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Comparative Simulation Studies on Fabrication of Thermos Flask Using Glass Fibre Reinforced Plastics and Stainless Steel

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Abstract: This paper investigates the fabrication of a thermos flask using reinforced plastic, with a focus on incorporating glass fiber reinforcement. The primary objective is to explore the feasibility of glass fiber as an alternative to traditional stainless steel in thermos flask construction, particularly in terms of heat retention and overall performance. A series of experiments and comparative analyses were conducted to evaluate the material's effectiveness. The findings reveal that while glass fiber-reinforced plastic offers advantages like reduced weight and increased flexibility, it does not surpass stainless steel in thermal insulation or durability. Despite these benefits, its lower performance in retaining heat limits its potential as a replacement for stainless steel in thermos flasks. Consequently, this study recommends further research into other reinforced plastics with better thermal insulation properties or enhancing glass fiber composites to improve their heat retention capabilities. The project underscores the need for continued innovation in material science to create more efficient, sustainable, and lightweight alternatives for thermal insulation applications, contributing to advancements in the design of thermos flasks and similar products.

Keywords: Thermos Flask; Reinforced Plastic; Glass Fibre; Heat Retention; Thermal Insulation; Material Science; Stainless Steel Alternatives; Composite Materials; Polypropylene Reinforced Plastic.

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1. Introduction

The concept of a thermally insulated container dates back to antiquity, with early examples found in civilizations like the Han Dynasty in China; however, the story of the thermos flask begins with Scottish physicist and chemist Sir James Dewar in 1892. While researching cryogenics, he aimed to keep liquefied gases at extremely low temperatures for extended periods. This led him to create a double-walled glass container with a vacuum between the layers, effectively minimizing heat transfer. This invention, known as the "Dewar flask", became a cornerstone of cryogenics research [1]. While Dewar focused on the flask's scientific applications, his invention's commercial potential did not go unnoticed. In 1904, two German glassblowers, Reinhold

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Burger and Albert Aschenbrenner, recognized the flask's ability to keep hot and cold contents at their desired temperatures. They modified Dewar's design, making it more robust and practical for everyday use. They named the product "Thermos", after the Greek word for "heat", and secured the trademark, inadvertently overshadowing Dewar's original contribution [2].

The core principle of the thermos flask relies on thermal insulation. Thermal insulation refers to the ability of a material or system to resist heat transfer [15]. Heat transfer occurs through three primary mechanisms: conduction, convection, and radiation. Conduction occurs when heat flows directly through a material due to molecular contact and collisions; convection occurs through the movement of fluids (liquids or gases) due to temperature differences, and radiation occurs through electromagnetic waves emitted by all objects with a temperature above absolute zero [3]-[4]. Thermal insulation is crucial in various fields, from maintaining comfortable temperatures in buildings to preserving contents like foods, beverages, etc., in thermos flasks [16]. The thermos flask incorporates some design mechanisms to help ensure little to no heat transfer to keep its contents' temperature [17].

A double-walled construction with a vacuum separating the inner and outer walls minimizes heat transfer through conduction. The Vacuum acts as a near-perfect insulator, significantly reducing the convective heat flow between the contents and the surrounding environment [18]. The inner wall is often coated with silver or other reflective materials to minimize radiative heat transfer between the contents and the outer wall. Thermal insulating materials are also used as air-tight stoppers and sealing mechanisms to limit conductive heat transfer through physical contact [5]. These combined factors help to render the thermos flask effective in maintaining temperature [19]. Early thermos flasks, primarily made of glass, faced challenges with fragility and weight. Innovation spurred using stainless steel, offering durability and improved insulation performance [6]. The development of double-walled stainless steel with a vacuum between them became the industry standard, offering superior heat retention and portability [8]. Typically, vacuum flasks are made of metal, borosilicate glass, or stainless steel. Cork or polyethene plastic is used to plug the entrance to maintain the temperature of the contents in the thermos flasks [9].

The search for more durable and lightweight materials has led to alternatives like reinforced plastics. Although the glass has been effective for thermos flasks, they are quite fragile and prone to breakage. Reinforced plastics have quite some advantages over glass in developing thermos flasks [7]. The reinforced plastic is significantly lighter than glass, making the flask more portable and user-friendly for outdoor activities and travel; reinforced plastics also offer improved impact resistance, reducing the risk of breakage [10]. Versatility and flexibility of designs, shapes, and sizes are also a plus in incorporating reinforced plastics into developing flasks. Depending on the specific materials and manufacturing process, the reinforced plastic has better insulation properties and is more cost-effective than the glass thermos flask [11].

Reinforced plastics are plastics whose characteristics have been enhanced by adding other materials [20]. Depending on the materials added and the manufacturing process, they can be sturdier, stronger, lighter, and more heat resistant [12]. There are many kinds and examples of reinforced plastics; thus, this calls for adopting good working knowledge of material selection [21]. A good designer should ensure careful selection of the reinforced plastic to adopt for any product; the thermos flask is no exception [13]. For the thermos flask, choosing a reinforced plastic material with high leak resistance, little to no odour/taste, and eco-friendly could help mitigate the negatives while still delivering better performance. This project aims to develop an efficient thermos flask using reinforced plastics 21]. The scope of the project covers the improvement of the glass and stainless-steel thermos flask with the adoption of reinforced plastics by carrying out a design analysis on several reinforced plastics and selecting the most effective one while running a 3-D simulation for the optimization and development of an efficient thermos flask in terms of heat insulation, durability, and sustainability [22]. The project entails the development of a functional thermos flask using reinforced plastic as the primary material, aiming for comparable or superior thermal insulation performance and durability compared to traditional glass and stainless-steel thermos flasks [23].

2. Materials and Methods

2.1. Conceptual Design of the Thermos Flask

The conceptual design of a thermos flask centers around creating a near-vacuum insulation layer between the inner and outer containers (flask walls) [24]. The thermos flask's design cleverly addresses all three heat transfer mechanisms. Combining a vacuum insulation layer, strategic material selection, and a well-designed stopper significantly reduces heat transfer, allowing thermos flasks to maintain temperatures for an extended duration (Figure 1) [25].

Figure 1: Exploded View of Thermos Flask Design

2.2. Heat Insulation Design

The rate of heat conduction through the cylindrical layer can be represented as [14] using Fourier's law of heat conduction:

$$Q_{\text{conduction,cylinder}} = -kA\frac{dt}{dr} \text{ in W} \tag{1}$$

Where:

$A = 2\pi rL$ is the heat transfer area at location r.

Because A is r-dependent, it changes depending on the direction of heat transmission. Dividing the aforementioned equation's variables and integrating from $r = r_1$, where $T(r_1) = T_1$, to $r = r_2$, where $T(r2) = T_2$, gives:

$$\int_{r_1}^{r_2} \frac{Q_{\text{conduct,cyl}}}{A}\, dr = -\int_{T_1}^{T_2} k dt \tag{2}$$

Substituting $A = 2\pi rL$ in equation (2) and performing integration we get;

$$Q_{\text{conduct,cyl}} = \frac{T_1 - T_2}{R_{\text{total}}} \tag{3}$$

Where $R_{\text{total}} = R_{\text{cylinder surface}} + R_{\text{cylinder base}}$ (4)

Where, $R_{\text{cylinder surface}} = \frac{In(\frac{r2}{r1})}{2\pi rl}$ equals the conduction resistance, which measures the thermal resistance of a cylindrical layer to heat conduction.

For heat transfer through the three-layered composite cylinders (i.e., bottle) subjected to convection on both sides, the thermal resistance network is given as:

$$R_{\text{Cyl.Surface Total}} = R_{\text{conv},1} + R_{\text{cyl},1} + R_{\text{cyl},2} + R_{\text{cyl},3} + R_{\text{conv},2} \tag{5}$$

$$R_{\text{Cyl.Surface Total}} = \frac{1}{h_1 A_1} + \frac{In(r_2/r_1)}{2\pi Lk_1} + \frac{In(r_3/r_2)}{2\pi Lk_2} + \frac{In(r_4/r_3)}{2\pi Lk_3} + \frac{1}{h_2 A_4}$$

The entire resistance to heat flow, including water convective heat transfer, the curved surface conduction resistance, and the surrounding air convective heat transfer, is represented by Equation (5) [26]. Equation (5) can be used to find the values of heat transfer via the curved surface by substituting the values of the variables [27].

From equation (2), $R_{\text{cylinder base}} = \frac{L}{kA}$; is the thermal resistance of the wall against heat conduction. Keep in mind that the geometry and thermal characteristics of the medium determine its thermal resistance [28]. An example of a three-layered composite cylinder subjected to convection on both sides is shown by the following thermal resistance network:

$$R_{Cyl.Base\ Total} = R_{conv1} + R_{b1} + R_{b2} + R_{b3} + R_{conv2} \quad (6)$$

$$R_{Cyl.Base\ Total} = \frac{1}{h_1 A} + \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k3A} + \frac{1}{h_2 A} \quad (7)$$

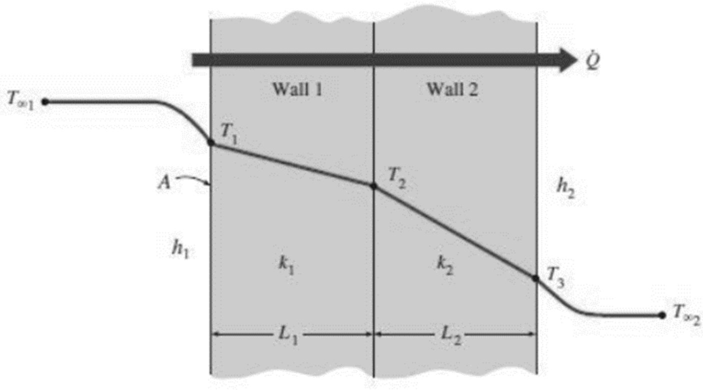


Figure 2: Concept behind the bottle base: inner bottle, vacuum, outer bottle

The overall barrier to heat flow, as shown in Equation (7), is the sum of the three separate processes: water convective heat transfer, curved surface conduction resistance, and surrounding air convective heat transfer (Figure 2) [29].

Where A = area of base & L_1, L_2, L_3 are the vacuum's thickness, the outer bottle's thickness, and the inner bottle's thickness, respectively. Finding the values of thermal resistance [30] is the next step after replacing the values of the variables in equation (6).

Thus, replacing the values of resistance yields R_{total} and after that $Q_{conduct,cyl}$. The value obtained for heat transfer has the unit J/sec [31].

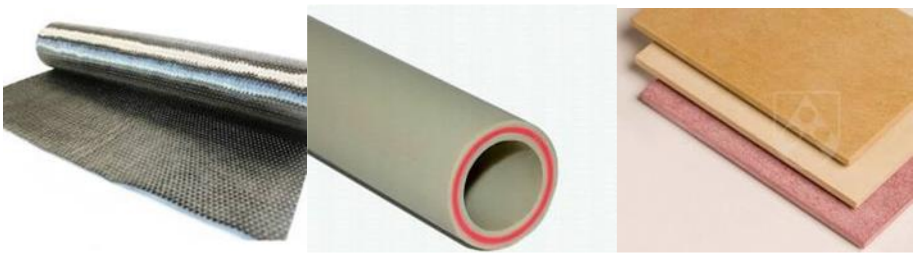
2.3. Material Selection

Selecting the optimal reinforced plastics for a thermos flask requires a multi-faceted approach considering various factors to ensure its performance and durability [32]. The selection process considers key factors such as thermal insulation properties, mechanical properties, chemical resistance, processability, cost and availability, lightweight construction, etc [33].

2.4. Candidate Reinforced Materials

Some samples of reinforced plastics were selected to evaluate and determine the most preferred to be used for developing the thermos flask [34]. Three reinforced plastic materials were selected for this evaluation:

- Glass Fibre Reinforced Plastic (GFRP)
- Carbon Fibre Reinforced Plastic (CFRP)
- Polypropylene Reinforced Plastic (PPRP)



CFRP PPRP GFRP

Figure 3: Proposed conceptual framework

2.5. Material Test Results

2.5.1. Thermal Properties

- **Thermal conductivity:** CFRP demonstrated the best thermal insulation with the lowest thermal conductivity, followed by GFRP and PPRP [35].
- **Heat retention test:** All materials showed good heat retention capabilities, with CFRP retaining heat for the longest duration (Table 1).

Table 1: Comparative analysis of the thermal performance of the reinforced plastics

Materials	Thermal Conductivity (W/mK)	Heat Retention
GFRP	0.35	Good
CFRP	0.20	Very Good
PPRP	0.50	Fair

2.5.2. Mechanical Properties

- **Tensile strength:** CFRP exhibited the highest tensile strength, followed by GFRP and PPRP.
- **Flexural strength:** Similar to the tensile strength, CFRP had the highest flexural strength, followed by GFRP and PPRP [36].
- **Impact resistance:** PPRP demonstrated the least impact resistance, followed by GFRP and CFRP.

Table 2: Comparative analysis of the mechanical properties of the reinforced plastics

Materials	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Resistance (KJ/m^2)
GFRP	2000	2500	100
CFRP	3500	4000	250
PPRP	40-50	60-70	2-3

2.5.3. Leak Resistance

- **Pressure test:** All materials passed the pressure test without leaks or failures.
- **Immersion test:** PPRP and GFRP showed negligible water absorption, while CFRP absorbed slightly more water. However, none of the reinforced materials leaked during the immersion test.

Table 3: Comparative analysis of the leak resistance of the reinforced plastics

Materials	Pressure Test	Immersion Test
GFRP	Pass	Pass
CFRP	Pass	Pass
PPRP	Pass	Pass

2.5.4. Cost Analysis

The cost analyses help determines the most cost-effective material (reinforced material) for developing thermos flasks (Table 4).

Table 4: Comparative cost analysis of the candidate reinforced plastic

Materials	Cost
GFRP	Moderate
CFRP	High
PPRP	Low

2.6. Test Discussion

GFRP: This reinforced material demonstrates good thermal insulation, making it ideal for maintaining temperature for beverages and other contents. Its good mechanical properties and leak resistance balance performance and durability [37].

CFRP offers the highest strength-to-weight ratio and excellent thermal conductivity, making it a lightweight option with good insulation; however, it is relatively expensive compared to other reinforced plastics (GFRP and PPRP) [38].

PPRP: This material presents the most cost-effective option, with good impact and leak resistance. However, its inferior thermal performance and lower mechanical strength limit its suitability for a high-performance thermos flask [39].

2.7. Result Evaluation

Based on the various laboratory test results, GFRP emerges as the most suitable material for developing the thermos flask due to its good thermal insulation, adequate combination of its mechanical properties, and relative affordability [40]. However, CFRP remains viable if a lighter material with superior strength and thermal heat retention capabilities is desired without considering cost [41]. PPRP offers a cost-effective alternative with good durability and leak resistance, but its thermal performance and mechanical properties are inferior to those of GFRP and CFRP [42].

3. Experimental Tests and Results

3.1. Thermal Performance Testing

The thermal performance testing helps assess the effectiveness of the thermos flask in maintaining beverage temperature. The rate of temperature change and the flask's ability to retain hot or cold temperatures for an extended duration are key factors to evaluate [43].

3.2. Durability Testing

Thermos flasks must withstand everyday use, including drops, bumps, impacts, scratches, etc. Therefore, thermos flasks that can withstand such challenges will be welcomed. Before choosing the Glass Fibre Reinforced Plastics (GFRP), a quick revaluation was conducted to check its suitability. From Table 2, it is clearly shown that GFRP has good strength to testify, though not the strongest in that table; GFRP provided balanced results [44].

During the fabrication and joining of the thermos flask, it was noticed to survive several drops and impacts from considerable heights, where it remained intact despite some unintentional mishandling. Also, sandpaper (an abrasive material) was used on the surfaces of the thermos flasks to apply some finishing touches. This was a fine indication of the material's durability against scratches. To review some of the numerical values for the GFRP thermos flasks, view Table 3 in Methodology; however, with real-life situation handling, the flask was observed to do very well in terms of durability.

3.3. Leakage Testing

This type of test is done to check the reliability and functionality of the thermos flask. This could help ensure beverage safety as leakage can compromise the flask's contents, allowing contamination and potential growth of harmful bacteria. As stated, the GFRP thermos flask was made using the hand layup technique. This calls for a manual approach to ensure uniformity of the layering of the flask walls. The thermos flask was tested to be free from leakages; however, not all of them. The thermos flask using the hand layup method was done in three ways, though they look identical. A particular flask seems to show leakage when observed using the tilting method. This problem was not a failure of the CSM-450. Still, improper impregnation of the fiberglass mat and the resin onto the mould affected the material's ability to cure adequately with the resin. This made some parts of the thermos flask unable to retain liquid, causing leakages. In conclusion, the GFRP is a good material and leakage-resistant. Still, a proper layup must be properly processed and manufactured to produce a consistent leakage-free container. Careless or improper layup techniques will not produce the desired result, and leakage may be detected. This calls for proper care and handling during the layup and curing process.

3.4. Comparison with Existing Thermos Flasks

This project allowed for the development of a reinforced plastic thermos flask. The product has been observed to have good qualities, but how do they fare compared to the other existing thermos flasks. A simulation between stainless and fiberglass reinforced was done to check the graphs and behaviours of both flasks. Images of the simulation are shown in Figure 3.

4. Results and Discussion

Figure 4 shows the simulation of the heat response for the stainless-steel thermos flasks, which immediately introduce hot contents into the flask. The temperature column helps to show the characteristics of the different sections in the flask, with the outside body already gaining heat energy from the internal part that contains the hot beverage.

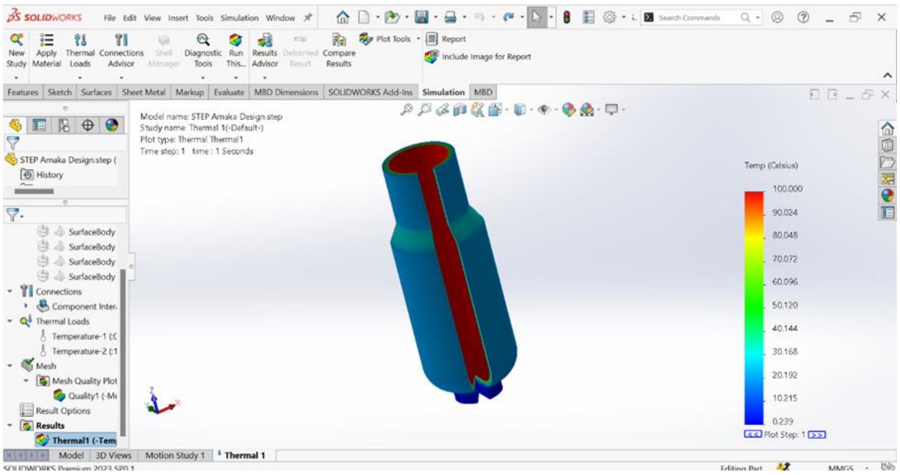


Figure 4: Heat response at the start (0s) of a stainless steel thermos flask

Almost immediately after the contents have been introduced, the outer body shows some temperature change, which can be seen from the change in colour in the temperature heat map column (Appendix A.). Similarly, Figure 5 shows that heat travels readily in a stainless steel thermos flask as both the internal and outer body achieve relatively the same temperature after introducing hot contents.

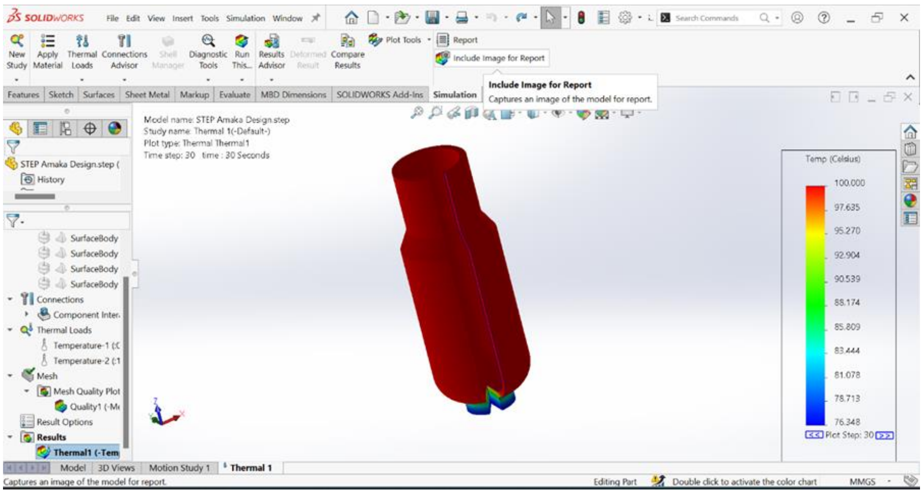


Figure 5: Heat response after some time (30s) of a stainless steel thermos flask

On the other hand, Figure 6 shows the immediate heat response of the glass fiber-reinforced plastics (GFRP). The simulation at the start depicts the slow response characteristics of the GFRP material as the external part did not readily undergo temperature change from the internal body of the flask.

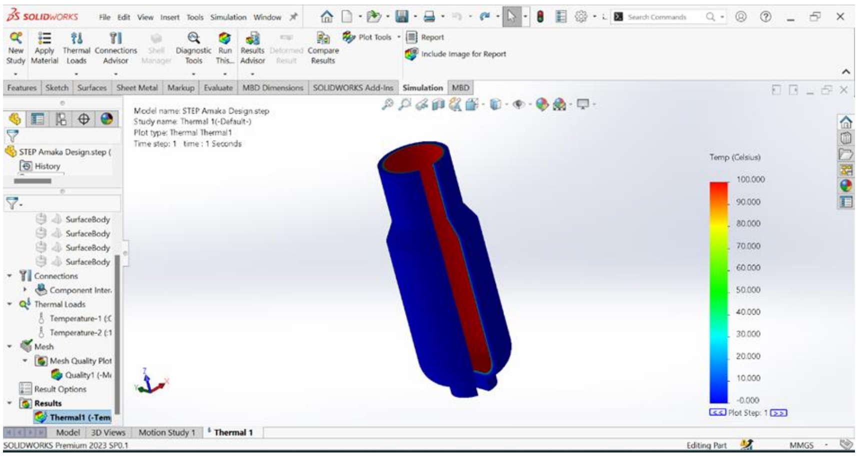


Figure 6: Heat response at the start (0s) of GFRP thermos flask

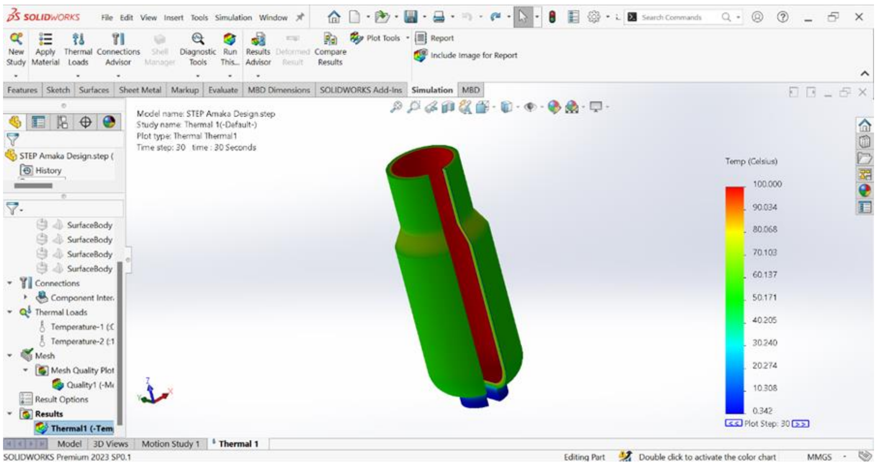


Figure 7: Heat response after some time (30s) of GFRP thermos flask

Figure 7 shows that after some time, say 30 seconds, the glass fibre-reinforced plastics (GFRP) thermos flask undergoes some temperature change. The outer body gains heat energy despite responding slower than stainless steel. The simulation shows that the outer body, after 30 seconds, possesses a green colour, indicating that the outer body becomes warmer than before due to heat from the inner part of the flask.

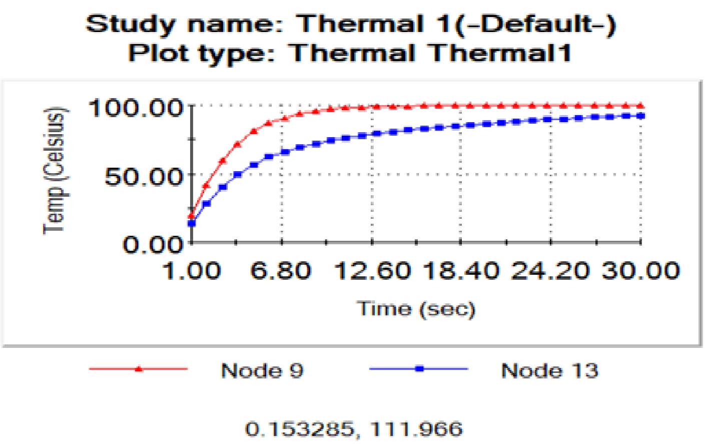


Figure 8: The response graph of a stainless steel thermos flask

Figure 8 shows the heat response of two points in the flask. It shows a temperature-time response graph indicating the characteristics of the stainless steel flask. The points exhibited sharp temperature changes over time, with the temperature curve reaching over 800C in about six seconds. Like in the simulation, the graph gives a clear response of the stainless steel flask over time when contents are being introduced.

The Brand Experience values are below 0.7, yet they are still considered valid indicators for making inferences since they are not excessively low. To show convergent validity, each item loading for a latent concept must be at least 0.5 and statistically significant, as shown by a correlated p-value of 0.05 or below.

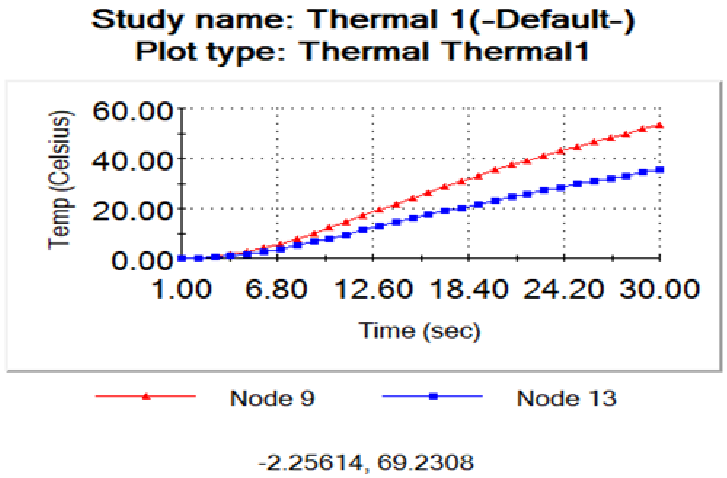


Figure 9: The response graph of the GFRP thermos flask

Figure 9 shows the graphical representation of the temperature change over time in a GFRP thermos flask. It shows a different curve from that of the stainless-steel thermos flask as the nodes show a slow temperature response of the hot contents over time; even after 30 seconds, none of the nodes achieved greater than 600C, contrasting that of the result in the stainless steel.

5. Conclusion

In this study, glass fibre-reinforced plastic (GFRP) thermos flasks successfully passed various tests and demonstrated the potential for good performance, provided that proper manufacturing processes are followed. The results indicate that GFRP could be a viable material for producing thermos flasks, offering an alternative to conventional materials like stainless steel. This brings diversity to the market and opens up more options for manufacturers to consider when designing thermos flasks. The project introduced a unique process of using reinforced plastics to develop thermos flasks, yielding promising results. However, there is room for further improvement in the manufacturing processes to minimize imperfections in the material, which could enhance the overall quality and performance of the flasks. Future research could focus on refining the production techniques, particularly by addressing the imperfections observed during testing, to improve the efficiency and durability of GFRP thermos flasks. Additionally, more studies could explore different resin formulations that may enhance the impact resistance and long-term durability of GFRP, making the material more suitable for everyday use. This study leaves ample opportunity for future researchers to develop better production methods and materials, ultimately contributing to the creation of durable, efficient, and sustainable thermos flasks. By continuing to innovate in this area, researchers can help push the boundaries of material science, resulting in even more advanced and effective thermal insulation solutions.

Appendix A.

A.1. Nomenclature

$Q_{conduct,cyl}$ = Heat transfer through the cylinder
A = Area of heat transfer
k = Thermal coefficient of conduction
T_1 = Inner temperature
T_2 = Outer temperature

r_1 = Inner radius for inner bottle
r_2 = Outer radius for inner bottle
r_3 = Radius for Vacuum
r_4 = radius of the outer bottle
k_1 = Thermal coefficient of the inner bottle
k_2 = Thermal coefficient of Vacuum
k_3= Thermal coefficient of the outer bottle
h_1 = Convective heat transfer of air
h_2 = Convective heat transfer of water
$R_{conv,1}$ = Thermal resistance of the convective heat transfer of air
$R_{conv,2}$ = Thermal resistance of the convective heat transfer of water
$R_{cyl,1}$ = Thermal resistance of the cylindrical layer(inner bottle)
$R_{cyl,2}$ = Thermal resistance of the cylindrical layer(Vacuum)
$R_{cyl,3}$ = Thermal resistance of the cylindrical layer(outer bottle)
L = Length of the bottle
L_1 = Thickness of inner bottle
L_2 = Thickness of Vacuum
L_3 = Thickness of outer bottle
R_{b1} = Thermal resistance of the base layer(inner bottle)
R_{b2} = Thermal resistance of the base layer(Vacuum)
R_{b3} = Thermal resistance of the base layer(outer bottle)
R_{total} = Total thermal resistance

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Ethics and Consent Statement: This research adheres to ethical guidelines, obtaining informed consent from all participants.

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