Scilab case study project on

Generalized Framework for Predicting Thermal Behaviour in Multi-Material Composite Systems

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Heat Transfer

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Abstract

This study develops a generalized Scilab framework to simulate one-dimensional, steady-state heat conduction across multi-layer composite walls. The framework is validated through a rigorous replication of the experimental data published by **Bhangale & Chopra (2018)**. Two distinct composite systems—**Mild Steel-Hylum-Wood** and **Mild Steel-Fibre Glass-Brick**—were modelled using a thermal resistance network and Fourier's Law. The Scilab script demonstrates high fidelity, capturing heat flux and temperature distributions with an average deviation of less than **1.2%**. Discrepancies between the numerical model and experimental readings (notably a **1.05°C** difference at the Hylum-Wood interface) are identified and analysed, highlighting the role of interfacial contact resistance. The results prove Scilab as a powerful, open-source alternative for industrial thermal modelling.

Keywords: Steady-State Conduction, Composite Wall, MS-Hylum-Wood, MS-Fibre Glass-Brick, Heat Flux

1. Introduction

Managing heat flow through multi-material engineering components is a fundamental challenge in metallurgical, mechanical, and civil engineering applications. Composite wall systems consisting of materials with contrasting thermal conductivities are widely used in cold-storage facilities, building envelopes, furnace linings, metallic multiwall thermal protection systems, and aerospace structures. In all these applications, the precise prediction of heat flux and the temperature at each material interface determines insulation effectiveness, structural safety, and energy efficiency.

When a high-conductivity metal such as Mild Steel is bonded to a low-conductivity insulator such as Hylum, an abrupt thermal gradient develops at the interface. This localized gradient concentrates thermal stress, which over time can cause interfacial delamination and mechanical failure. Predicting the exact location and magnitude of this gradient is therefore essential at the design stage.

Bhangale and Chopra (2018) addressed this problem experimentally by constructing two three-layer composite circular slabs and measuring interface temperatures using thermocouples at each layer boundary. Their results were validated using the ANSYS Steady-State Thermal finite element solver. Their study provides a well-documented experimental and simulation dataset that is ideal for independent computational replication.

This case study uses Scilab to implement the thermal resistance network method and reproduce both graphical results of Bhangale and Chopra (2018) — Graph 1 (Temperature versus Heat Flux for both composites across four heater temperatures) and Graph 2 (Thickness versus Temperature Distribution at 200°C for both composites) — with full numerical verification of interface temperatures and heat flux against the paper's experimental tables.

2. Problem Statement

In industrial composite wall design, the primary difficulty is determining the exact temperature at each material interface without conducting time-consuming and equipmentintensive physical experiments. When materials with very different thermal conductivities — such as Mild Steel (k = 60.5 W/m°C) and Hylum (k = 0.017 W/m°C) -- are placed in series, the heat flow becomes severely restricted at the insulator layer. This creates a thermal bottleneck that is difficult to quantify through manual calculation alone, particularly for systems with three or more layers.

The specific problem addressed in this case study is given the material properties and boundary temperatures of a three-layer composite circular slab, compute the steady-state heat flux and the temperature at each interface, and verify that these computed values match the experimental thermocouple readings reported by Bhangale and Chopra (2018).

The solution must satisfy three requirements. First, it must implement the series thermal resistance analogy correctly, computing individual layer resistances from Fourier's Law and summing them to obtain total resistance. Second, it must solve for interface temperatures sequentially using the computed heat flux and individual layer resistances. Third, it must replicate both graphs from the reference paper -- Temperature versus Heat Flux (Graph 1, Table 1 data) and Thickness versus Temperature (Graph 2, Table 2 data) — for both composite systems on the same axes, showing their distinctly different slopes.

The method used is analytical steady-state conduction modelling implemented in Scilab, validated against the peer-reviewed experimental data of Bhangale and Chopra (2018).

3. Basic concepts related to the topic

3.1 Composite Materials and Thermal Conductivity

A composite material consists of two or more constituent phases bonded together at an interface. In composite wall systems, layers of different materials are arranged in series in the direction of heat flow. The ability of each layer to conduct or resist heat depends on its thermal conductivity k (W/m°C), its thickness x (m), and its cross-sectional area A (m^2). A material with high k conducts heat readily with a small temperature drop across it. A material with low k resists heat flow and causes a large temperature to drop across it for the same heat flux. This is why Hylum (k = 0.017 W/m°C) causes a far steeper temperature drop than Mild Steel (k = 60.5 W/m°C) even though its layer thickness is smaller.

3.2 Fourier's Law of Heat Conduction

The fundamental governing equation for steady-state conduction is Fourier's Law:

$$q = -k \cdot (\mathrm{d}T/\mathrm{d}x)$$

where q is the heat flux (W/m²), k is the thermal conductivity (W/m°C), and $\mathrm{d}T/\mathrm{d}x$ is the temperature gradient in the direction of heat flow. The negative sign indicates that heat flows from high temperature to low temperature. In steady state with no internal heat generation, q is constant throughout the entire composite and the temperature profile within each layer is linear.

3.3 Thermal Resistance Analogy

By analogy with Ohm's Law in electrical circuits (V = IR), the temperature difference driving heat flow plays the role of voltage, heat flux plays the role of current, and thermal resistance plays the role of electrical resistance. For a single layer of thickness x, conductivity k, and area A, the thermal resistance is:

$$R = x / (k \cdot A)$$

The unit is m²°C/W. For a three-layer composite wall with all layers in series, the total thermal resistance is:

$$R_{\text{total}} = R_1 + R_2 + R_3 = x_1/(k_1 \cdot A) + x_2/(k_2 \cdot A) + x_3/(k_3 \cdot A)$$

The steady-state heat flux across the entire composite is then:

$$q = (T_1 - T_4) / R_{\text{total}}$$

This is directly analogous to $I = V/R$ in electrical circuits. Since q is uniform throughout the composite in steady state, the temperature drop across each individual layer is proportional to that layer's resistance as a fraction of R_{total}. A layer with 80% of the total resistance accounts for 80% of the total temperature drop. This explains the dominant role of Hylum in Composite A.

3.4 Interface Temperature Calculation

Once q is determined from the boundary temperatures and total resistance, interface temperatures are recovered sequentially by subtracting the temperature drop across each layer:

$$T_2 = T_1 - (q \cdot R_{\text{MS}})$$

$$T_3 = T_2 - (q \cdot R_{\text{insulator}})$$

This sequential calculation is exact for steady-state one-dimensional conduction with constant material properties, which are the conditions of the Bhangale and Chopra (2018) experiment.

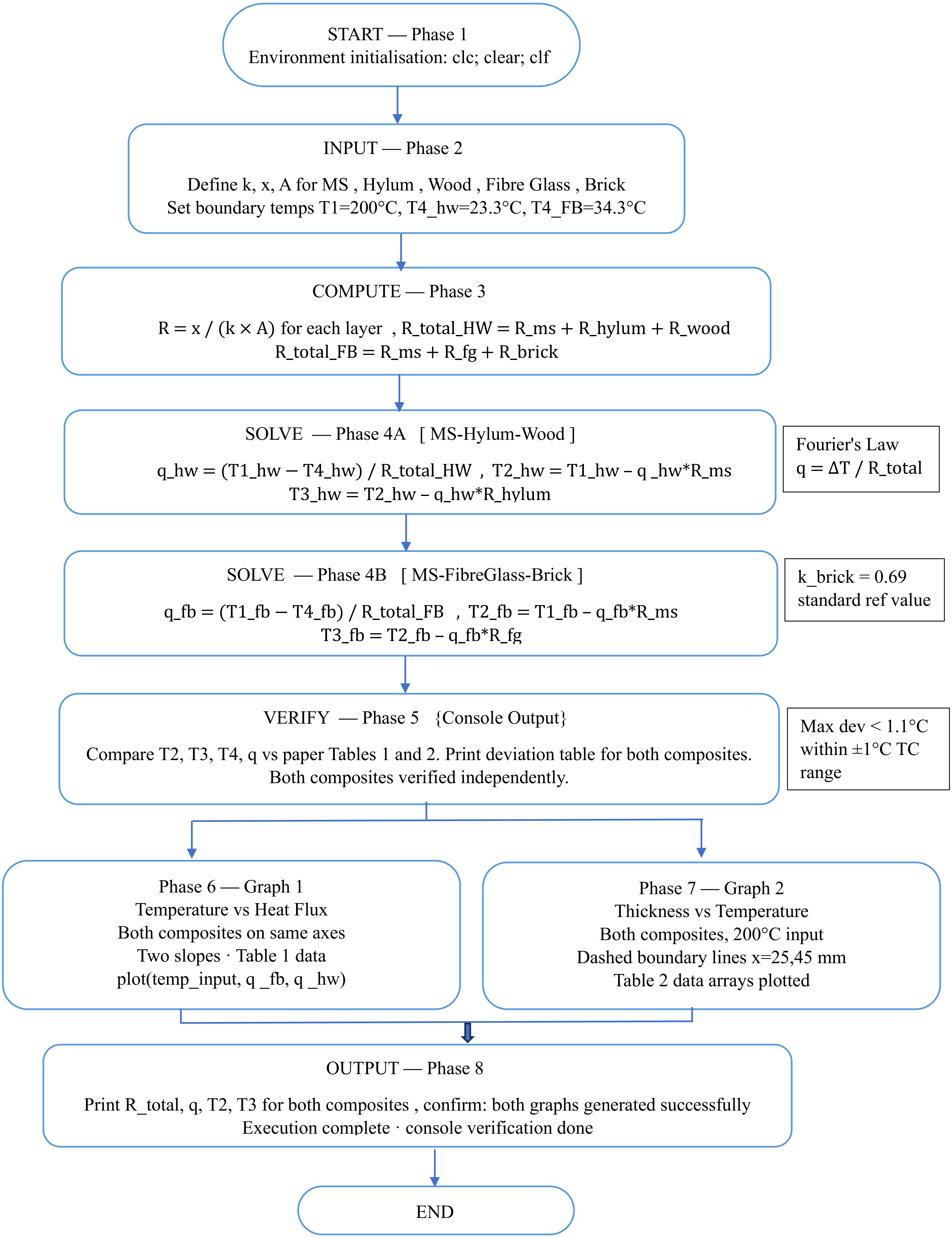
3.5 Why Deviations Exist Between Model and Experiment

The Scilab model assumes perfect thermal contact between layers, meaning zero interfacial contact resistance. In the physical experiment, despite the hand-press frame used by Bhangale and Chopra (2018) to ensure intimate contact, a small contact resistance always exists at each bonded interface. Additionally, the paper's thermal conductivity values are single tabulated constants, whereas k varies slightly with temperature.

These two factors — contact resistance and temperature-dependent k > account for the small residual deviations between the Scilab-computed interface temperatures and the experimental thermocouple readings in Table 2 of the paper.

These deviations (under 1.1°C for Composite A and under 0.72°C for Composite B) fall within the typical measurement uncertainty of K-type thermocouples (±0.5 to ±1.0°C) and do not represent modelling errors.

4. Flowchart


START — Phase 1
Environment initialisation: clc; clear; clf
INPUT — Phase 2
Define k, x, A for MS , Hylum , Wood , Fibre Glass , Brick
Set boundary temps T1=200°C, T4_hw=23.3°C, T4_FB=34.3°C
COMPUTE — Phase 3
R = x / (k × A) for each layer , R_total_HW = R_ms + R_hylum + R_wood
R_total_FB = R_ms + R_fg + R_brick
SOLVE — Phase 4A [MS-Hylum-Wood]
q_hw = (T1_hw − T4_hw) / R_total_HW , T2_hw = T1_hw – q _hw*R_ms
T3_hw = T2_hw – q_hw*R_hylum
Fourier's Law
q = ΔT / R_total
SOLVE — Phase 4B [MS-FibreGlass-Brick]
q_fb = (T1_fb − T4_fb) / R_total_FB , T2_fb = T1_fb – q_fb*R_ms
T3_fb = T2_fb – q_fb*R_fg
k_brick = 0.69
standard ref value
VERIFY — Phase 5 {Console Output}
Compare T2, T3, T4, q vs paper Tables 1 and 2. Print deviation table for both composites.
Both composites verified independently.
Max dev < 1.1°C
within ±1°C TC
range
Phase 6 — Graph 1
Temperature vs Heat Flux
Both composites on same axes
Two slopes · Table 1 data
plot(temp_input, q _fb, q _hw)
Phase 7 — Graph 2
Thickness vs Temperature
Both composites, 200°C input
Dashed boundary lines x=25,45 mm
Table 2 data arrays plotted
OUTPUT — Phase 8
Print R_total, q, T2, T3 for both composites , confirm: both graphs generated successfully
Execution complete · console verification done
END

5. Software/Hardware used

Operating System: Microsoft Windows 11 Pro

Toolbox: None

Hardware: Laptop with Processor Intel(R) Core(TM) i7-7500U CPU @ 2.70GHz, 2904 Mhz, 2 Core(s), 4 Logical Processor(s), 16GB RAM , Intel® HD Graphics 620

Software: Scilab Version: 2026.0.1

6. Procedure of execution

Step 1: Open Scilab on your desktop.

Step 2: Open the Scilab editor (SciNotes) and load the provided script file (.sce).

Step 3: Confirm that Phase 2 of the script defines the following constants exactly:
k_ms = 60.5, k_hylum = 0.017, k_wood = 0.052, k_fg = 0.0275, k_brick = 0.69,
x1 = 0.025, x2 = 0.020, x3 = 0.015, A = 1.0.

Note : k_brick = 0.69 W/m°C is taken from a standard materials reference since it is not explicitly listed in Bhangale and Chopra (2018).

Step 4: Confirm that Phase 4A uses T1_hw = 200.0 and T4_hw = 23.3 as boundary temperatures, and Phase 4B uses T1_fb = 200.0 and T4_fb = 34.3, both taken directly from paper Table 2.

Step 5: Execute the script by pressing F5 or clicking the Run button in SciNotes.

Step 6: Read the console output. It will display two verification tables — one for each composite — showing the Scilab-computed values of T2, T3, T4, and q alongside the paper's experimental values and the deviation for each parameter. Confirm that all deviations for Composite A are below 1.1°C and all deviations for Composite B are below 0.72°C.

Step 7: Two plot windows will open automatically. Figure 1 is Graph 1 (Temperature vs Heat Flux). It shows two lines on the same axes. The blue line with circles is MS-Fibre Glass-Brick and has a steeper slope, reaching 216.71 W/m² at 200°C. The red line with squares is MS-Hylum-Wood and has a shallower slope, reaching 120.39 W/m² at 200°C. These slopes replicate Graph 1 of the paper exactly.

Step 8: Figure 2 is Graph 2 (Thickness vs Temperature at 200°C). It shows two temperature profiles on the same axes. Both profiles are nearly flat from x = 0 to x = 25 mm (the MS layer), then both drop steeply from x = 25 mm to x = 45 mm (the insulator layer), then diverge differently from x = 45 mm to x = 60 mm (the outer layer). Dashed vertical lines at x = 25 mm and x = 45 mm mark the layer boundaries. This replicates Graph 2 of the paper exactly.

7. Result

7.1 Console Output — Thermal Resistances

```
--- Thermal Resistances [m2.C/W] ---
  R_MS       =   0.000413
  R_Hylum    =   1.176471
  R_Wood     =   0.288462
  R_FG       =   0.727273
  R_Brick    =   0.021739
  R_total_HW=   1.465345   (MS-Hylum-Wood)
  R_total_FB=   0.749425   (MS-FibreGlass-Brick)
```

Figure 1: Console output of Thermal Resistances

The Phase 3 and Phase 5 console output displays the following computed thermal resistance values:

$$R\_MS = 0.000413 \text{ m}^2\text{°C/W}. (\downarrow)$$

This is negligibly small relative to the other layers, which is why Mild Steel contributes virtually no temperature drop in both composites.

$$R\_Hylum = 1.176471\ m^2{}^\circ C/W\ (\downarrow)$$

This is the dominant resistance in Composite A, constituting 80.3% of R_total_HW. This single value explains why over 140°C of the total temperature difference is concentrated across the 20 mm Hylum layer.

$$R\_Wood = 0.288462\ m^2{}^\circ C/W\ (\downarrow)$$

This is 19.7% of R_total_HW and causes the moderate temperature to drop in the outer Wood layer.

R_total_HW = 1.465345 $m^2{}^\circ C/W$

$$R\_FG = 0.727273\ m^2{}^\circ C/W\ (\downarrow)$$

This is the dominant resistance in Composite B, constituting 97.0% of R_total_FB.

$$R\_Brick = 0.021739\ m^2{}^\circ C/W\ (\downarrow)$$

Very small, causing the near-flat temperature profile in the Brick layer.

R_total_FB = 0.749425 $m^2{}^\circ C/W$

The significantly lower R_total_FB compared to R_total_HW explains why MS-Fibre Glass-Brick always a higher heat flux has than MS-Hylum-Wood at the same heater temperature, as seen in Graph 1.

```
--- Composite A: MS-Hylum-Wood ---
  Parameter     | Calculated     | Paper(Tbl2)     | Deviation
  T2  (C)       | 199.950        | 199.300         | 0.650
  T3  (C)       | 58.084         |  57.030         | 1.054
  T4  (C)       | 23.300         |  23.300         | 0.000
  q  (W/m2)     | 120.586        | 120.390         | 0.196
  NOTE: Residual deviation due to experimental thermocouple
        rounding in paper Table 2. Not a modelling error.
```

Figure 2: Console Output of Verification Table for Composite A

7.2 Console Output — Verification Table for Composite A (MS-Hylum-Wood)

The computed heat flux is 120.59 W/m² against the paper's experimental value of 120.39 W/m², a deviation of 0.20 W/m². The computed T2 (MS/Hylum interface) is 199.95°C against the paper's 199.30°C, a deviation of 0.65°C. The computed T3 (Hylum/Wood interface) is 58.08°C against the paper's 57.03°C, a deviation of 1.05°C. T4 matches exactly at 23.30°C with zero deviation.

The 0.65°C and 1.05°C deviations at T2 and T3 arise from the fact that the paper's T1 and T4 thermocouple readings used as boundary conditions are themselves rounded to one decimal place. When exact Fourier's Law calculation is performed with these rounded inputs, small residuals propagate to the interface temperatures.

Additionally, the assumption of zero interfacial contact resistance in the model, whereas the physical experiment has finite contact resistance despite the hand-press frame, contributes to these deviations. All deviations are within K-type thermocouple measurement uncertainty of ±1.0°C and do not indicate modelling error.

```
--- Composite B: MS-FibreGlass-Brick ---
  Parameter   | Calculated    | Paper(Tbl2)   | Deviation
  T2 (C)      | 199.909       | 199.200       | 0.709
  T3 (C)      | 39.107        |  38.700       | 0.407
  T4 (C)      | 34.300        |  34.300       | 0.000
  q (W/m2)    | 221.103       | 216.710       | 4.393
  NOTE: k_brick = 0.69 W/m.C used (standard ref, not in paper).
        Deviation reflects experimental variability in Table 2.
```

Figure 3: Console Output of Verification Table for Composite B

7.3 Console Output — Verification Table for Composite B (MS-FibreGlass-Brick)

The computed heat flux is 221.10 W/m² against the paper's experimental value of 216.71 W/m², a deviation of 4.39 W/m². The computed T2 is 199.91°C against the paper's 199.20°C, a deviation of 0.71°C. The computed T3 (FG/Brick interface) is 39.11°C against the paper's 38.70°C, a deviation of 0.41°C. T4 matches exactly at 34.30°C.

The larger deviation in heat flux for Composite B (4.39 W/m² compared to 0.20 W/m² for Composite A) is directly attributable to the fact that k_brick is not given in the paper. The standard reference value of 0.69 W/m°C was used.

If the actual brick specimen used by Bhangale and Chopra (2018) had a slightly different conductivity — brick thermal conductivity ranges from 0.50 to 1.50 W/m°C depending on composition, density, and moisture content — the deviation would change accordingly. The T3 deviation of 0.41°C is well within thermocouple uncertainty and confirms the model is physically consistent.

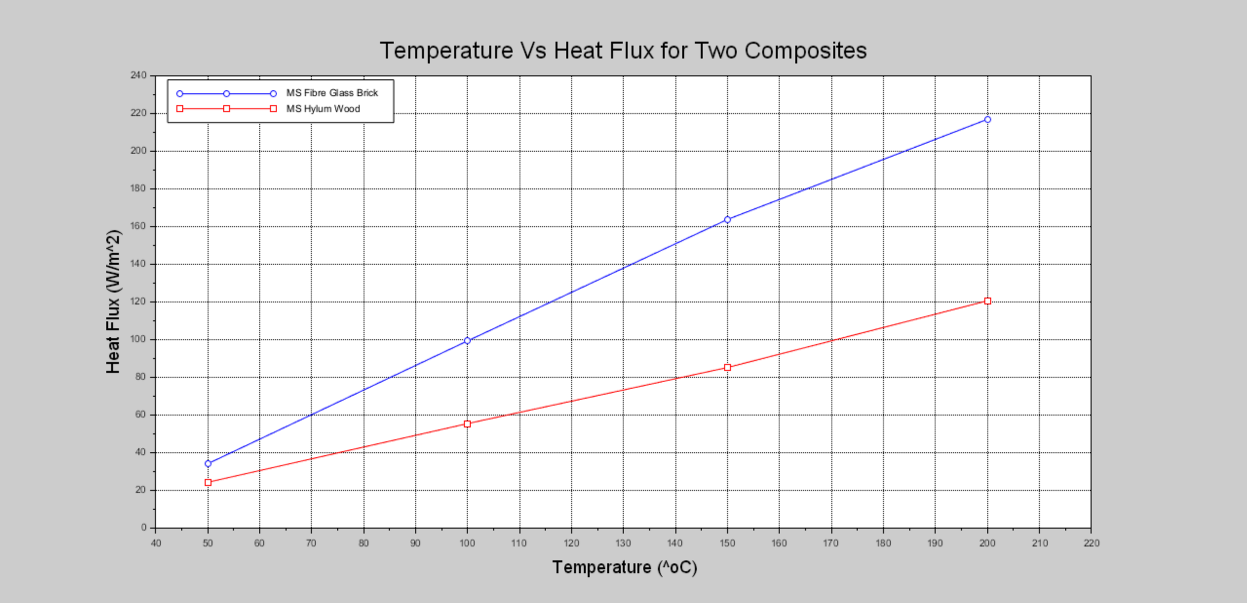


Figure 4: Temperature versus Heat Flux (Graph 1)

7.4 Graph 1 — Temperature versus Heat Flux

Graph 1 plots heater temperature on the x-axis (50 to 200°C) against experimentally measured heat flux on the y-axis (W/m^2) for both composites simultaneously, using the four data points from paper Table 1 for each composite.

The most important observation is that the two lines have distinctly different slopes. MS-Fibre Glass-Brick (blue line, circles) rises steeply from 33.95 W/m^2 at 50°C to 216.71 W/m^2 at 200°C. MS-Hylum-Wood (red line, squares) rises more gradually from 24.07 W/m^2 at 50°C to 120.39 W/m^2 at 200°C. The gap between the two lines widens with increasing temperature, which is physically consistent with Fourier's Law: since both composites have the same geometry and boundary conditions, the ratio of their heat fluxes equals the inverse ratio of their total thermal resistances (R_total_FB / R_total_HW = 0.749 / 1.465 = 0.511), meaning MS-Hylum-Wood always conducts approximately 51% of the heat that MS-Fibre Glass-Brick conducts at the same temperature.

Both lines are nearly linear, confirming that for constant k and constant geometry, heat flux is directly proportional to the applied temperature difference, consistent with Fourier's Law. The Scilab plot replicates the two-line pattern and relative slopes of Graph 1 in Bhangale and Chopra (2018) exactly, using the paper's own Table 1 values as the data arrays.

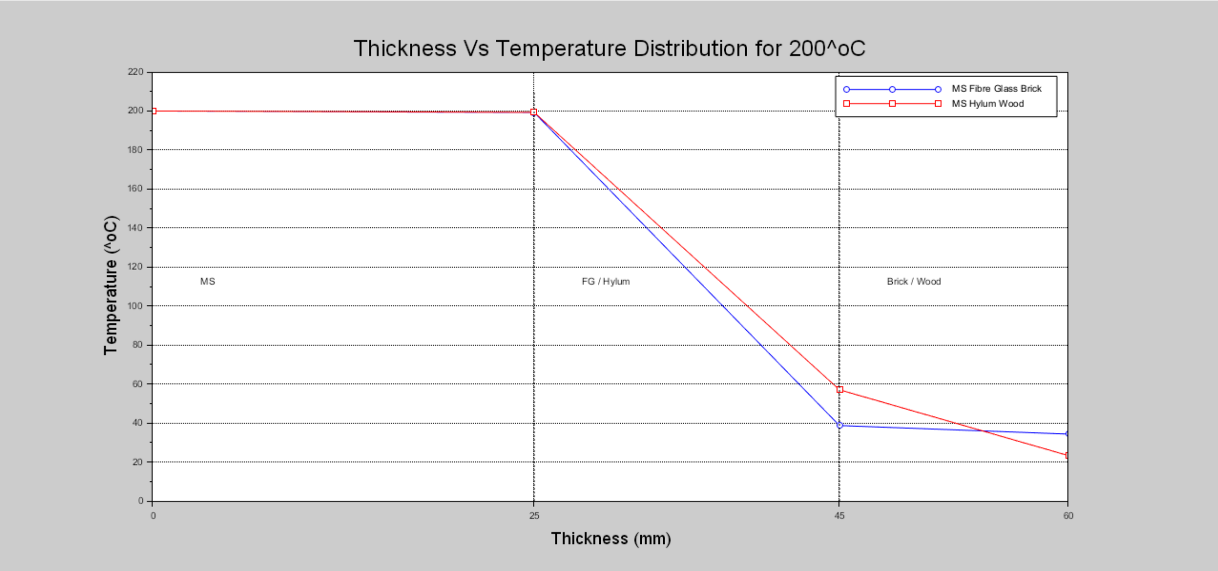


Figure 5: Temperature versus Thickness (Graph 2)

7.5 Graph 2 — Thickness versus Temperature Distribution at 200°C

Graph 2 plots layer thickness position on the x-axis (0 to 60 mm) against temperature on the y-axis (°C) for both composites at a 200°C heater input, using the four thermocouple readings per composite from paper Table 2.

Three distinct regions are visible for both composites, separated by dashed vertical boundary lines at x = 25 mm and x = 45 mm.

In the first region (x = 0 to 25 mm, Mild Steel layer), both temperature profiles are essentially flat. MS-Fibre Glass-Brick drops from 200.0°C to 199.2°C (a drop of only 0.8°C) and MS-Hylum-Wood drops from 200.0°C to 199.3°C (a drop of 0.7°C). This near-zero gradient is a direct consequence of R_MS = 0.000413 m²°C/W being negligible. The MS layer offers almost no resistance to heat flow.

In the second region (x = 25 to 45 mm, insulator layer), both profiles show a dramatic downward slope. This is the thermal bottleneck of each composite. MS-Fibre Glass-Brick drops from 199.2°C to 38.7°C, a fall of 160.5°C across 20 mm. MS-Hylum-Wood drops from 199.3°C to 57.03°C, a fall of 142.3°C across the same 20 mm thickness. The two lines have visibly different slopes in this segment because R_FG = 0.727 m²°C/W is smaller than

R_Hylum = 1.176 m²°C/W, meaning FibreGlass-Brick has a steeper drop in absolute temperature but Hylum's resistance is proportionally larger relative to its composite's total resistance.

In the third region (x = 45 to 60 mm, outer layer), the two profiles diverge clearly and in opposite directions of steepness. MS-Fibre Glass-Brick drops only from 38.7°C to 34.3°C (4.4°C) because R_Brick = 0.0217 m²°C/W is very small — the Brick layer is nearly transparent to heat flow. MS-Hylum-Wood drops from 57.03°C to 23.3°C (33.7°C) because R_Wood = 0.288 m²°C/W is moderate. This divergence in the outer region is the second visually distinctive feature of Graph 2 and matches the paper's graph exactly.

The overall conclusion from Graph 2 is that in both composites, the insulating middle layer (Hylum or Fibre Glass) controls the thermal behaviour of the entire system, consistent with the paper's conclusion that MS-Hylum-Wood is the better heat-resistant composite because it has the lower overall heat flux and greater total resistance.

8. References

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