CHE212 INNOVATION PROJECT

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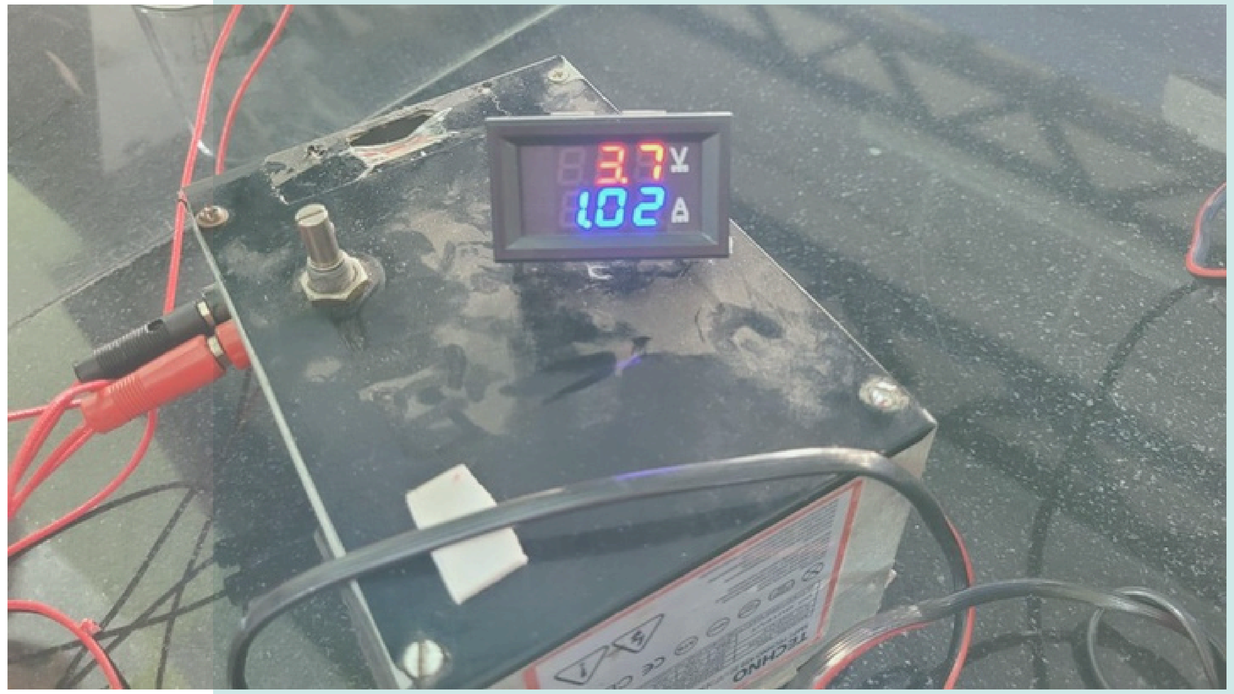
CONDUCTION IN SERIES

INTRO OF THE PROBLEM

In this experiment, we extended our study of steady-state conduction in a single metal to a series combination of metals. We examined heat conduction across three metal pairs—Cu-Al, Al-Fe, and Fe-Cu—to analyze the thermal behavior in a multi-material setup.



OBJECTIVE

To calculate experimental resistance of the setup and compare it with theoretical resistance as well as perform a transient analysis

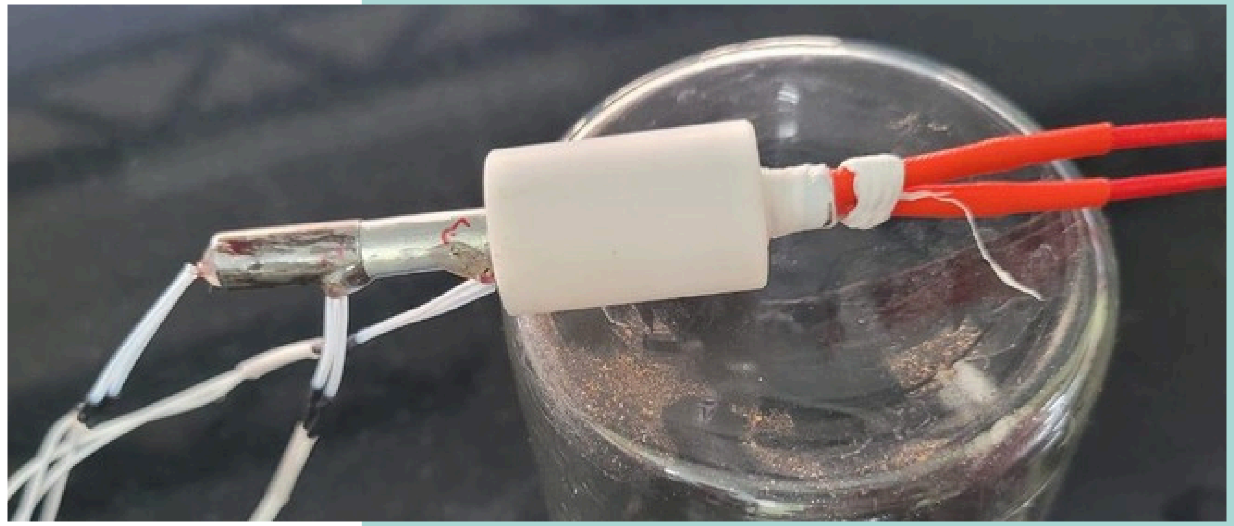
MATERIALS REQUIRED

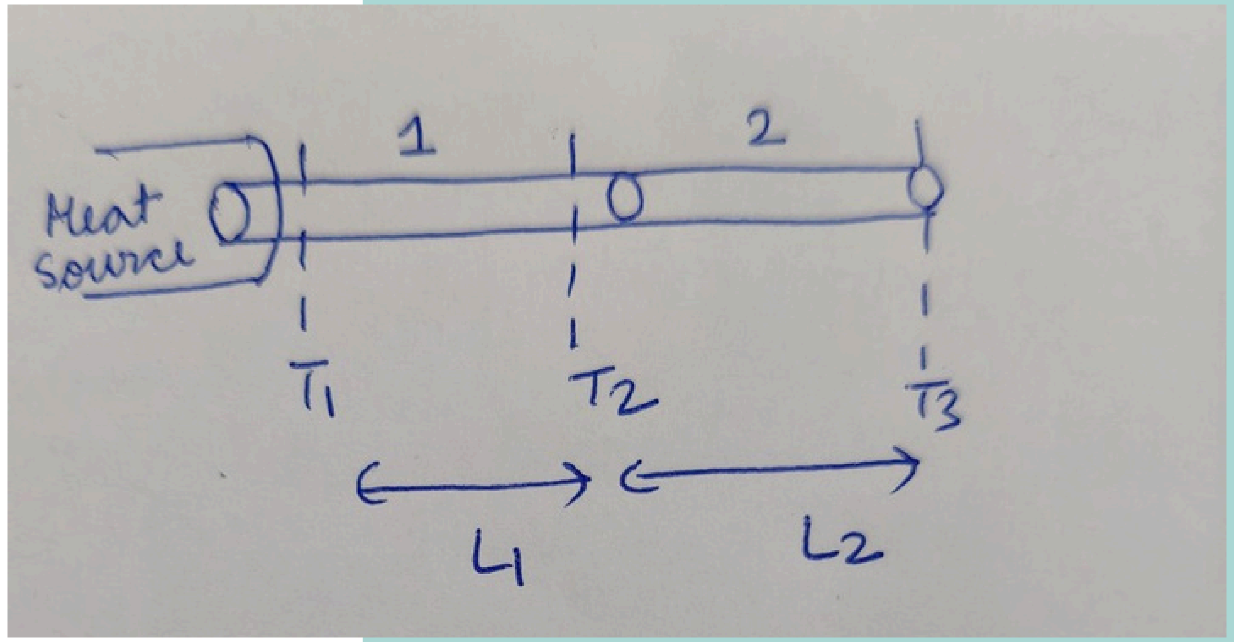
- Three metal rods(Cu, Al ,Fe)
- Power source
- Power display

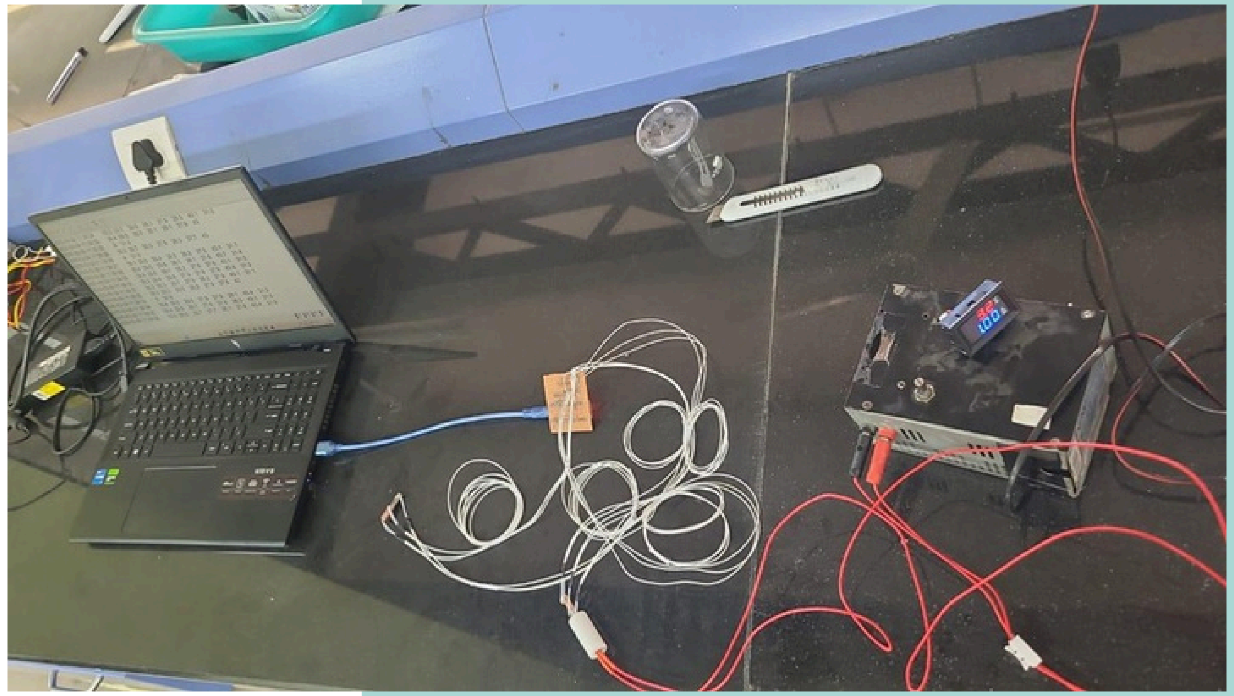
EXPERIMENTAL SETUP

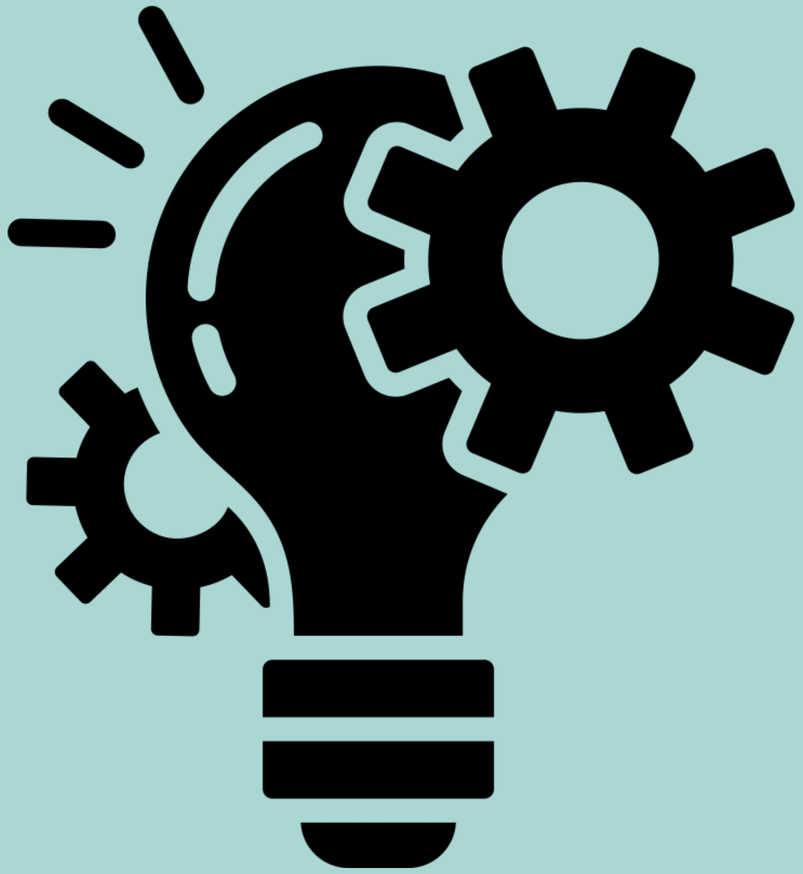
- The experimental setup consists of three series combinations—Cu-Al, Al-Fe, and Fe-Cu—using two rods each.
- Temperature sensors (T1 at the hot end, T2 at the junction, and T3 at the cold end) were attached to monitor the temperature profile.
- A constant heat source was applied at one end, and data was logged using an Arduino and power display.
- The entire assembly was insulated with Teflon to minimize heat loss.
- Collected data is as follows :

ROD PAIR	MATERIAL	LENGTH (mm)	RADIUS (mm)
Fe - Al	Fe	15	6
	Al	15.5	5.54
Cu - Al	Cu	16	6
	Al	14.5	5.54
Fe - Cu	Fe	15.5	6
	Cu	14	6









INNOVATION ASPECT

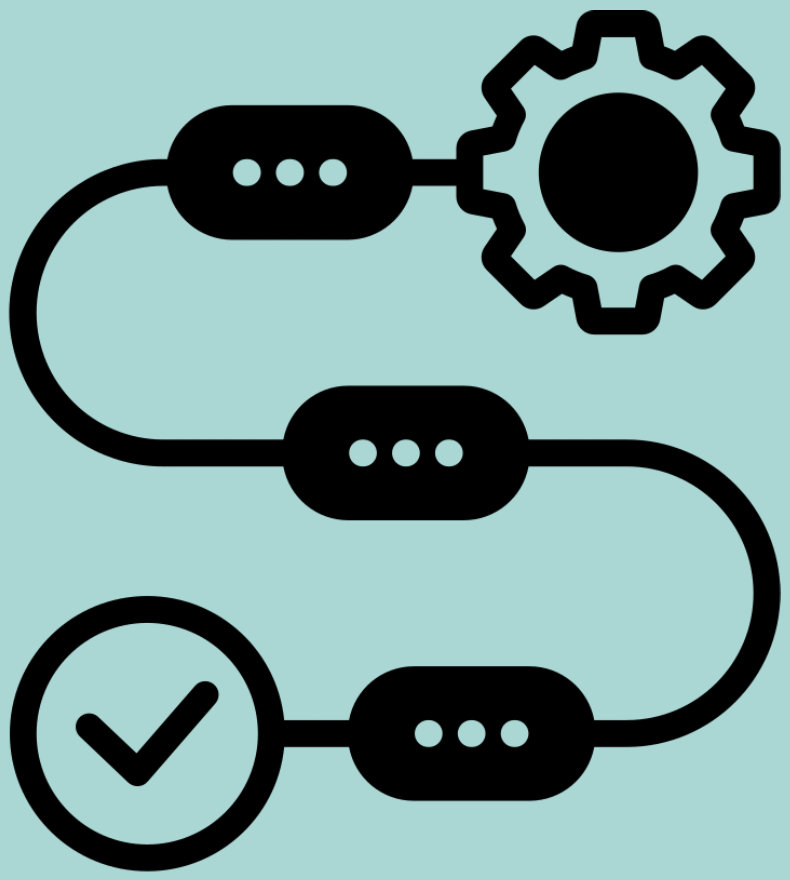
- Using the temperature data obtained from the sensors, we will calculate the experimental resistance of the setup, and then compare it with the theoretical resistance at steady state. We will check if the resistance trends match the theory.

- We will also compare the transient portion of the the Temperature-Time plot to see its relation with the experimental trend.

METHODOLOGY

Procedure:

- Ensure firm contact between rods to reduce contact resistance.
- Start the heat source and record temperatures from three sensors (T1, T2, T3) every 3 seconds using a data logger.
- Wait until steady-state is reached (temperatures stabilize).
- Repeat the process for all three metal combinations.
- Measure each rod's length and diameter.

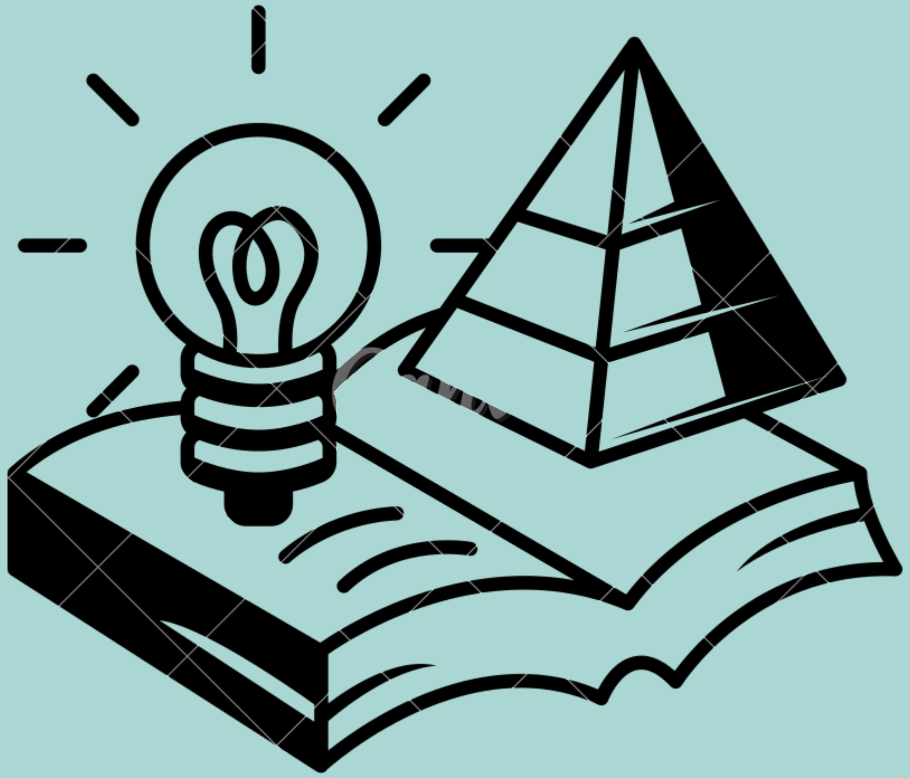


METHODOLOGY

Contact Method:
To maximize contact, metal A is made slightly longer and tapered to fit into a drilled hole in metal B, forming a tight, screw-like joint. While this may introduce minor error, it ensures better thermal contact.

Sources of Error:

- Slight unaccounted overlap where metals form concentric cylinders.
- T1 sensor placed ~3 mm from the rod’s end due to insulation constraints (accounted for in calculations).
- Possible heat loss through the Teflon insulation and imperfect heater-rod contact.



THEORY

FOURIER LAW : $Q = \frac{kA(T_1 - T_2)}{L}$

In series heat conduction, heat flows sequentially through materials like copper, iron, and aluminum. The heat flow rate (Q dot) remains constant, while temperature drops occur at the interfaces.

Analogous to electrical resistance, $R_{\text{th}} = \frac{L}{kA}$ R_{th}: thermal resistance (K/W)

For series conduction, $R_{\text{total}} = R_1 + R_2 + R_3 + \cdots = \sum_{i=1}^{n} \frac{L_i}{k_i A}$

Total heat transfer, $Q = \frac{\Delta T_{\text{total}}}{R_{\text{total}}}$

For a rod segment i , $\Delta T_i = Q \cdot R_i = Q \cdot \frac{L_i}{k_i A}$

R theoretical = L/KA

R exp = Del T/Q dot

Assumptions:

Steady-state conditions, one-dimensional heat flow, perfect thermal contact, and negligible or accounted heat loss to surroundings.

SIMULATION

To estimate expected results, we simulated transient and steady-state conduction in a copper rod.
Parameters:

- $k = 385$ W/m·K, $\alpha = 1.11\times10^{-4}$ m²/s
- Length = 0.1 m, discretized into 21 points ($\Delta x = L/20$)
- Initial temp: 25°C
- Boundary conditions: $T(0, t) = 100°C$, $T(L, t) = 0°C$

Governing Equations

- **1. Fourier's Law (Steady-State):**

$$Q = -k\frac{dT}{dx}$$

- **2. 1D Heat Equation (Transient):**

$$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2}$$

Numerical Method: Explicit Finite Difference

Discretized form at interior node i, time step n:

$$T_i^{n+1} = T_i^n + \mathrm{Fo}\left(T_{i+1}^n - 2T_i^n + T_{i-1}^n\right)$$

Where:

- $\mathrm{Fo} = \frac{\alpha\Delta t}{(\Delta x)^2}$: Fourier number
- Stability condition: $\mathrm{Fo} \leq 0.5$ for stability in explicit FDM

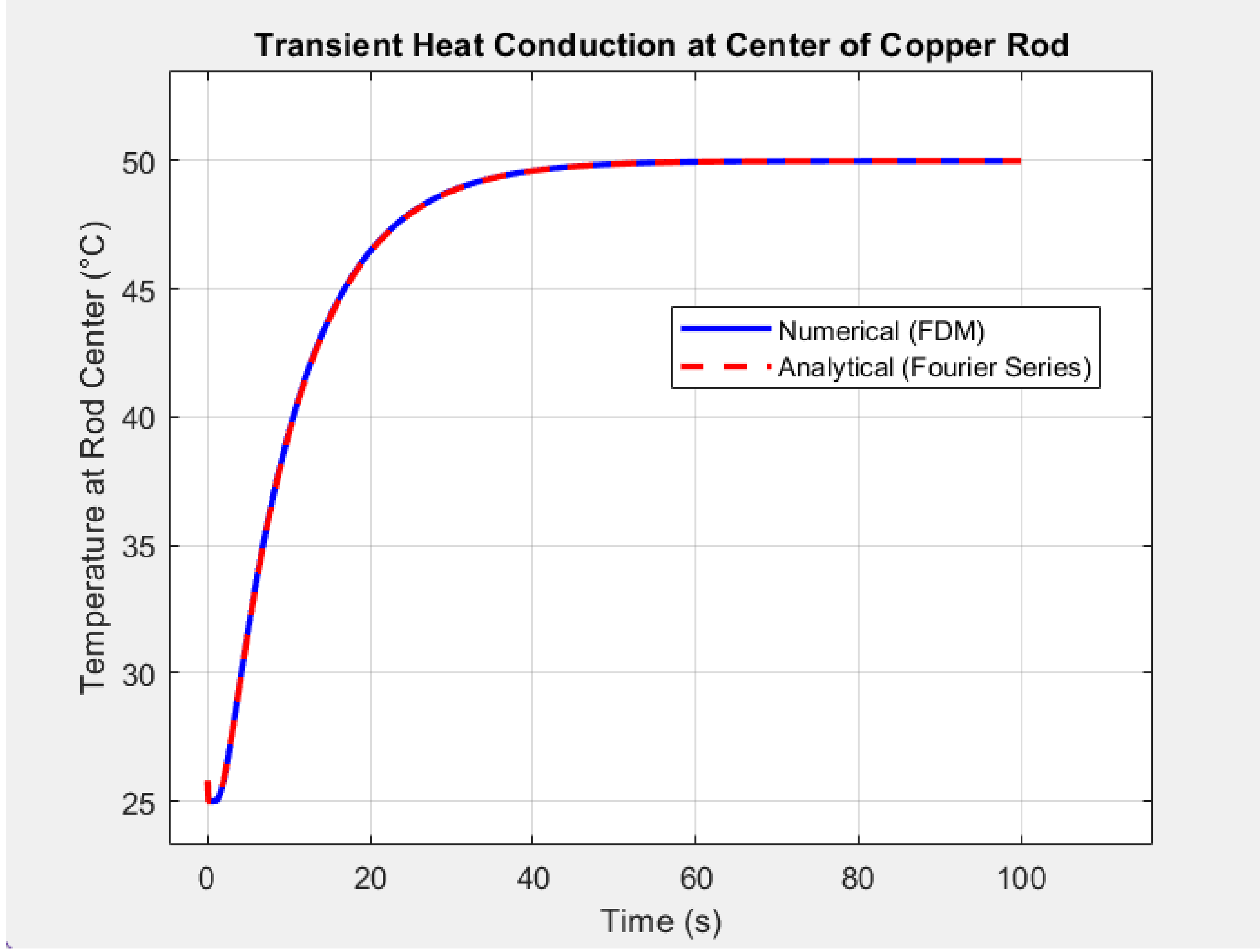
Analytical Solutions

- **Steady-State:**

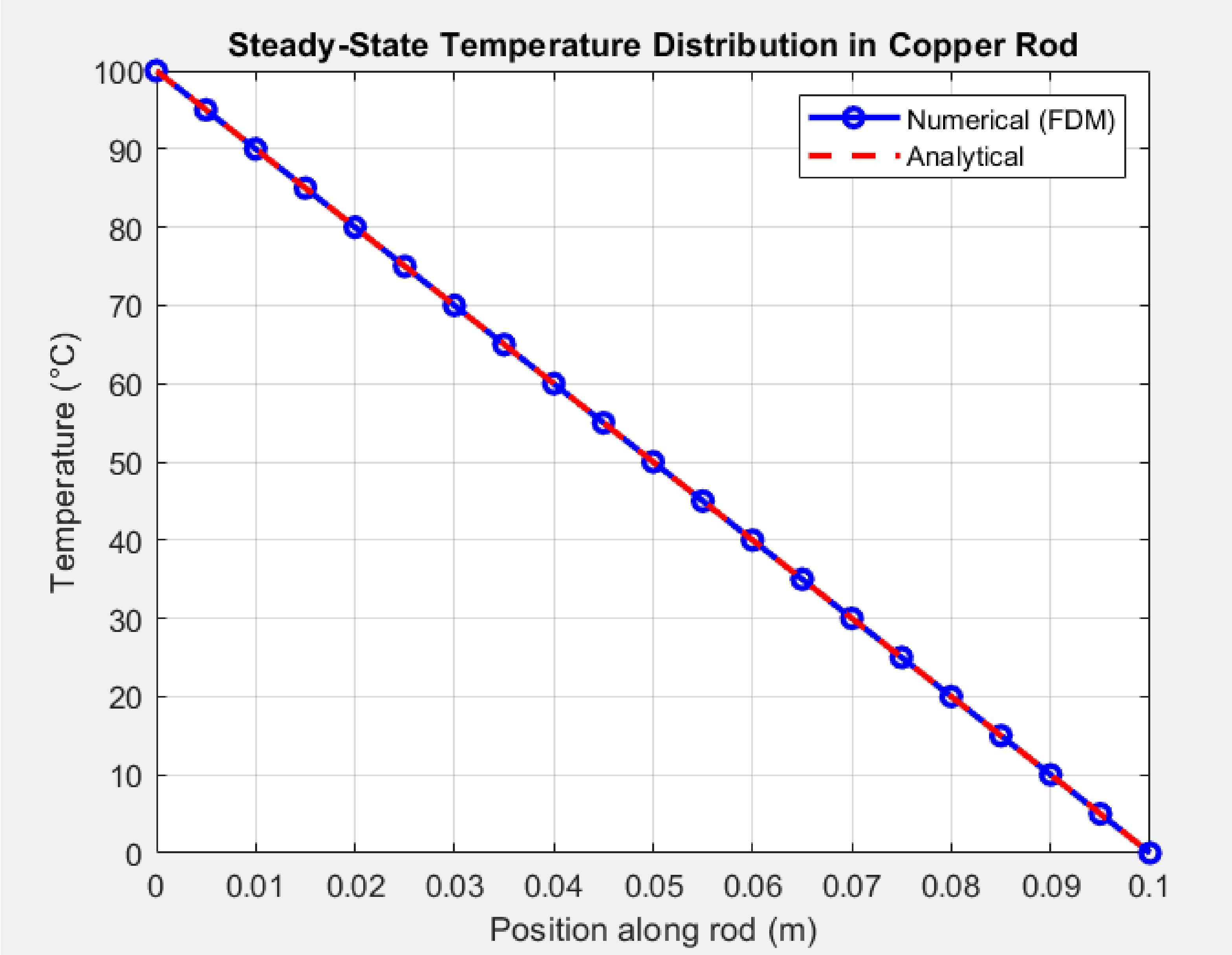
$$T(x) = T_{\text{left}} - (T_{\text{left}} - T_{\text{right}})\frac{x}{L}$$

- **Transient (at point $x = L/2$, Fourier series):**

$$T(x,t) = T_s(x) + \sum_{n=1,3,5,\ldots}^{\infty} \frac{4(T_0 - T_s)}{n\pi}\sin\left(\frac{n\pi x}{L}\right)\exp\left(-\alpha\left(\frac{n\pi}{L}\right)^2 t\right)$$



Transient Heat Conduction at Center of Copper Rod
Temperature at Rod Center (°C)
Time (s)
Numerical (FDM)
Analytical (Fourier Series)
25
30
35
40
45
50
0
20
40
60
80
100



Steady-State Temperature Distribution in Copper Rod
Temperature (°C)
Position along rod (m)
Numerical (FDM)
Analytical
0
10
20
30
40
50
60
70
80
90
100
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

RESULTS

Setup	Heating End	T1 (°C)	T2 (°C)	T3 (°C)	R_{12} (Ω) (exp)	R_{23} (Ω) (exp)	R Total (Exp) (Ω)	R_1 (Ω) (theo)	R_2 (Ω) (theo)	R Total (Theo) (Ω)
Al-Cu	Al	56.3	55.3	51.2	0.30012	1.2305	1.530612	0.50545	0.35675	0.8622
Al-Fe	Al	55.0	52.3	51.8	0.81032	0.15006	0.9604	0.5471	1.662	2.2091
Fe-Cu	Fe	51.8	50.2	48.6	0.4802	0.4802	0.9604	1.3852	0.311825	1.697025

ANALYSIS

There's a noticeable deviation between theoretical and experimental thermal resistances:

Al-Cu Setup: R exp is higher than R th.
Al-Fe & Fe-Cu Setups: R exp is lower than R th.

Possible Reasons:

A) R exp > R th (Al-Cu):

- Heat loss to surroundings (convection, radiation)
- Contact resistance (gaps, oxidation)
- Lateral heat leakage or poor insulation
- Readings taken before true steady state
- Unaccounted drops at interfaces or clamps

ANALYSIS

B) R exp < R th (Al-Fe, Fe-Cu):

- Overestimated length or underestimated area in theory
- Heat bypass through clamps/supports
- Higher actual conductivity (due to material purity or temp effects)
- Overestimated input power (Q)
- Extra conduction from air currents or radiation

Al-Cu

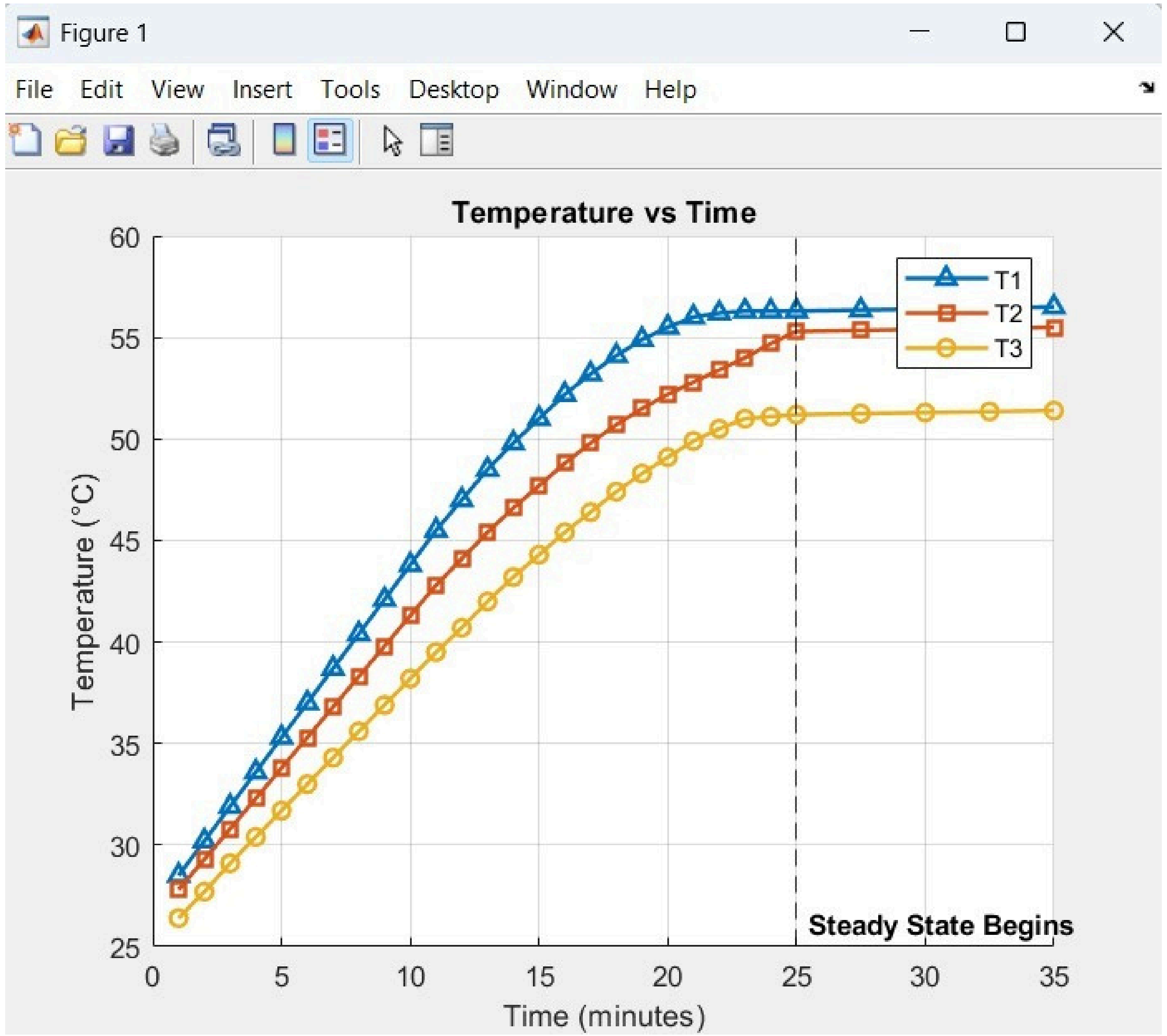


Figure 1
File Edit View Insert Tools Desktop Window Help
Temperature vs Time
T1
T2
T3
Temperature (°C)
Time (minutes)
Steady State Begins
60
55
50
45
40
35
30
25
0
5
10
15
20
25
30
35

Fe-Cu

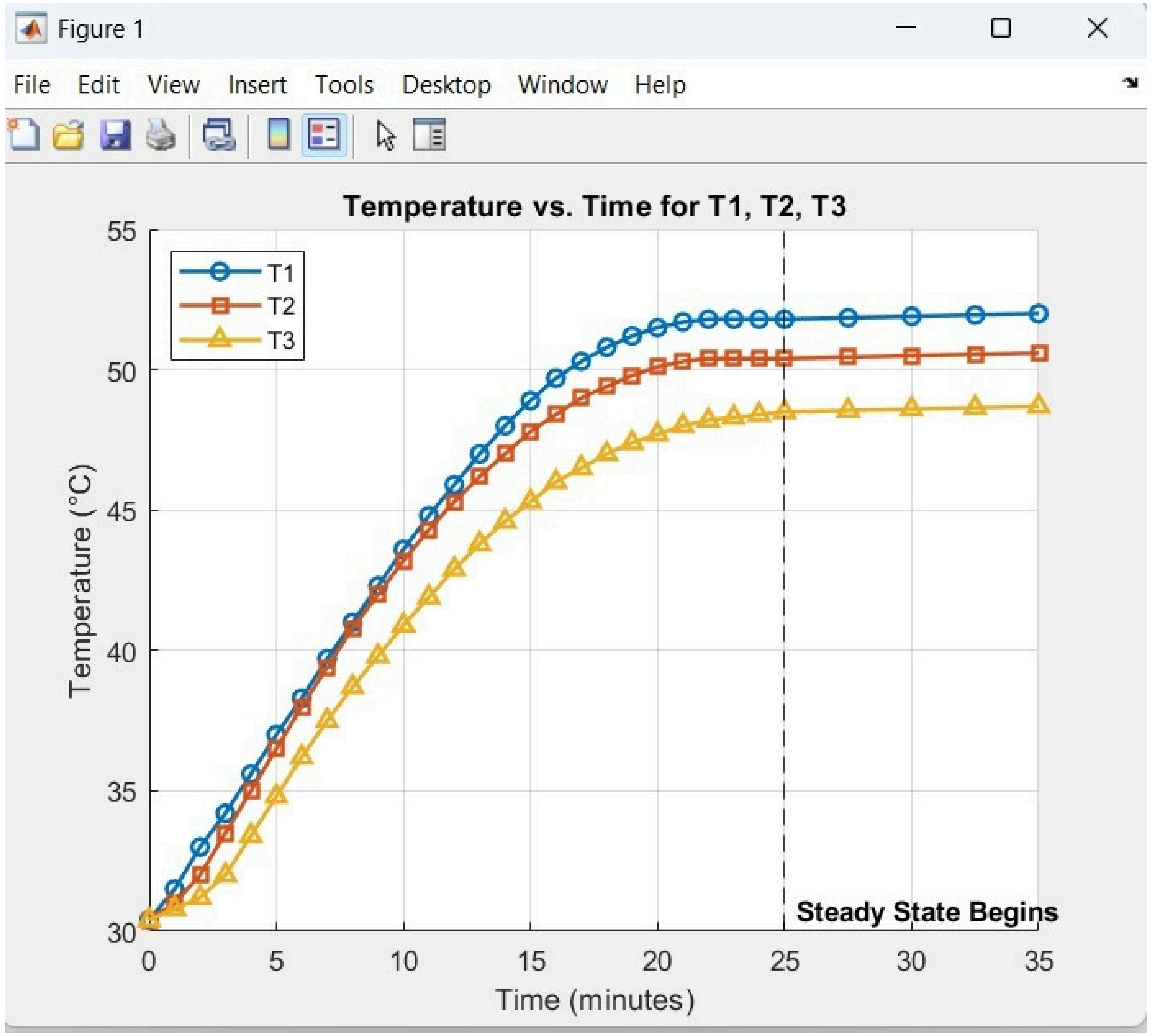
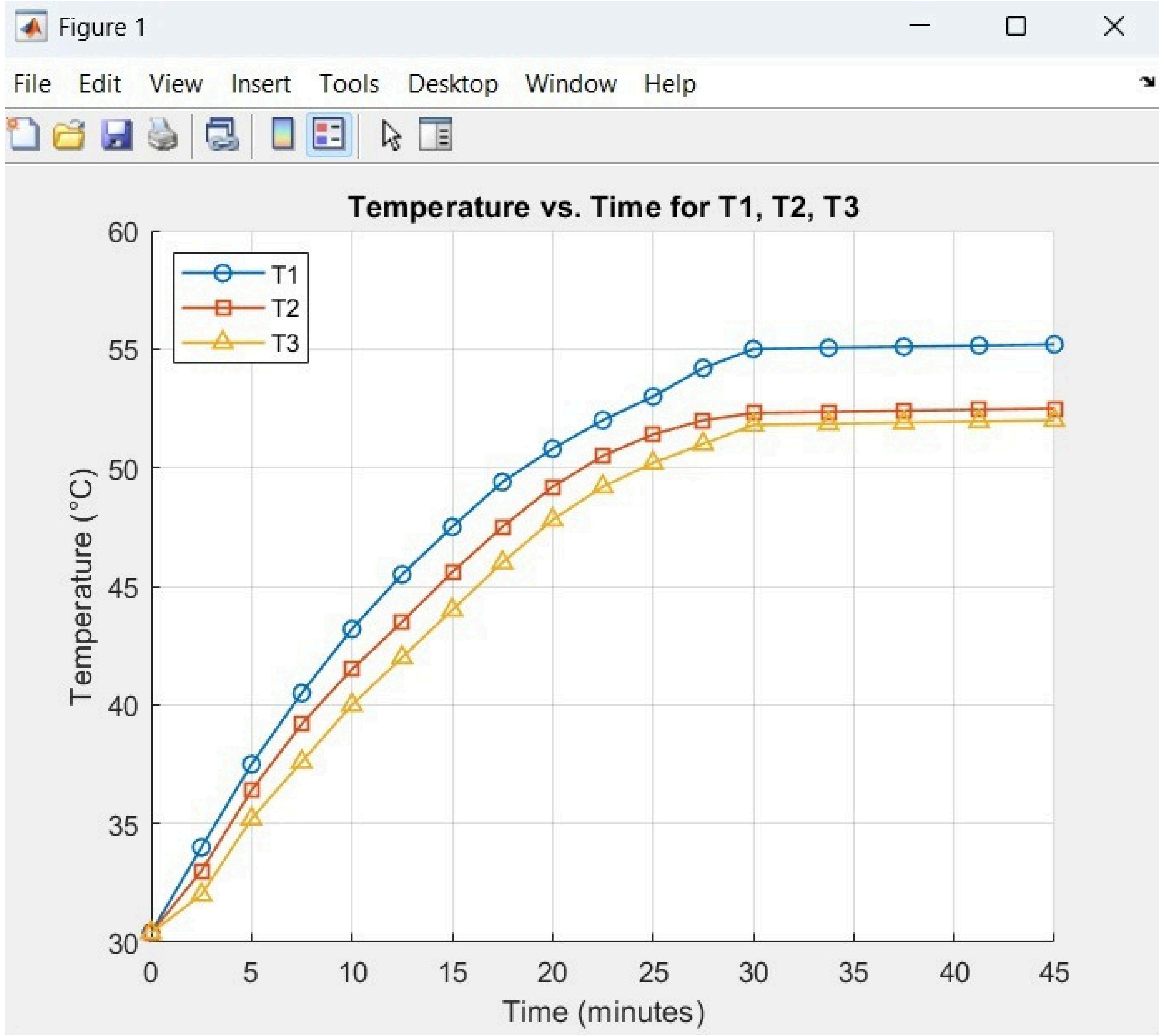


Figure 1
File Edit View Insert Tools Desktop Window Help
Temperature vs. Time for T1, T2, T3
T1
T2
T3
Temperature (°C)
Time (minutes)
Steady State Begins
55
50
45
40
35
30
0
5
10
15
20
25
30
35

Al-Fe



TRANSIENT ANALYSIS

- Al-Cu and Fe-Cu setups reached steady state in ~25 minutes, while Al-Fe took ~30 minutes. All setups followed a similar temperature rise and stabilization, consistent with simulation trends.

Possible reasons:

- Higher conductivity of copper enables faster heat transfer.
- Al-Fe's slower response may be due to aluminum's high specific heat.
- Greater interface resistance in Al-Fe may delay heat flow.

CONCLUSION

- **Theoretical vs Experimental:** Experimental thermal resistance values showed fair agreement with theory, with deviations due to heat loss, contact resistance, and measurement limits.
- **Material Effects:** Copper had the lowest resistance, confirming its high conductivity. Aluminum and iron showed higher resistance when paired.
- **Steady-State Behavior**: All setups exhibited an initial transient rise before stabilizing. Time to steady state matched material thermal properties.

FUTURE WORK

- **Improve Insulation:** Reduce environmental heat loss for better experimental accuracy.
- **Model Contact Resistance**: Include interfacial resistance in theoretical models.
- **Explore Complex Systems:** Test multilayer or non-metallic materials for real-world applications.

THANK YOU