

Heat Analysis of a Vacuum Flask

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Abstract

Materials with low thermal conductivity like aerogel, acrylic, aluminum silicate, superfine glass wool, and phenolic foam are often used as insulation materials in engineering and have noticed increasing applications in other spheres of life, like thermal insulation in buildings and vacuum flasks. The objective of this research is to study the temperature variation of the coffee over 10 hours in a selected vacuum flask while varying the geometrical and material properties of the flask. In other words, change the parameters (without changing the fluid capacity) to minimize the heat loss over time. The range of the bottleneck radius used is from 40 mm to 60 mm, with a step size (increment) of 5 mm. The width of the whole flask is proportional to the bottleneck radius, with constant fluid capacity. The initial design used an outer and inner steel layer with plastic foam in between, and the bottleneck is made from nylon with a radius of 50 mm. This design allows the hot fluid to be at 55 °C after 10 hours in atmospheric conditions. The temperature of the coffee in the vacuum flask made of steel layers with aerogel as insulation was 72.3 °C after 10 hours, while the steel layers and CO₂ insulation were 67.9 °C and the acrylic layer and aerogel were 77.89 °C after a 10-hour duration in still air. This simulation was carried out using COMSOL, and the result shows that an acrylic layer and aerogel at a bottleneck radius of 60 mm were the best combination. Verification and validation were carried out to test for convergence of the numerical and analytical solutions.

Keywords: Vacuum Flask. Thermal Insulation. Simulation. Aerogel. Acrylic. COMSOL. Aluminium Silicate. Verification and Validation.

1. Introduction

A vacuum flask, Figure 1, commonly called a thermos flask or Dewar flask, was invented by Sir James Dewar in 1892 [1]. Vacuum flasks' main purpose is to keep the beverage hot or cold for long periods of time and for other purposes in the industry [1]. A vacuum flask consists of two flasks (vessels) that are placed within each other. There is a gap between them that is evacuated of air,

creating a near-vacuum that reduces heat transfer by convection or conduction; this influence leads to a constant temperature for the beverage for a long time. Some common materials used in most industries are metal, foam, plastic, and borosilicate glass, while the cover (opening) is made from cork or polyethylene plastic. The vacuum flask resembles a jug more than anything else. Most flasks contain a vacuum-sealed inner chamber and an exterior chamber comprised of plastic or metal that is surrounded by two layers of glass. The inner bottle's silver covering and the vacuum between its two sides prohibit heat from transferring by radiation or convection, respectively [2]. The glass walls' thinness prevents heat from conditionally escaping or entering the flask. Supplemental insulation is provided by the casing that the flask is enclosed in.

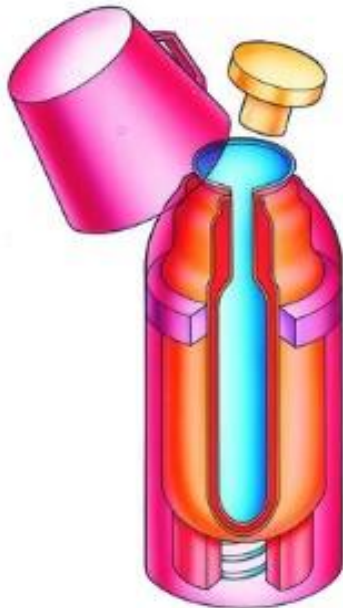


Figure 1: Vacuum Flask design [1]

Insulation, or more specifically, thermal insulation, is a general term used to describe substances that act as a barrier between areas of markedly different temperatures to minimize heat absorption or loss. Thermal insulation materials, structures, and manufacturing techniques are being improved for use in low-temperature applications. Examples of low-temperature applications include storage tanks for cryogenics, superconducting electric power transmission equipment, cold boxes for low-temperature industrial processes, and containers for food and other perishable items [3]. Heat is transferred by convection through the circulatory system in both liquids and gases. The flow that develops because of density differences due to temperature fluctuations is known as free convection. External forces (wind, ventilators, etc.) cause forced convection to flow.

The thermal radiation process takes place when thermal energy is emitted, similarly to how light is released. Convection and radiation are the processes by which heat is lost to or obtained from the atmosphere, respectively, whereas conduction is the technique by which heat is transmitted through molecular interaction [4]. Low thermal conductivity is a property of materials that include a lot of microscopic gaps that may convey gases or air. These gaps are too small to effectively transmit heat by convection or radiation, which reduces the conduction of energy. Natural or artificial materials can be used as thermal insulation. In a gas-containing volume where some of the air as well as other gases have been evacuated, "vacuum insulation" refers to a space that is only partially vacant.

The vacuum flask is made up of two flasks that are nestled inside one another and connected at the top. Air is partially evacuated from the space between the two flasks, generating a partial vacuum that lessens temperature distribution, or convection. Typically, vacuum flasks are made of metal,

borosilicate glass, stainless steel foam, or plastic. Cork or polyethene plastic is used to plug the entrance to maintain the temperature of the fluid. Thus, heat transmission is reduced by the vacuum flask design. Conduction, convection, and radiation are the three methods of heat transmission; however, the vacuum flask design eliminates all of them [5]. The newest motion vacuum flask in stainless steel, 0.75L (capacity), as shown in Figure 2, the seal is leakproof, and it has excellent insulation thanks to the quality double-walled thermal liner made of Cromargan. The stainless steel 18/10 means drinks stay hot for 12 hours and cold for up to 24 hours.



Figure 2: WMF Motion Vacuum flask stainless steel, 0.75. [2]

1.1. Problem Statement:

The objective is to study the temperature variation of the coffee over 10 hours for a selected vacuum flask. Then, carrying out a parametric sweep on the geometrical and material properties of the flask to enhance its performance. In other words, change the parameters (without changing the fluid capacity) to minimize the heat loss over some time.

2.0. Method

The initial design as seen in Figure 3 used an outer and inner steel layer with plastic foam in between, the bottleneck is made from nylon with a radius of 50 mm. Figure 3 shows the temperature distribution after 10 hr of the selected design.

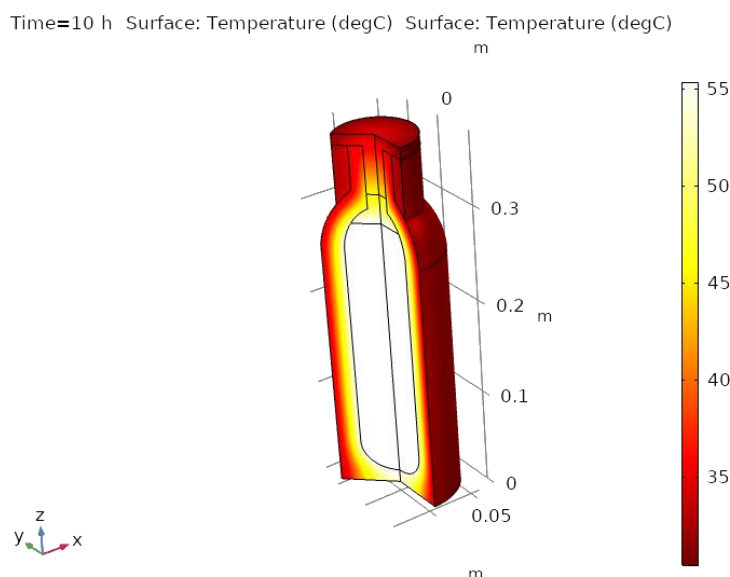


Figure 3: Temp. distribution to the initial design.

As is shown in Figure 4 the temperature of the coffee is 55 °C, which is the highest, and it starts to decrease until it reaches the minimum at the outer layer. Figure 5 illustrates the isothermal domain temperature for the selected design over 10 hours.

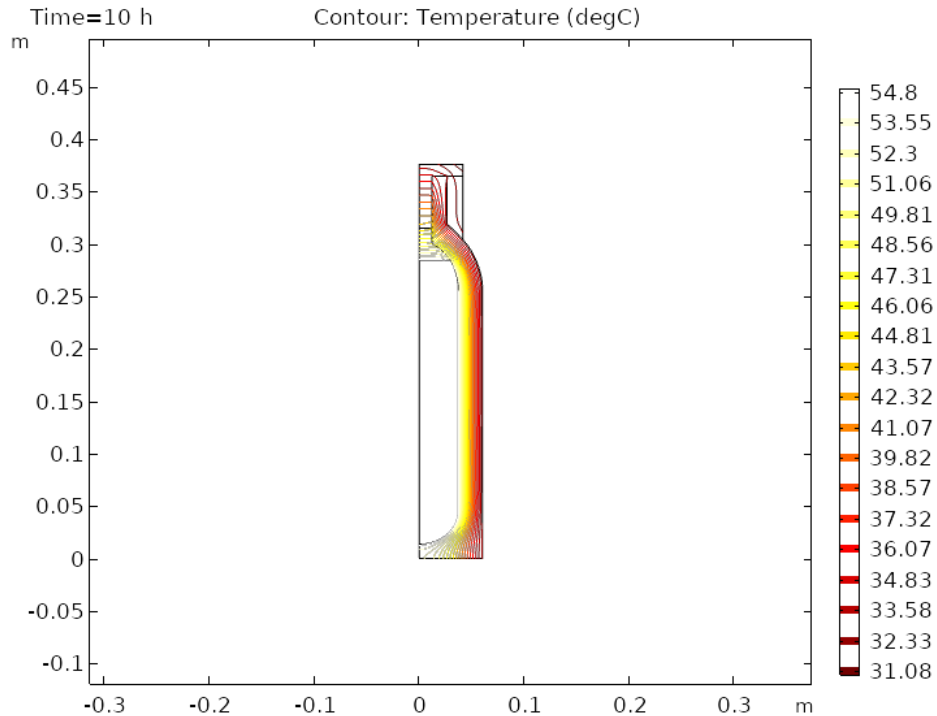


Figure 4: Isothermal Contour of the initial design.

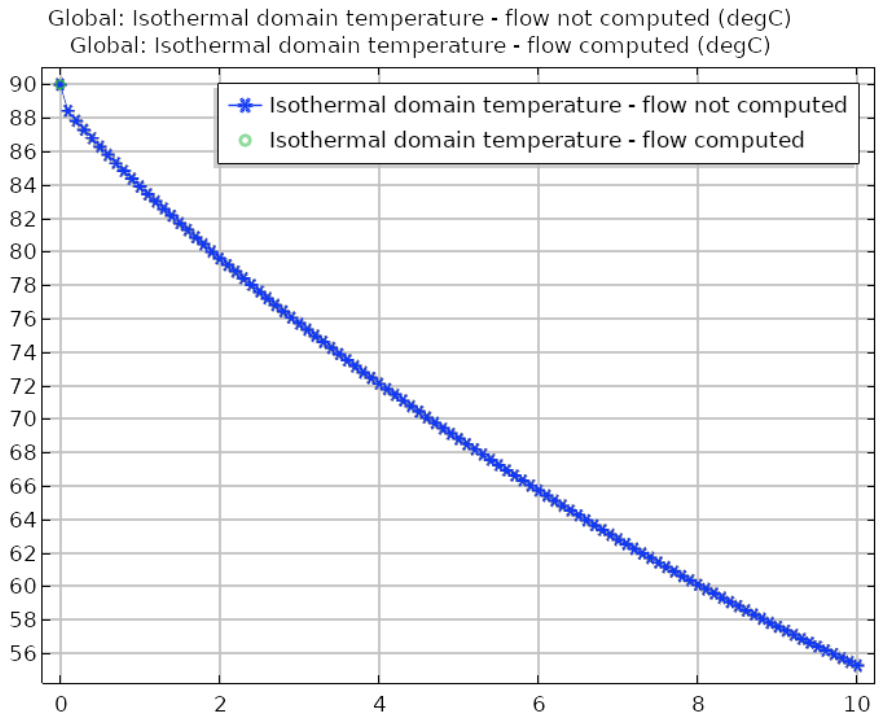


Figure 5: Isothermal domain temperature of the initial design.

As is seen in Figure 5, the temperature started at 90 C and reached 55 C after 10 hours.

2.1 Design Ideas:

To design or re-design a product, the goal or the purpose of the product must be the priority regarding the constraints or limits. The vacuum flask is a product which maintains the heat of hot beverages as long as possible. When considering the design of a vacuum flask, the main physics is heat transfer in solids and liquids. Figure 6 shows a section view of the vacuum flask which will be adjusted and redesigned.

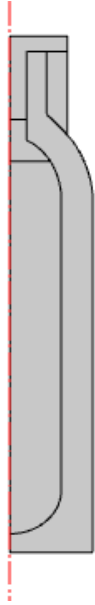


Figure 6: Section view.

The goal is to keep the heat in the coffee for as long as possible without changing the capacity of the liquids. The design given used an outer and inner steel layer with plastic foam in between, and the bottleneck is made from nylon with a radius of 50 mm. This design allows the coffee, as previously shown, to be at 55 °C after 10 hours in atmospheric conditions. There are many ways to insulate the heat even longer, by looking through the materials used or by altering the shape and size of the flask in many ways. The first idea that comes to mind is to look for materials with lower thermal conductivity. Changing the steel layers with less thermally conductive material, Table 1 shows different materials with their thermal conductivity values.

Table 1: Different materials with their thermal conductivity value. [6]

Material	Conductivity (Watts/meter-°C)
Acrylic	0.200
Air	0.024
Aluminum	250.000
Copper	401.000
Carbon Steel	54.000
Concrete	1.050
Glass	1.050
Gold	310.000
Nickel	91.000
Paper	0.050
PTFE (Teflon [®])	0.250
PVC	0.190
Silver	429.000
Steel	46.000
Water	0.580
Wood	0.130

The next step is to replace the insulation material which is plastic foam in the given design with another material. Figure 7 shows different materials that can be used as insulation.

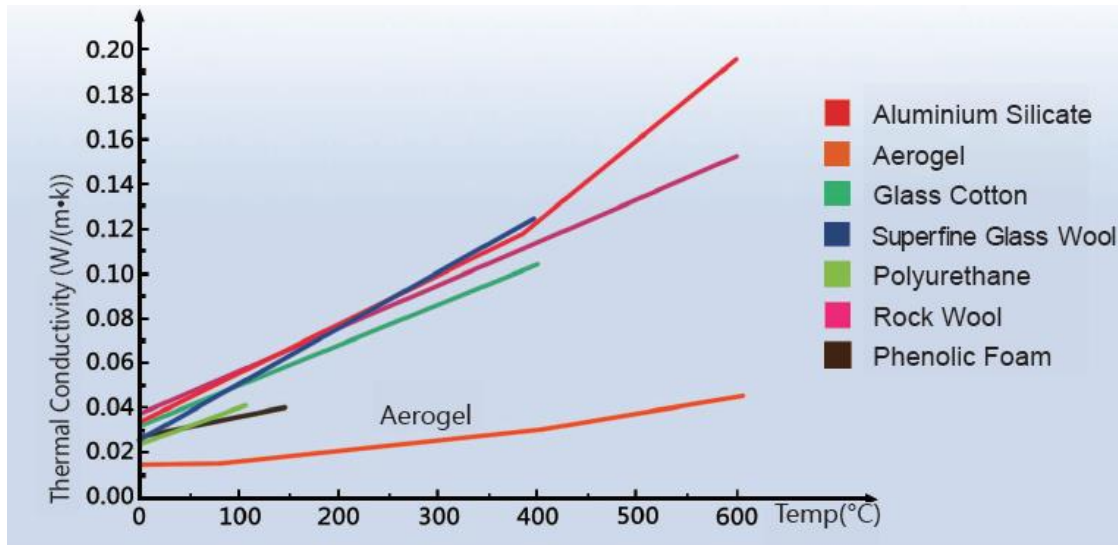


Figure 7: Materials with their thermal conductivity. [7]

The plastic foam can be replaced by gas if wanted. Table 2 shows multiple gases with their thermal conductivity.

Table 2: Thermal conductivity for various gases. [8]

	Thermal Conductivity at 300 K (W/mK)
Air	0.026
Ar	0.018
CO	0.025
CO ₂	0.017
H	0.182
He	0.151
N ₂	0.026
Ne	0.049
O ₂	0.027

3.0 Results and Discussion:

Tables 3, 4, 5 and 6 show the results of each study mentioned previously. These results will be used and compared with each other to determine the most suitable design.

Study 1: Steel layers with aerogel in between temperature values:

Table 3: Steel layer and aerogel temp. values

Radius (mm)	t (hr)	Temperature (°C)
40.000	10.000	67.541
45.000	10.000	69.466
50.000	10.000	70.735
55.000	10.000	71.645
60.000	10.000	72.339

Output:

The highest heat loss after 10 hr was at radius = 40 mm with a value of 67.541 °C
 The lowest heat loss after 10 hr was at radius = 60 mm with a value of 72.339 °C

Study 2: Steel layers with CO₂ in between temperature values:Table 4: Steel layer and CO₂ temp. values

Radius (mm)	t (hr)	Temperature (° C)
40.000	10.000	61.947
45.000	10.000	64.257
50.000	10.000	65.868
55.000	10.000	67.046
60.000	10.000	67.961

Output:

The highest heat loss after 10hr was at Radius = 40 mm with a value of 61.947 °C
 The lowest heat loss after 10hr was at Radius = 60 mm with a value of 67.961 °C

Study 3: Acrylic layers with aerogel in between temperature values:

Table 5: acrylic layer and aerogel temp. values.

Radius (mm)	t (hr)	Temperature (° C)
40.000	10.000	72.013
45.000	10.000	74.353
50.000	10.000	75.911
55.000	10.000	77.038
60.000	10.000	77.896

Output:

The highest heat loss after 10hr was at Radius = 40 mm with a value 72.013 °C
 The lowest heat loss after 10hr was at Radius = 60 mm with a value of 77.896 °C.

Study 4: Acrylic layers with CO₂ in between temperature values:Table 6: acrylic layer and CO₂ temp. values.

Radius (mm)	t (hr)	Temperature (° C)
40.000	10.000	65.715
45.000	10.000	68.442
50.000	10.000	70.358
55.000	10.000	71.778
60.000	10.000	72.898

Output:

The highest heat loss after 10hr, was at Radius = 40 mm with a value of 65.715 °C
 The lowest heat loss after 10hr, was at Radius = 60 mm with a value 72.898 °C

It can be seen from these tables that the best radius in all of these is R= 60 mm, and the best combination is Acrylic with aerogel because they have the minimum heat loss after 10hr and the

temperature = 77.896 °C. This is convenient, as the thickness of the insulation increases the more heat is held within the fluid.

The selection of the proper design would be the acrylic layer and aerogel combination with a bottleneck radius equal to 60 mm. As shown from the results, there is less than one Celsius degree difference between 55 mm and 60 mm radius, therefore, increasing the radius, even more, would not add much and can increase the cost. Figure shows the temperature distribution after 10h of the selected design. As it is shown in Figures 8 and 9, the temperature of the coffee is 77.9 °C, which is the highest, and it starts to decrease until it reaches the minimum of 26 C at the outer layer. Figure 9 shows the isothermal contours for the selected design after 10 hr.

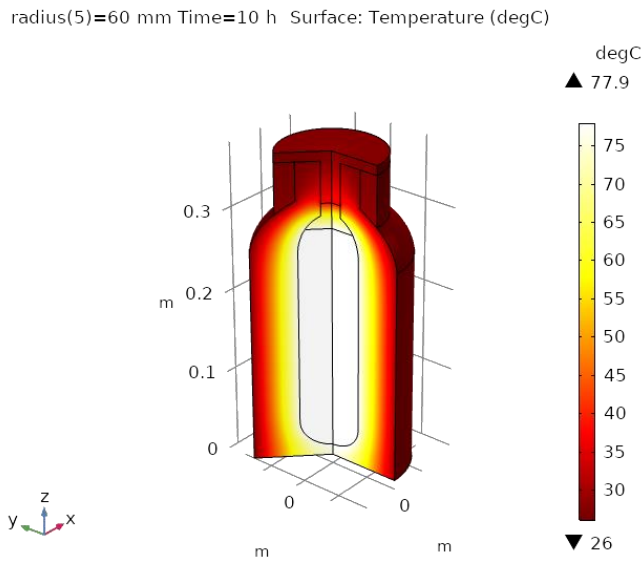


Figure 8: Temp. distribution to the selected design.

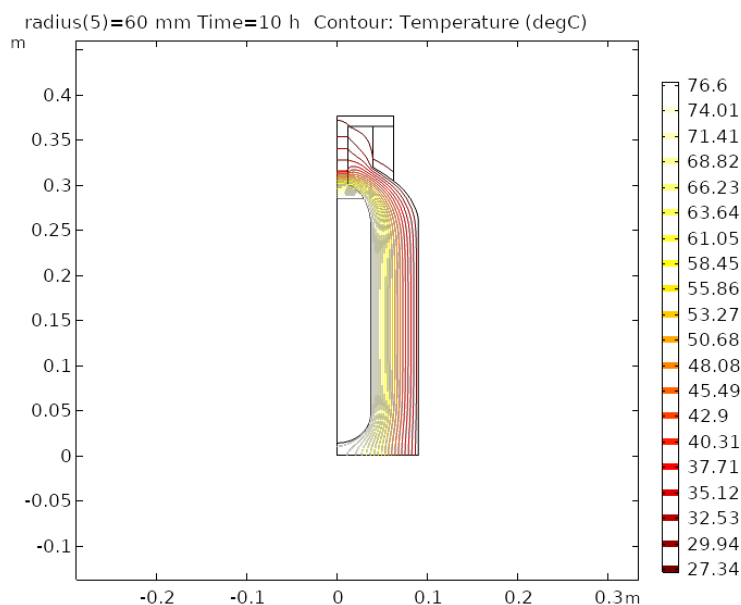


Figure 9: Isothermal Contour of the selected design.

Figure 10 illustrates the isothermal domain temperature for the selected design over 10 hours.

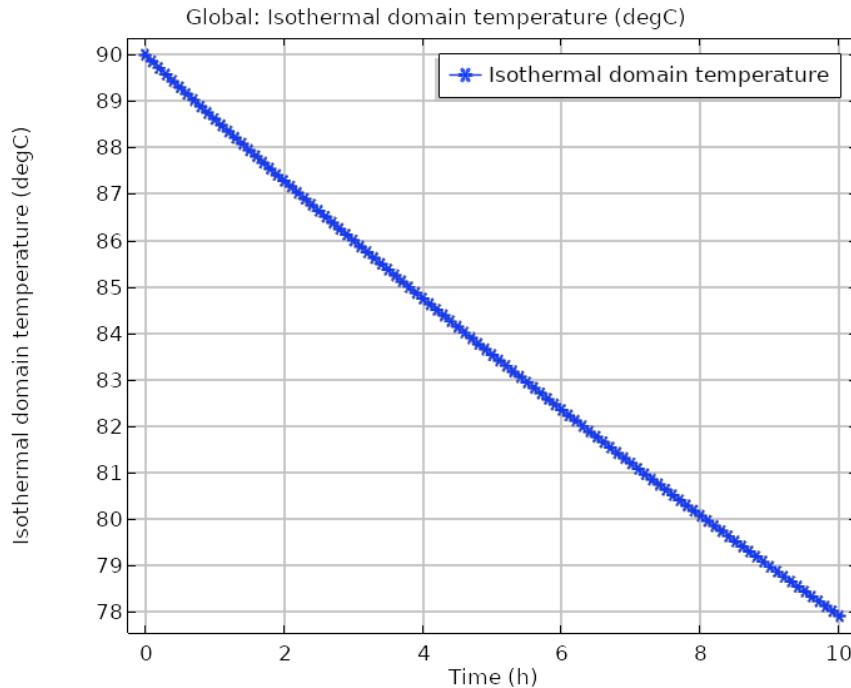


Figure 10: Isothermal domain temperature of the selected design.

As is seen in the Figure 10, the temperature started at 90 C and reached 77.9 C after 10 hours. Table 7 summarizes the results of the initial and selected design.

Table 7: Results summary

Property	Initial Design	Selected Design
Outer Material	Steel	Acrylic
Inner Material		
Material in-between	Plastic foam	Aerogel
Neck size, Radius (mm)	40	60
Starting Temperature (C)	90	90
Temperature after 10h (C)	55	77.9

Figure 11 represents the temperature distribution for the initial and selected designs. Figure 11 shows the huge reduction in heat loss between the initial and selected designs. Hence, it shows the huge reduction in temperature.

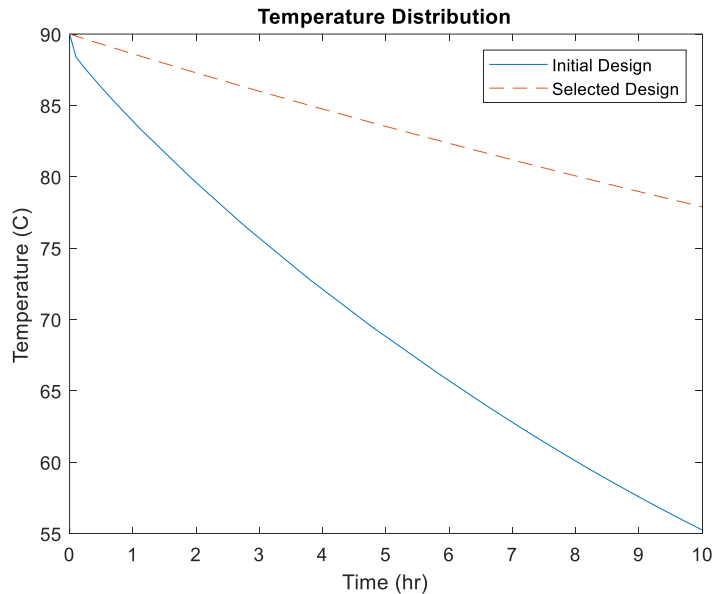


Figure 11: Initial and selected designs temperature distribution.

3.1 Verification and Validation:

To check for convergence of the numerical solution using the FEA code, the vacuum flask thermal analysis was done analytically. Here the flask is modelled in form of a flat surface made of composite materials. [9]. Some assumptions were made to simplify the analytical solution, which are:

- 1- The inner and outer layers are thin.
- 2- Heat transfer in the inner and outer thin layers will be neglected, which means heat transfer will only be considered in the aerogel layer.
- 3- Heat transfer from the top and bottom of the bottle will not be considered.

Now, after considering these assumptions, the system is divided into two nodes, which are at the inner surface and outer of the vacuum flask. Boundary conditions were prescribed at the outer surface of the flask is 25 degrees Celsius and is left for 10 hours to determine the final temperature of the fluid. Figure 12 shows system model specifications.

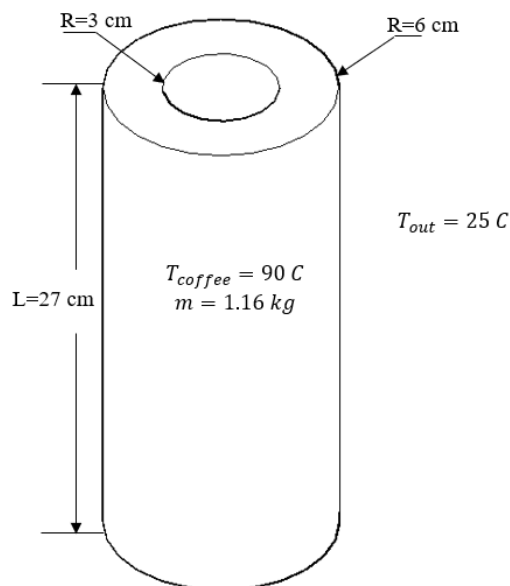


Figure 12: System Specifications.

For the model presented in the figure above, the rate of heat transfer can be found using the following equation:

$$\frac{dQ}{dt} = mc \frac{dT}{dt} \quad (1)$$

Where m is the mass in kg and c is specific heat, which is 4182 J/kg. K for water. In addition, the rate of radial heat transfer can also be found using the following equation:

$$\frac{dQ}{dt} = \frac{2\pi kL}{\ln\left(\frac{b}{a}\right)} [T_a - T_b] \quad (2)$$

Where k is the thermal conductivity of the insulating material, which is 0.012 W/m. K for aerogel as it was obtained from COMSOL, L is the total length, and b and a are the outer and inner radiuses, respectively. Now, Equation 1 is set to be equal to Equation 2 and terms are re-arranged to obtain the following equation:

$$\frac{2\pi kL}{mc\left(\ln\left(\frac{b}{a}\right)\right)} = \frac{dT}{T_a - T_b} \quad (3)$$

Substituting with the values of the parameters in equation 3 results in the following:

$$\frac{2\pi \times 0.012 \times 0.27}{1.16 \times 4182 \times \ln\left(\frac{0.06}{0.03}\right)} dt = \frac{dT}{T-25} \quad (4)$$

This corresponds to:

$$6.054210^{-6} dt = \frac{dT}{T-25} \quad (5)$$

Now, taking the integral for both sides as follows:

$$6.0542 \times 10^{-6} \int_0^{36000} dt = - \int_{90}^T \frac{dT}{T-25} \quad (6)$$

It should be highlighted that the negative sign was added for the sign convention. Solving equation (6) results in the following:

$$42 \times 10^{-6} \times (36000 - 0) - \frac{T-25}{90-25} \quad (7)$$

Solving the above equation results in a final temperature of 77.27 C after 10 hours. Comparing the analytical and numerical solutions shows that both values are very close to each other with a 0.81% error. This gives confidence in the obtained numerical results.

Furthermore, Figure 13 below shows the temperature distribution throughout the 10 hours both analytically and numerically. Please refer to the appendix for the MATLAB code.

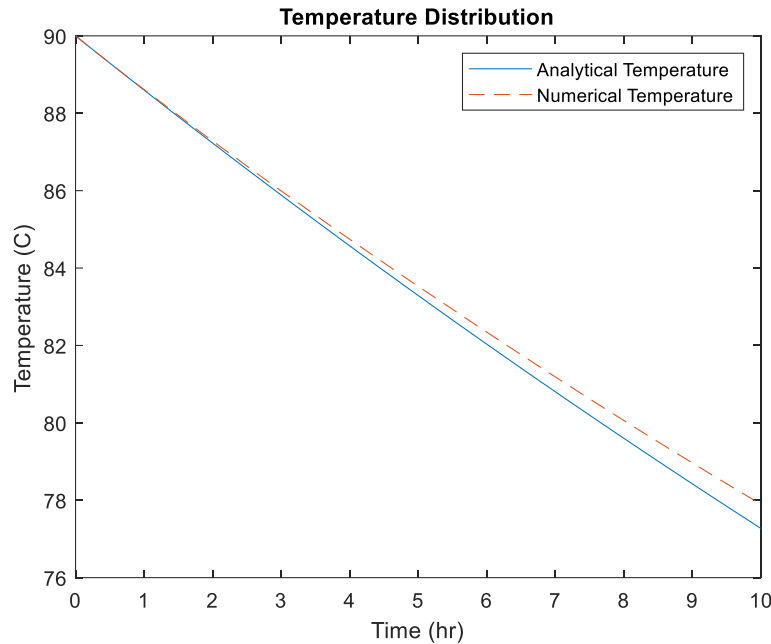


Figure 13: Analytical and numerical results.

As is shown in Figure 13, both results are close to each other with a small deviation that starts to increase as time increases. This deviation is a result of the assumptions mentioned previously. However, these assumptions did not affect the results significantly.

4.0 Conclusions and Future Scope:

It was concluded that choosing materials with lower thermal conductivity led to reducing the heat loss of the coffee significantly. Furthermore, the most suitable design was found to be acrylic layers with aerogel in between, which was chosen based on different studies that were applied to the flask. Temperature reduction in the initial design, which was steel layers with plastic foam in between, was found to be 3 times the reduction in the adjusted design. Finally, the analytical solution was obtained, and it was concluded, from the similarity of the results, that the numerical solution is applicable, where the error between the two solutions was found to be less than 1%. In the future, a more accurate analytical method to calculate heat loss should be considered that eliminates the deviation caused by the assumptions. Also, the numerical solution can be obtained using different software to build more confidence in the obtained numerical results. Finally, a wider range of materials can also be considered to enhance the results and reduce heat loss over time.

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Appendix:

```

clc
clear all
k=0.012;% Thermal Conductivity (W/m.K)
L=0.27; %Length (m)
m=1.16; %Mass (kg)
c=4182; %Specific heat (J/kg.K)
a=0.03; %Inner radius (m)
b=0.06; %Outer radius (m)
t=0:0.1:10; %Time (s)
factor=(2*pi*k*L/(m*c*log(b/a))); %dt factor
numerical=[ 90.0000 89.8578 89.7166 89.5764 89.4366 89.2975 89.1599 89.0223
88.8848 88.7472 88.6122 88.4787 88.3452 88.2118 88.0783 87.9449 87.8114 87.6779
87.5445 87.4121 87.2827 87.1534 87.0241 86.8947 86.7654 86.6361 86.5067 86.3774
86.2481 86.1197 85.9943 85.8688 85.7434 85.6179 85.4925 85.3670 85.2416 85.1161
84.9907 84.8661 84.7440 84.6219 84.4998 84.3777 84.2556 84.1335 84.0114 83.8893
83.7672 83.6460 83.5274 83.4088 83.2902 83.1716 83.0530 82.9344 82.8158 82.6972
82.5786 82.4603 82.3432 82.2264 82.1098 81.9935 81.8774 81.7616 81.6461 81.5308
81.4158 81.3011 81.1868 81.0728 80.9590 80.8455 80.7324 80.6195 80.5069 80.3946
80.2826 80.1709 80.0595 79.9485 79.8377 79.7273 79.6172 79.5073 79.3978 79.2886
79.1796 79.0710 78.9627 78.8546 78.7469 78.6395 78.5323 78.4255 78.3190 78.2127
78.1068 78.0012 77.8958];
%numerical results from COMSOL
for i=1:length(t)
    T(i)=(65/exp(factor*t(i)*3600))+25;
end
plot(t,T)
ylabel('Temperature (C)')
xlabel('Time (hr)')
title('Temperature Distribution')
hold on
plot(t,numerical,'--')
legend('Analytical Temperature','Numerical Temperature')

```