# ANALYSIS OF HEAT TRANSFER IN CERAMIC AND STEEL MUGS


Group 4

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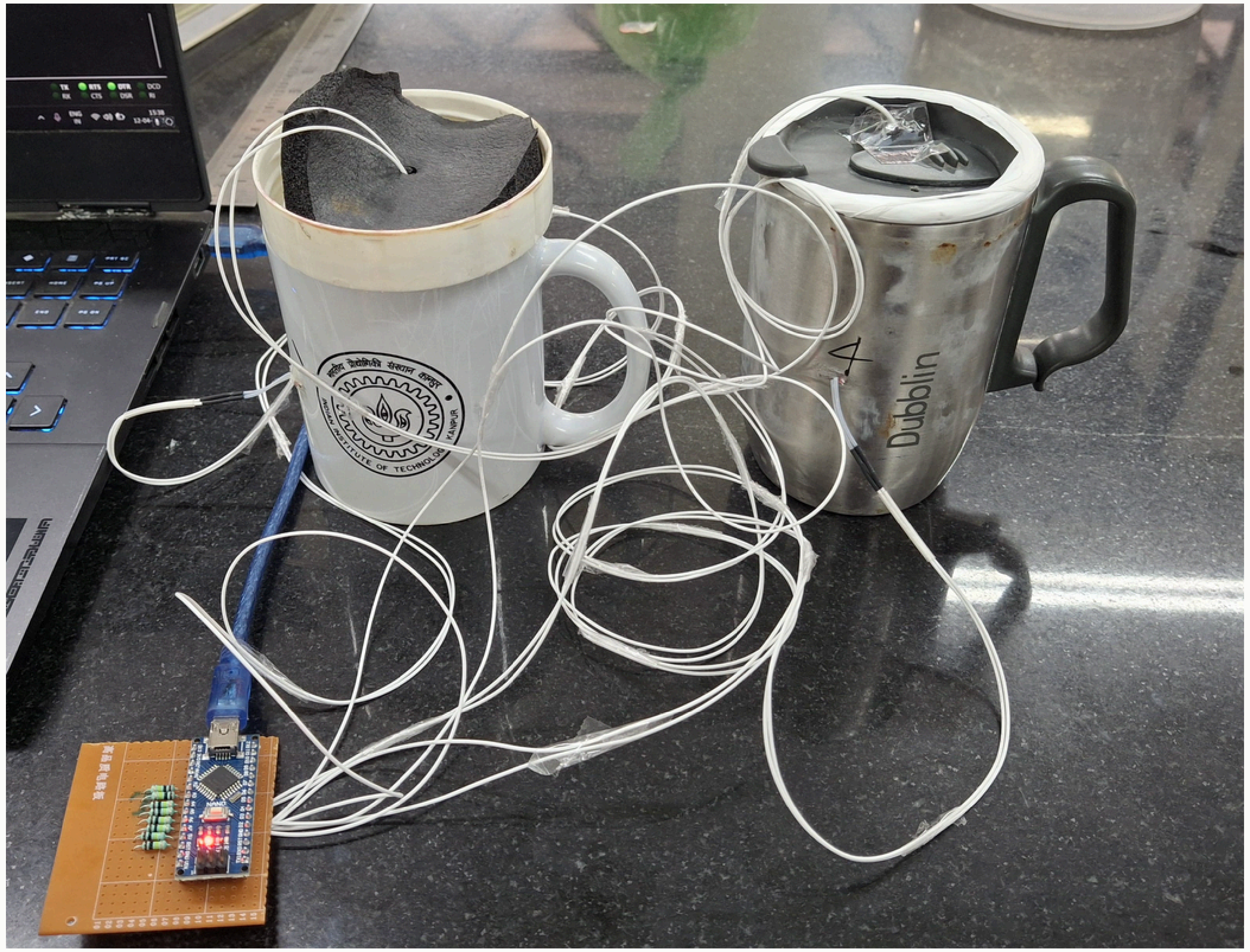


Heat Transfer

# TABLE
## of contents

# Introduction to the Problem

Investigate and compare the heating and cooling behaviours of a normal mug and a vacuum mug. Analyse temperature change over time to model heat loss using Newton's Law of Cooling.

- Thermal insulation is critical in various applications ranging from buildings to every-day-items
- Beverage containers represent a practical application of insulation principles in daily life
- Understanding heat transfer mechanisms can improve insulation technology

# Problem Statement:

- How do vacuum-insulated mugs perform compared to standard ceramic mugs?
- Can Newton's Law of Cooling accurately model and quantify this difference?

# Experimental Setup

1

Common Setup:

- Two temperature sensors (inner & outer wall surfaces).
- Hot water poured into the mugs at time zero.
- Data collected continuously using logging system.
- Laptop

2

Ceramic Mug:

- Solid ceramic construction with uniform wall thickness.
- Heat flows primarily through conduction and convection.

3

Vacuum Mug:

- Double-walled stainless-steel with vacuum insulation.
- Reflective coating on walls to reduce radiative heat transfer.

4

Environmental Conditions:

- Experiment performed at room temperature.
- Initial temperatures near 28–30°C for both mugs.


# Innovative Aspects

- First-hand comparison of two everyday mugs using scientific methods.
- Integration of sensor data thermal analysis.
- Explanation of Newton’s law of heating, Fourier’s law, and Stefan–Boltzmann radiation law.
- Insight into how design (vacuum vs. solid ceramic) impacts thermal performance.
- Foundation for future product design in thermal containers and consumer products.

# Methodology (Ceramic Mug)

- The ceramic mug was  at room temperature.
- Sensors were attached:
- One in contact with the inner surface (hot water side).
- One on the outer wall of the mug.
- Hot water poured in at t = 0; data recording started immediately.
- Inner and outer temperatures were recorded.
- The process continued until near thermal equilibrium was observed.
- Data was plotted and analyzed to interpret thermal behavior.

# Methodology (Vacuum Mug)


- Same steps as ceramic mug for consistency and comparability.
- Mug was at room temperature initially.
- Sensors fixed on inner and outer surfaces of the vacuum-insulated wall.
- Hot water poured, data logging initiated at $t = 0$.
- Data collected to observe insulation behavior.
- Specific attention given to the lag in outer surface temperature.

# Theory – Heat Transfer Mechanisms

## Conduction:

- Dominant in ceramic mug.
- Governed by Fourier's law:
- q=−kdTdx

## Convection:

- Present on both inner and outer surfaces.
- Newton's Law:
- q=hA(Ts−T∞)
- Vacuum mug eliminates convection in the insulation layer.

## Radiation:

- Affects both mugs but minimized in vacuum mug.
- Modeled by Stefan-Boltzmann law:
- q=εσ(T14−T24)

# Temperature Analysis

- ***Temperature Evolution***

<u>Vacuum Mug:</u>

- Inner temp rose from ~28.4°C to ~93.2°C.
- Outer surface rose slowly, peaking at ~43°C.

<u>Ceramic Mug:</u>

- Inner temp rose quickly to ~87°C.
- Outer surface lagged behind but reached ~70°C.

- ***Temperature Difference Analysis***

<u>Vacuum Mug:</u>

- Maximum $\Delta T \approx 60$°C between inner and outer walls.
- Outer surface temperature increases slowly.

<u>Ceramic Mug:</u>

- Maximum $\Delta T \approx 56$°C.
- Gradient narrows over time as heat conducts through walls.

# Calculation

Natural convection of hot water against the inner wall yields a film coefficient in the range 50–3 000 W/m²·K; for a stationary mug filled with ≈60 °C water, we choose a representative hwater≈500 W/m2⋅Khwater ≈500W/m2⋅K which lies well within the free-convection range for liquids

## Correlation and Rayleigh Number

Using the **Churchill–Chu correlation** for a long horizontal cylinder in quiescent air:

$$\mathrm{Nu}_D = \left[0.6 + \frac{0.387\,\mathrm{Ra}_D^{1/6}}{\left(1 + (0.559/\,\mathrm{Pr})^{9/16}\right)^{8/27}}\right]^2 \quad (10^{-5} < \mathrm{Ra}_D < 10^{12})$$

# Calculation

With:

- Characteristic length $D = 0.08\ \mathrm{m}$
- Temperature difference $\Delta T = 60 - 25 = 35\ K$
- Film temperature =42.5 C
- Air properties at $T_f$: $\beta = 1/(T_f + 273) = 0.00317\ \mathrm{K}^{-1},\ \nu = 1.7 \times 10^{-5}\ \mathrm{m}^2/\mathrm{s},\ \mathrm{Pr} = 0.71$

Compute

$$\mathrm{Ra}_D = \frac{g\,\beta\,\Delta T\,D^3}{\nu^2}\,\mathrm{Pr} \approx 1.37 \times 10^6$$

$$\mathrm{Nu}_D \approx (0.6 + 0.387 \cdot 10.54/1.204)^2 \approx 15.9$$

$$h_{\mathrm{air}} = \frac{\mathrm{Nu}_D\,k_{\mathrm{air}}}{D} = \frac{15.9 \times 0.026}{0.08} \approx 5.2\ \mathrm{W/m^2 \cdot K}$$

# Calculation

## Radiative Heat Transfer: Outer Surface

The radiative film coefficient between a surface at $T_s$ and surroundings at $T_\infty$ is

$$h_{\mathrm{rad}} = \varepsilon\,\sigma\,(T_s^2 + T_\infty^2)\,(T_s + T_\infty)$$

where $\sigma = 5.67 \times 10^{-8}\,\mathrm{W/m^2 \cdot K^4}$

- **Ceramic** ($\varepsilon \approx 0.9$):
  $T_s = 333\,K,\ T_\infty = 298\,K \Rightarrow$
  $h_{\mathrm{rad}} \approx 0.9 \times 5.67 \times 10^{-8} \times (333^2 + 298^2) \times (333 + 298) \approx 6.4\ \mathrm{W/m^2 \cdot K}.$
- **Vacuum Mug (polished steel, $\varepsilon \approx 0.07$)**:
  yields $h_{\mathrm{rad}} \approx 0.5\ \mathrm{W/m^2 \cdot K}.$

# Calcualution

## Newton’s Law of Cooling in Lumped Form

### Differential Equation

$$\frac{dT}{dt} = -\frac{h\,A}{m\,c}(T - T_\infty)$$

### Integrated (Exponential) Solution

$$T(t) = T_\infty + \left[T(0) - T_\infty\right] \exp\!\left(-t/\tau\right), \quad \tau = \frac{m\,c}{h\,A}$$

where $\tau$ is the **thermal time constant**

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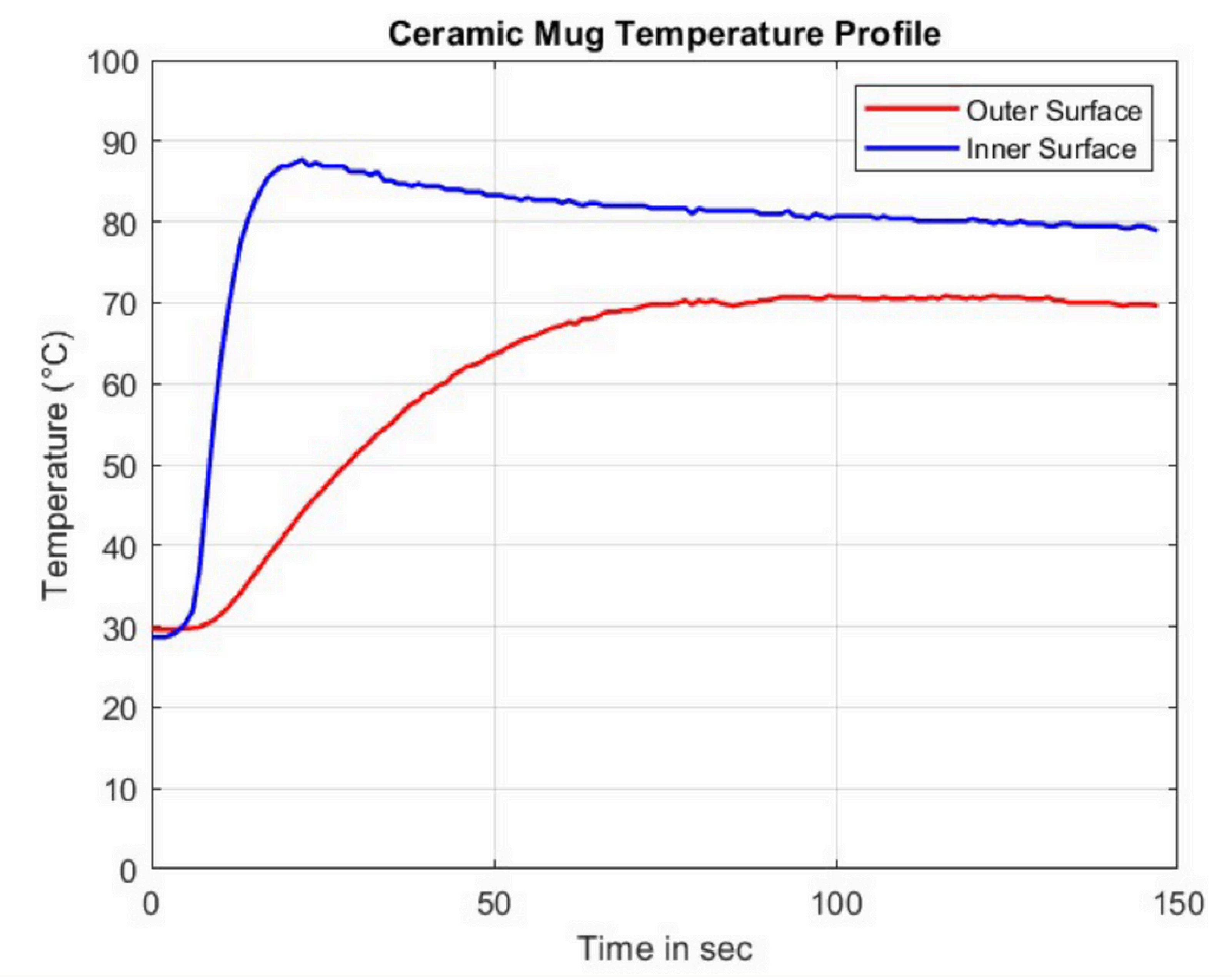
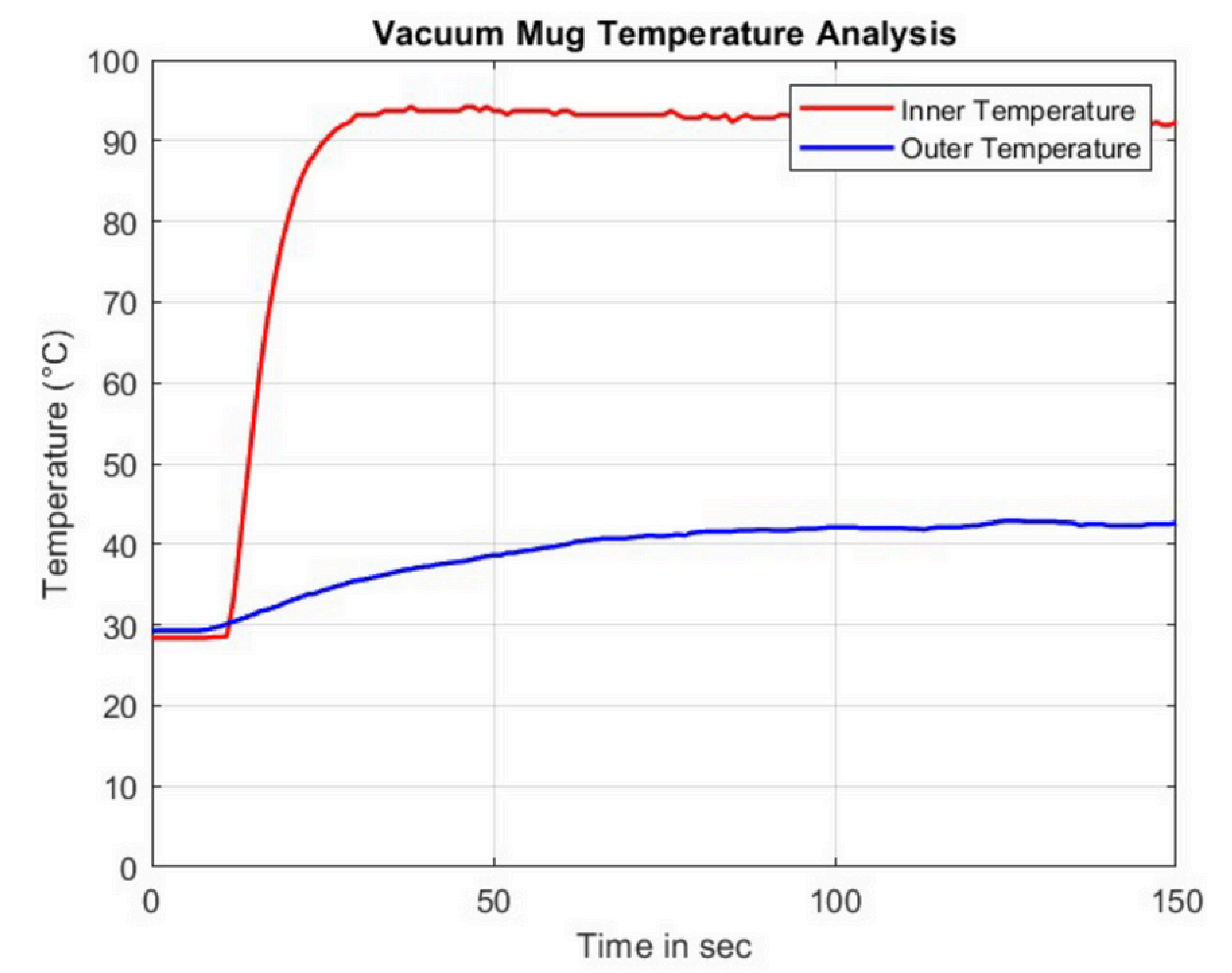
# Graphs




Temperature Difference Analysis
(Ceramic mug)




Temperature Difference Analysis
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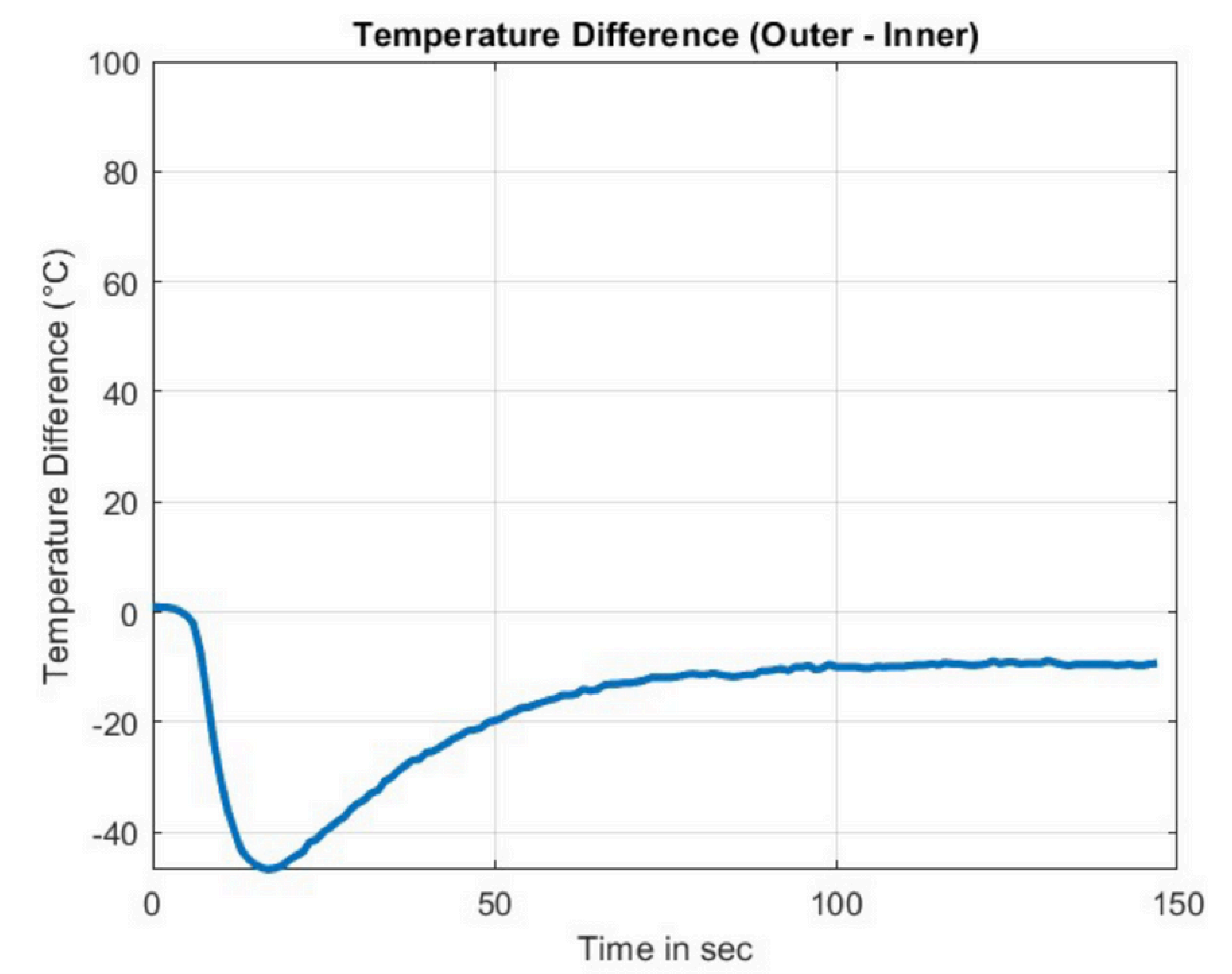


Temperature Difference Analysis
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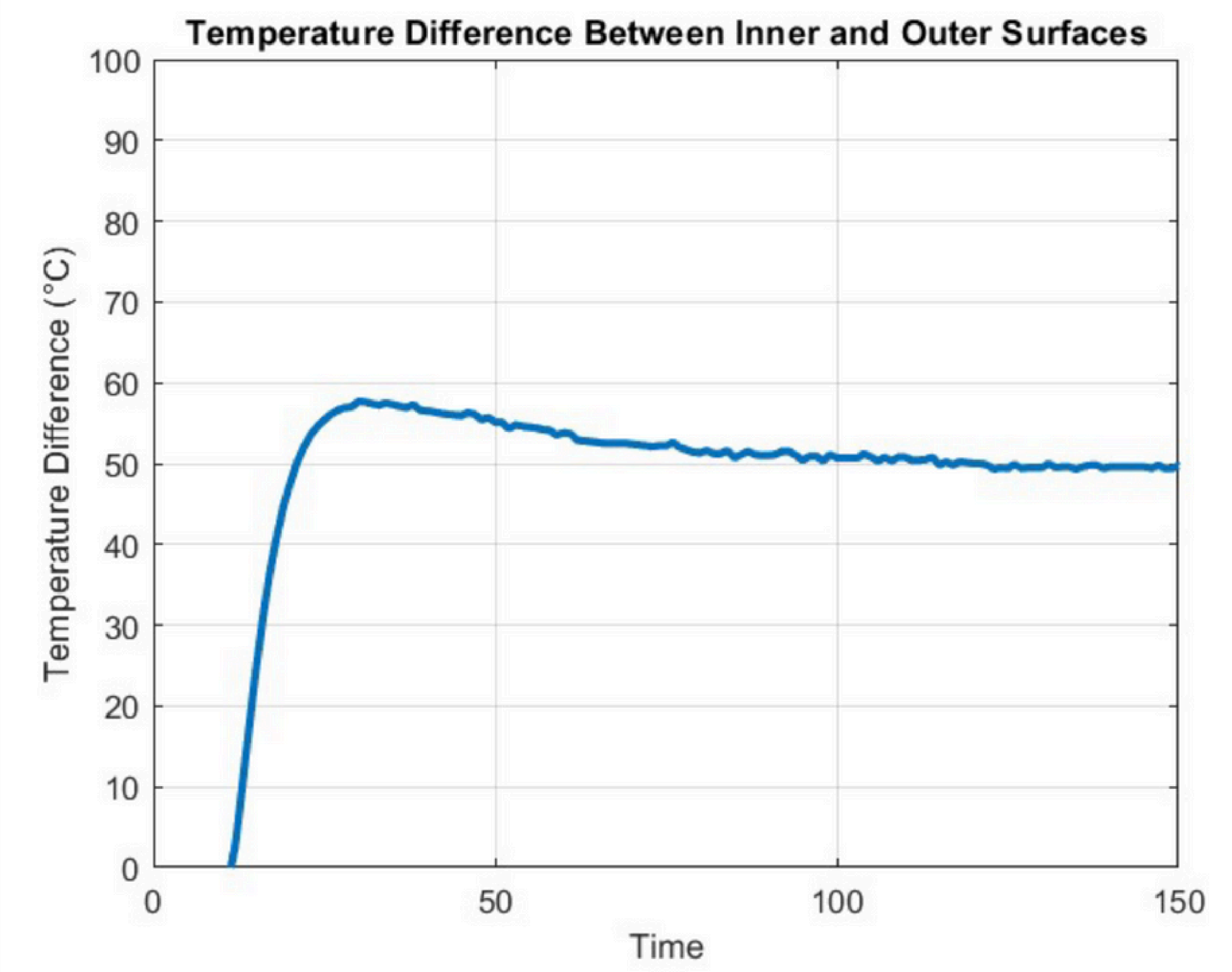
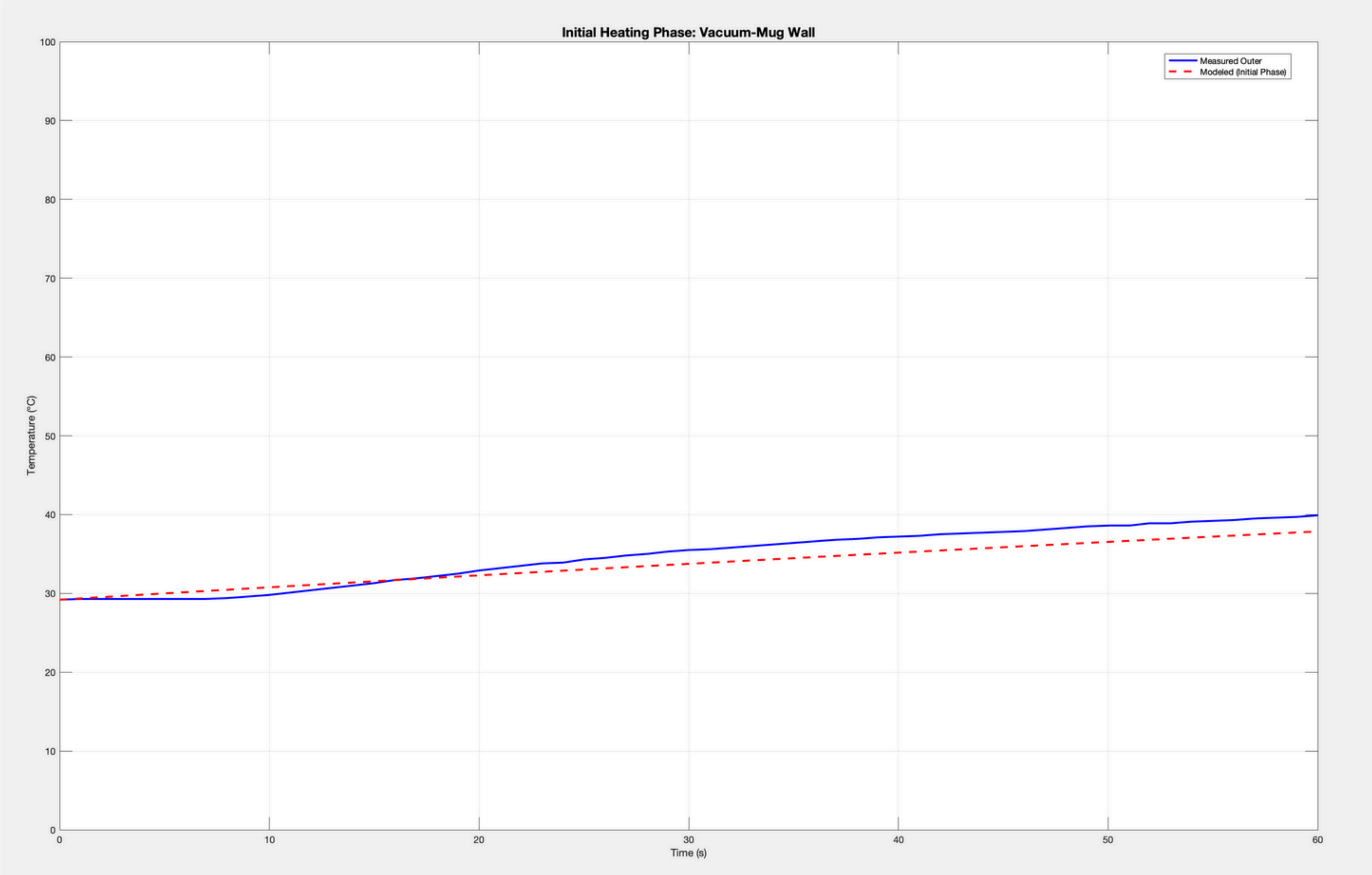



Temperature Difference Analysis
(Vacuum mug)

# GRAPH




Modelled vs Original for
(Vacuum mug)

```
% raw data
data = [28.4 29.2 28.4 29.3 28.4 29.3 28.4 29.3 28.4 29.3 28.4 29.3 28.4 29.3 28.4 29.3 28.4 29.4 28.5 29.6
28.5 29.8 28.6 30.1 33.2 30.4 40.6 30.7 48.3 31 55.7 31.3 62.4 31.7 68.2 31.9 72.9 32.2 77.1 32.5 80.4 32.9
83.3 33.2 85.5 33.5 87.3 33.8 88.5 33.9 89.7 34.3 90.6 34.5 91.4 34.8 91.9 35 92.3 35.3 93.2 35.5 93.2 35.6
93.2 35.8 93.2 36 93.7 36.2 93.7 36.4 93.7 36.6 93.7 36.8 94.2 36.9 93.7 37.1 93.7 37.2 93.7 37.3 93.7 37.5
93.7 37.6 93.7 37.7 93.7 37.8 94.2 37.9 94.2 38.1 93.7 38.3 94.2 38.5 93.7 38.6 93.7 38.6 93.2 38.9 93.7 38.9
93.7 39.1 93.7 39.2 93.7 39.3 93.7 39.5 93.7 39.6 93.2 39.7 93.7 39.9 93.7 40 93.2 40.3];
inner_temp = data(1:2:end);
outer_temp = data(2:2:end);
% for the mug stainless steel 304
rho = 8000;       % density
cp  = 900;        % specific heat
h   = 100;        % convective coefficient (W/m^2·K)
dt  = 1;          % time step (s)
% Dimensions of the cup
R_top = 0.071; R_bot = 0.054; H = 0.085; t = 0.004;
r_top = R_top - t; r_bot = R_bot - t;
% Frustum slant and inner surface area
s = sqrt((r_top - r_bot)^2 + H^2);
A = pi * (r_top + r_bot) * s;
% Shell volume and mass
V_outer = (pi*H/3)*(R_top^2 + R_top*R_bot + R_bot^2);
V_inner = (pi*H/3)*(r_top^2 + r_top*r_bot + r_bot^2);
V_shell = V_outer - V_inner;
m = rho * V_shell;
% Lumped modelling
Bi = h * t / 15;  % using k ≈ 15 W/m·K
fprintf('Mass = %.3f kg, Area = %.3f m^2, Biot = %.3f\n', m, A, Bi);
% Modelling for heating phase only
diffs = diff(outer_temp);
idx_peak = find(diffs < 0, 1, 'first') + 1;
if isempty(idx_peak)
   idx_peak = length(outer_temp);
end
% Using heting phase
n0 = idx_peak;
t_inner = inner_temp(1:n0);
t_outer = outer_temp(1:n0);
T_inf = mean(t_inner);
T_model = zeros(1, n0);
T_model(1) = t_outer(1);
for i = 2:n0
   dTdt = (h*A)/(m*cp) * (T_inf - T_model(i-1));
   T_model(i) = T_model(i-1) + dTdt * dt;
end
% Plot
time = (0:n0-1)*dt;
figure;
plot(time, t_outer, 'b-', 'LineWidth', 2); hold on;
plot(time, T_model, 'r--', 'LineWidth', 2);
xlabel('Time (s)');
ylabel('Temperature (°C)');
xlim([0,60]);
ylim([0 100]);
legend('Measured Outer', 'Modeled (Initial Phase)');
title('Initial Heating Phase: Vacuum-Mug Wall');
grid on;
```

# Discussion (Ceramic MUG)

<u>ConductionThermal Response Analysis</u>
The data exhibits distinct phases:
Initial heating phase

The inner temperature rises rapidly as hot water is introduced, while the outer tem- perature shows minimal change. This demonstrates the thermal inertia of the ceramic material. The inner surface temperature quickly reaches approximately 77 ◦ C within 10 minutes, while the outer temperature has only increased to about 31 ◦ C.

Heat propagation phase

The outer temperature begins to rise more noticeably as heat conducts through the ceramic wall. The rate of temperature increase on the outer surface is significantly slower than the inner surface due to the ceramic's thermal resistance. During this phase, the inner temperature stabilizes around 86-87 ◦ C, while the outer temperature continues to climb steadily, reaching about 51 ◦ C by the 30-minute mark.

Quasi-equilibrium phase

Both temperatures begin to stabilize but maintain a differential, indicating ongoing heat transfer. The system approaches a steady state where heat gain equals heat loss to the environment. The temperature difference between inner and outer surfaces decreases gradually as the system approaches thermal equilibrium. By the end of the experiment, the inner surface is at approximately 79 ◦ C while the outer surface is at 70 ◦ C.

# Discussion (Vacuum Mug)

<u>Phase Analysis</u>

<u>Phase I: Initial Equilibrium</u>

At the beginning of the experiment, both the inner and outer surfaces of the mug were near room temperature:

• Inner temperature: approximately 28.4 $^{\circ}$C

• Outer temperature: approximately 29.2 $^{\circ}$C to 29.3 $^{\circ}$C

The slightly higher temperature of the outer surface may be attributed to the ambient conditions or recent handling of the mug. During this phase, the system was in thermal equilibrium with its surroundings, with minimal temperature gradient across the vacuum layer.

<u>Phase II: Heating Phase</u>

Upon introduction of hot liquid, a dramatic temperature increase was observed on the inner surface:

- Inner temperature rose from 28.4 $^{\circ}$C to approximately 93.2 $^{\circ}$C
- The temperature rise followed a characteristic exponential pattern
- The rate of temperature increase was most rapid in the early stages, gradually slowing as it approached maximum
- This behavior can be modeled by Newton's law of heating:
- $T(t) = T_{env} + (T_{final} - T_{env})(1 - e^{-kt})$ (1)
- where $T(t)$ is the temperature at time $t$, $T_{env}$ is the initial temperature, $T_{final}$ is the final temperature, and $k$ is the heating constan


<u>Phase III: Steady State</u>

After reaching peak temperature, the inner surface exhibited:

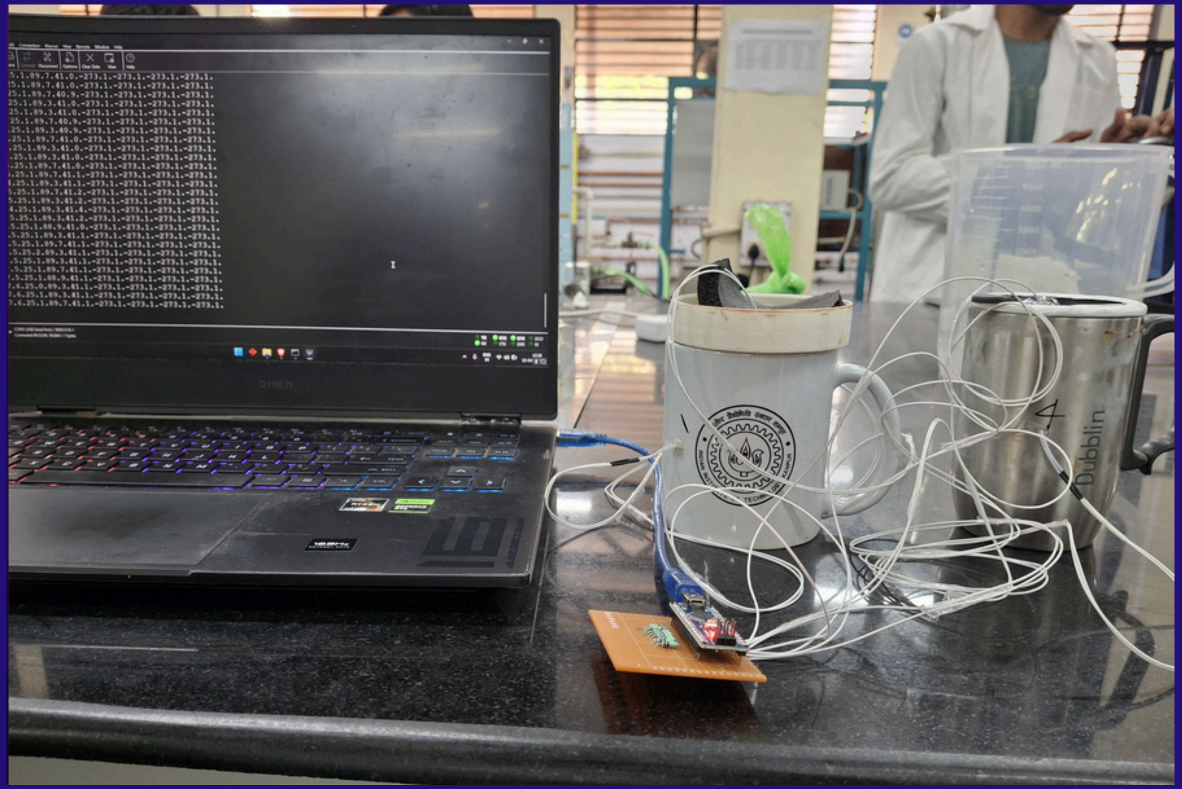
• Temperature stabilization around 90 $^{\circ}$C to 94 $^{\circ}$C

• Gradual cooling over extended time

• Approximately linear temperature decline in the later stages

The outer surface temperature increased much more slowly, reaching a maximum of only about 43 $^{\circ}$C, demonstrating the effectiveness of the vacuum insulation. The considerable delay and reduced magnitude of the outer temperature response highlight the vacuum layer's ability to impede heat transfer.

# Conclusion and Future Work



Conclusions:

1: Vacuum mugs minimize heat loss better than ceramic mugs.
2: Heat transfer in ceramic mugs is governed by conduction + convection.
3: The experiment validated theoretical predictions.

Future Work:

1: Compare other materials (e.g., glass, plastic, metal).
2: Analyze effect of initial water temperatures.
3: Examine long-term thermal retention and repeated use.
Evaluate mug geometry and coatings on heat transfer.

# THANK YOU !!