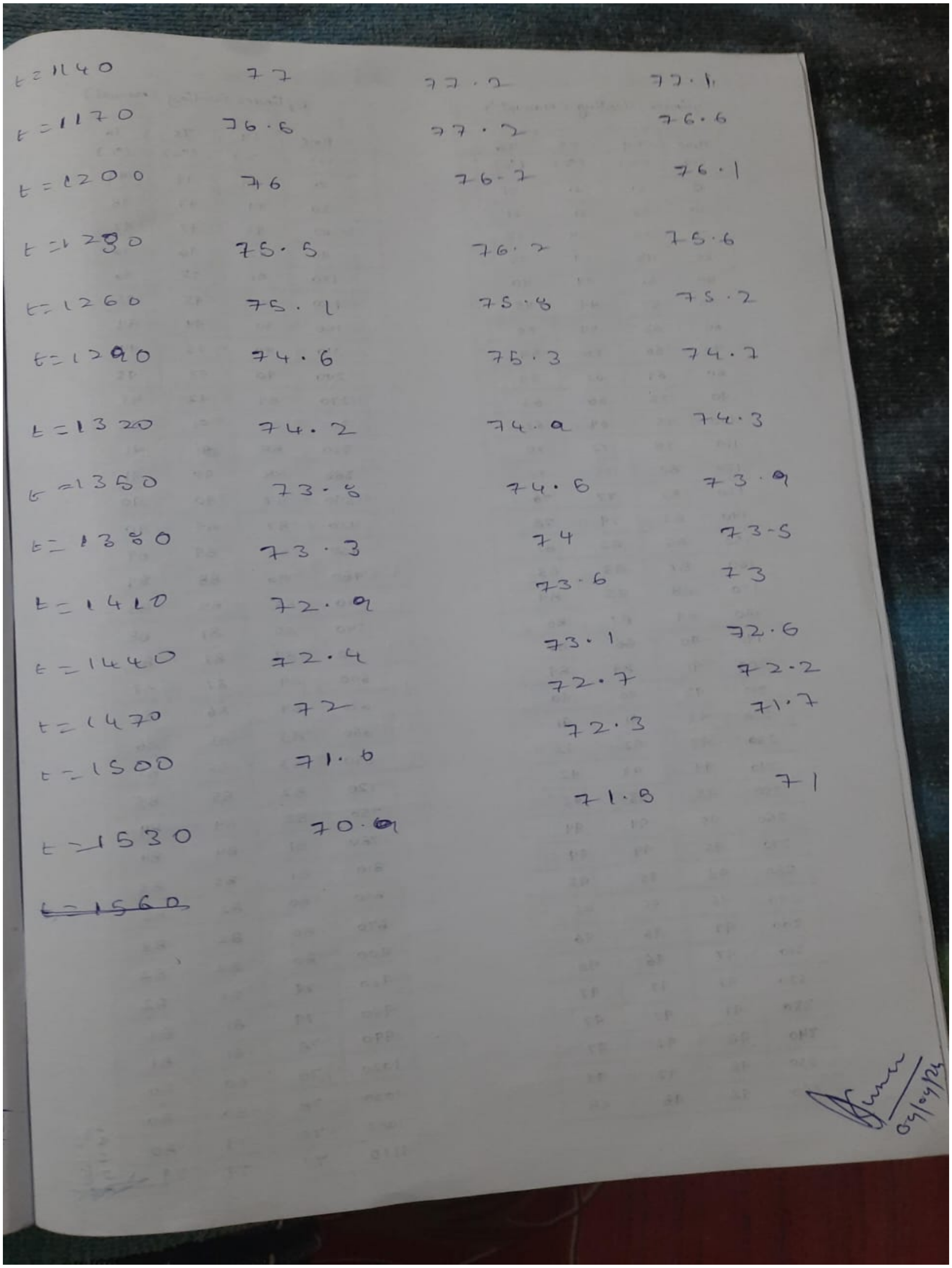
Figure 13: Data for Cooling of Sphere (automatic) - 1



t=570	87.1	87.9	87.3
t=600	86.5	87.3	86.7
t=630	85.9	86.7	86.1
t=660	85.2	86	85.4
t=690	84.7	85.5	84.9
t=720	84.1	84.9	84.3
t=750	83.6	84.3	83.7
t=780	83	83.8	83.1
t=810	82.4	83.2	82.6
t=840	82	82.7	82.1
t=870	81.4	82.1	81.5
t=900	80.9	81.6	81
t=930	80.5	81.2	80.6
t=960	80	80.7	80.1
t=990	79.7	80	79.4
t=1020	78.7	79.5	78.9
t=1050	78.4	79.1	78.5
t=1080	77.9	78.7	78.1
t=1110	77.4	78.1	77.6

Figure 14: Data for Cooling of Sphere (automatic) - 2



t=1140	77	77.2	77.1
t=1170	76.6	77.2	76.6
t=1200	76	76.7	76.1
t=1230	75.5	76.2	75.6
t=1260	75.1	75.8	75.2
t=1290	74.6	75.3	74.7
t=1320	74.2	74.9	74.3
t=1350	73.8	74.6	73.9
t=1380	73.3	74	73.5
t=1410	72.9	73.6	73
t=1440	72.4	73.1	72.6
t=1470	72	72.7	72.2
t=1500	71.6	72.3	71.7
t=1530	70.9	71.8	71
~~t=1560~~			

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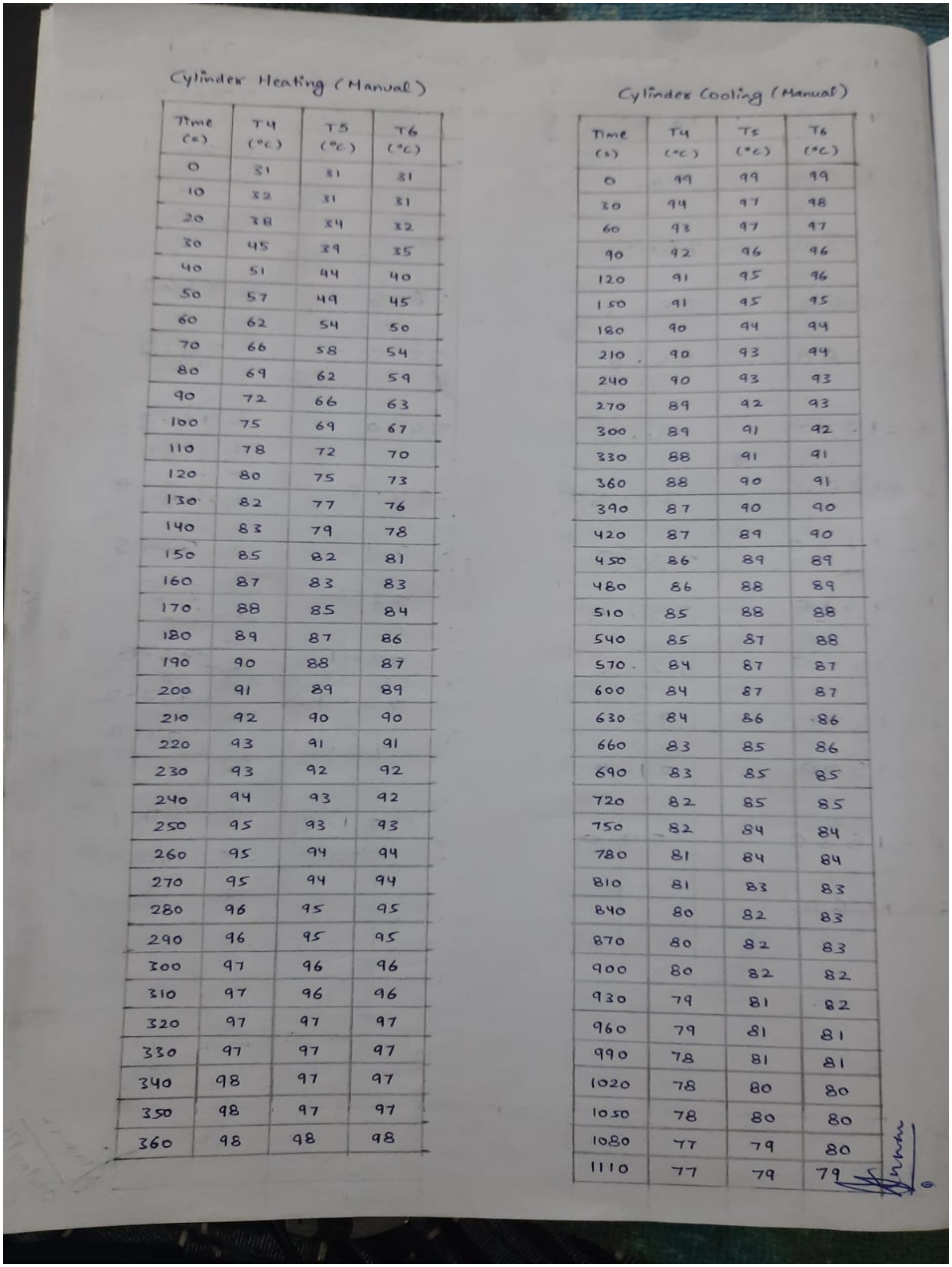
Figure 15: Data for Cooling of Sphere (automatic) - 3



Cylinder Heating (Manual)

Time (s)	T4 (°C)	T5 (°C)	T6 (°C)
0	31	31	31
10	32	31	31
20	38	34	32
30	45	39	35
40	51	44	40
50	57	49	45
60	62	54	50
70	66	58	54
80	69	62	59
90	72	66	63
100	75	69	67
110	78	72	70
120	80	75	73
130	82	77	76
140	83	79	78
150	85	82	81
160	87	83	83
170	88	85	84
180	89	87	86
190	90	88	87
200	91	89	89
210	92	90	90
220	93	91	91
230	93	92	92
240	94	93	92
250	95	93	93
260	95	94	94
270	95	94	94
280	96	95	95
290	96	95	95
300	97	96	96
310	97	96	96
320	97	97	97
330	97	97	97
340	98	97	97
350	98	97	97
360	98	98	98

Cylinder Cooling (Manual)

Time (s)	T4 (°C)	T5 (°C)	T6 (°C)
0	99	99	99
30	94	97	98
60	93	97	97
90	92	96	96
120	91	95	96
150	91	95	95
180	90	94	94
210	90	93	94
240	90	93	93
270	89	92	93
300	89	91	92
330	88	91	91
360	88	90	91
390	87	90	90
420	87	89	90
450	86	89	89
480	86	88	89
510	85	88	88
540	85	87	88
570	84	87	87
600	84	87	87
630	84	86	86
660	83	85	86
690	83	85	85
720	82	85	85
750	82	84	84
780	81	84	84
810	81	83	83
840	80	82	83
870	80	82	83
900	80	82	82
930	79	81	82
960	79	81	81
990	78	81	81
1020	78	80	80
1050	78	80	80
1080	77	79	80
1110	77	79	79

Figure 16: Data for Heating & Cooling of Cylinder (manual)

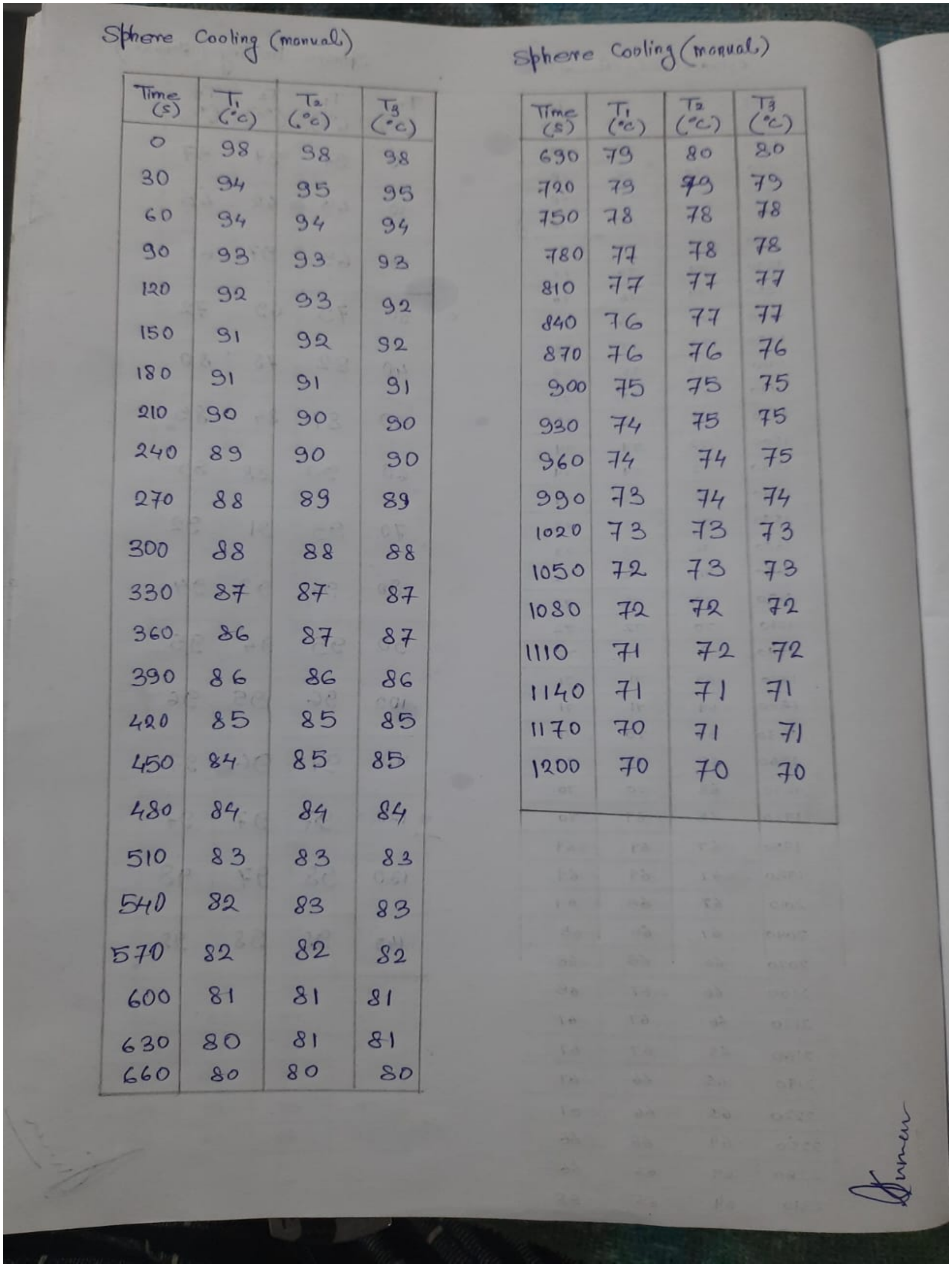
Cylinder Cooling (Manual)

Time (s)	T_4 (°C)	T_5 (°C)	T_6 (°C)
1140	76	78	79
1170	76	78	78
1200	76	77	78
1230	75	77	78
1260	75	77	77
1290	74	76	77
1320	74	76	76
1350	74	76	76
1380	73	75	76
1410	73	75	75
1440	73	75	75
1470	72	74	75
1500	72	74	74
1530	72	74	74
1560	71	73	74
1590	71	73	73
1620	71	73	73
1650	71	72	73
1680	70	72	72
1710	70	72	72
1740	70	71	72
1770	69	71	71
1800	69	71	71
1830	69	70	71
1860	68	70	70
1890	68	70	70
1920	68	69	70
1950	67	69	69
1980	67	69	69
2010	67	68	69
2040	67	68	68
2070	66	68	68
2100	66	67	68
2130	66	67	67
2160	65	67	67
2190	65	66	67
2220	65	66	67
2250	64	66	66
2280	64	65	66
2310	64	65	65

Sphere Heating (Manual)

Time (s)	T_3 (°C)	T_2 (°C)	T_1 (°C)
0	37	37	37
10	49	42	45
20	65	57	61
30	75	69	72
40	82	78	80
50	87	84	85
60	90	88	89
70	93	91	92
80	94	93	94
90	95	94	95
100	96	95	96
110	97	96	97
120	97	97	97
130	98	97	98
140	98	98	98

Figure 17: Data for Cooling of Cylinder & Heating of Sphere (manual)



Sphere Cooling (manual)

Time (s)	T_1 (°c)	T_2 (°c)	T_3 (°c)
0	98	98	98
30	94	95	95
60	94	94	94
90	93	93	93
120	92	93	92
150	91	92	92
180	91	91	91
210	90	90	90
240	89	90	90
270	88	89	89
300	88	88	88
330	87	87	87
360	86	87	87
390	86	86	86
420	85	85	85
450	84	85	85
480	84	84	84
510	83	83	83
540	82	83	83
570	82	82	82
600	81	81	81
630	80	81	81
660	80	80	80

Sphere Cooling (manual)

Time (s)	T_1 (°c)	T_2 (°c)	T_3 (°c)
690	79	80	80
720	79	79	79
750	78	78	78
780	77	78	78
810	77	77	77
840	76	77	77
870	76	76	76
900	75	75	75
930	74	75	75
960	74	74	75
990	73	74	74
1020	73	73	73
1050	72	73	73
1080	72	72	72
1110	71	72	72
1140	71	71	71
1170	70	71	71
1200	70	70	70

Figure 18: Data for Cooling of Sphere (manual)