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Article

A Next-Generation Mobile Food Dispensing Cart with Enhanced Heat Prevention and Automated Mixing

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Abstract

The invention under consideration presents a mobile liquid food dispensing cart designed to address both mechanical inefficiency and thermal performance limitations commonly encountered in mobile food service systems. The device consists of a thermally insulated stainless-steel tank mounted on a wheeled base frame, a lid incorporating an integrated bearing-supported stirrer to maintain uniform temperature and consistency of the liquid, and an ergonomic handle post. The novelty of this study lies in the system-level integration of mechanical dispensing, fluid mixing, and analytically guided thermal design within a single mobile unit. From a mechanical perspective, an ergonomically actuated dispensing mechanism comprising a handlebar-mounted brake lever, Bowden cable, and spring-loaded normally closed valve enables controlled and hygienic dispensing. From a thermal perspective, the innovation extends beyond material selection to the analytical integration of insulation design with fluid thermal behavior under transient operating conditions. Heat loss from the stored liquid was evaluated by considering dominant heat-transfer mechanisms, including transient conduction through the tank and insulation layers and convection at the fluid–wall and external surfaces. A lumped-capacitance–based transient heat-transfer framework was employed to compare multiple insulation materials under identical geometric and ambient conditions. The results demonstrate that the proposed system can maintain liquid temperatures above the safe serving limit of 60 °C for over two hours, with polyisocyanurate insulation achieving the highest retention time of approximately 131 minutes. The combined mechanical–thermal design results in a passive, energy-efficient, hygienic, and self-sustained solution for mobile liquid food dispensing applications.

Keyword

Mobile liquid food dispensing cart, Thermal insulation, Holding time, Stirring mechanism, Polyisocyanurate, Transient heat transfer

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1. Introduction

Mobile food dispensing solutions are in high demand due to the growth of outdoor events, catering businesses, and urban vending. In addition to ensuring the quality of consumables like tea, milk, soup, liquid food and cold beverages while maintaining their safety throughout the dispensing period, these systems should be able to combine portability and convenience. One of the most important things in this regard is keeping liquids at the ideal temperature because too much cooling or heating can alter the flavours, safety levels, and nutritional value. Therefore, effective thermal management is at the heart of the design of mobile dispensing carts [1]. Insulation systems are consequently significant in handling this problem because the quantity of heat exchanged between the liquid that is stored and the environment are minimized. The thermal conductivity (k), density (ρ), specific heat capacity (Cp), and thickness are some of the parameters used to determine performance of an insulation material, which together determine the overall thermal resistance of the storage unit. Mechanisms of heat transfer also need to be taken into consideration in practical application terms through conduction, convection and radiation. In the case of cylindrical storage tanks, which are usually employed in dispensing systems, the theoretical basis of predicting the heat loss is offered by Fourier law of conduction and the general thermal resistance model [2,3]. Along with an insulation layer, stirring systems may be necessary in mobile food carts to avoid settling, sedimentation, or local temperature differences in the liquid. The integrated stirring systems provide even distribution of heat and thus thermal efficiency hence consumer satisfaction. Although there are many mobile food dispensing cart designs, little research has been done on the integrated stirring and insulation systems that are optimized to handle both hot and cold liquid foods [4]. In this study, five types of insulation materials, namely, Jute, cotton, and polyisocyanurate (PIR), rockwool and cellular glass are compared to identify their comparative performance in preserving liquid food temperatures. The analysis uses analytical computations in assessing the holding time [5]. The analysis is founded on the analytical transient analysis of heat transfer, in which unsteady-state energy equations are solved to determine how long a liquid takes to cool down with an initial temperature (Ti) to a critical final temperature (Tf) under ambient conditions [6]. Specifically, the lumped capacitance model. Capacitance is utilized and the parameters which are experimentally relevant, including the geometry of the tank, thickness of insulation, thermal conductivity and coefficient of convectional heat transfer [7,8]. Initial thermal resistance prediction of a steel tank in a cylindrical shape Packed with cotton insulation as in the analytical model indicate that the tank will contain hot liquids of approximately 2 hours 7.5 minutes to near ambient temperature at 60 °C to 90 °C through natural thermal exchange. These kinds of analyses offer a standard by which other insulation material types can be evaluated in order to identify the optimal setup. Through a methodical consideration of the thermal efficiency of various insulations the study offers a design enhancement benchmark to mobile dispensing carts [9]. The results of the research would help to promote the creation of energy-efficient, convenient, and clean mobile liquid food dispensing solutions. The strategic choice of thermal insulation is a critical point of the attainment of such energy efficiency. This study examines the efficiency of different materials, such as Jute, cotton, and PIR, rockwool and cellular glass to achieve the best thermal protection in the portable use. As the concept of sustainable and convenient food service systems is being increasingly promoted, the suggested design (Figure 1) can be used in catering services, street vendors, institutional and hospital food delivery, and in emergency-relief efforts [10]. The lumped capacitance approach employed in this study is valid when the internal thermal resistance of the fluid is significantly smaller than the external convective resistance, which is quantified by the Biot number (Bi). The Biot number is defined as

$$Bi = \frac{hLc}{k} \tag{1}$$

where h is the convective heat-transfer coefficient at the fluid–wall interface, *L_c* is the characteristic length of the liquid volume, and k is the thermal conductivity of the fluid.

Figure 1. Mobile liquid food dispensing cart.

For the cylindrical tank considered in this study, the characteristic length was taken as the ratio of liquid volume to wetted surface area. Based on the thermophysical properties of water and typical natural convection coefficients for liquid–metal interfaces, the estimated Biot number for the present system was found to be less than 0.1, satisfying the standard criterion for the applicability of the lumped capacitance model. This indicates that temperature gradients within the liquid are negligible and that the liquid temperature can be reasonably assumed to be spatially uniform during transient cooling. The presence of an integrated bearing-supported stirring mechanism further enhances internal mixing, reducing thermal stratification and strengthening the validity of the lumped capacitance assumption for the mobile liquid food dispensing application.

2. Literature Review

Use of thermal insulation of food and beverage storage systems has been extensively researched because of its importance in ensuring product quality, retention times, and minimized energy. The choice of the insulation material has a direct impact on the rate of heat transfer by conduction and convection, and thus, it determines the overall thermal efficiency of storage and dispensing systems [10]. Thermal protection in containers has used traditional thermal insulators like cotton, jute or mineral wool (rockwool) because of their availability and inexpensive nature. A natural fiber, cotton and jute, offer an intermediate thermal performance with thermal conductivities of 0.035-0.045 W/m*k. They are biodegradable and hence appealing in terms of sustainability, although the concern is their tendency to absorb water, low durability, and low fire resistance [2]. By comparison, Rockwool is a kind of inorganic fibrous substance, made of melted basalt, whose thermal conductivity is at 0.034 W/m*k. It is more fire-resistant and dimensionally stable than organic fibers, which is why it is applicable in industrial thermal-insulation [4]. In the contemporary thermal management systems, Polyurethane (PU) and PIR foams have come out as a better insulation. PIR, especially, has low thermal conductivity (0.020-0.026 W/m*k) and improved fire resistance compared to PU, which is why it is highly applicable in the application where the efficiency of insulation is essential along with fire resistance [7]. In food processing and cold-chain logistics research, it is demonstrated that cold-chain panels lined with PIR can hold their temperatures significantly longer than fibre-lined counterparts, which also matches the performance increase in the analytical calculations in this study [11]. Cellular glass insulation (consisting of hermetically sealed glass cells) has some unique advantages: it is absolutely moisture proof, most chemical-resistant, and dimensionally stable, as well as non-combustible [10]. Having a thermal conductivity of 0.040-0.060 W/m*K, it loses out to PIR in the insulation thickness to unit performance. Nonetheless, its strength and anti-aging effect make it interesting to use in hot-liquid storage when the durability and long-term stability are in the priority list. Recent uses in brewery and pharmaceutical tanks prove its usefulness in terms of maintaining hygiene and prevention of microbial growth related to moisture intrusion [12]. In mobile food dispensing carts, where thermal performance and weight, cost and food-safety are highly valued, insulation materials are constrained by trade-offs between thermal performance and weight, cost and food-safety. Studies on mobile dispensing systems have pointed at the necessity of reducing heat loss without using external sources of energy [13]. The lumped capacitance methods (and transient heat transfer methods in general) are widely used to model the cooling rate of liquids in insulated tanks [14]. These analyses have shown how even slight increases in insulation conductivity can greatly increase the holding time, especially of hot liquids like tea, milk, and soup [15]. Comparative analysis in the literature demonstrates that there are big differences in insulation performance when comparing material classes. The natural fibers like cotton and jute can naturally retain heat on hot liquids of about 2 hours, but highly developed polymeric foams like PIR can hold the heat longer due to their low thermal conductivity [3]. Rockwool, which provides a slightly better insulation than natural fibers, is not as compact as PIR. Cellular glass offers durability and fire resistance, but it is less effective than PIR in extending holding time [16]. The comparative studies are typically based on controlled experiments or computerized simulations. Nevertheless, even simple analytical heat-transfer calculations (e.g. models based on conduction) may provide some insight into relative insulation performance without necessarily needing to involve Complicated modelling. These ways of analysis can indicate at how holding time are to be meaningfully extended by minor modification in thermal conductivity or variation in thickness of insulation [17].

3. Methodology

The methodology of the research is a mix of mechanical design development and analytical thermal calculations to ascertain the performance of a liquid in a mobile food dispensing cart that has inbuilt stirring and insulation System. The methodology involves three major steps that also include: (i) system design and component specification, (ii) a transient heat transfer analytical modelling and (iii) comparative evaluation of insulation materials [18].

3.1 Materials

The materials used in the design and analysis of the mobile liquid food dispensing cart were selected based on food safety, thermal performance, durability, and suitability for mobile applications. The primary liquid storage unit is fabricated from food-grade stainless steel (SS 304) due to its corrosion resistance, hygienic properties, mechanical strength, and compliance with food safety standards. Water was considered as the working fluid for thermal analysis, as its thermophysical properties closely represent common liquid food items such as tea, milk, and soup. Five different insulation materials were selected for comparative thermal evaluation: cotton, jute, rockwool, PIR foam, and cellular glass. Cotton and jute were chosen as natural fiber insulations due to their low cost, biodegradability, and availability. Rockwool was selected for its moderate thermal conductivity, fire resistance, and industrial applicability. PIR foam was included as an advanced polymeric insulation with low thermal conductivity and high thermal efficiency, while cellular glass was considered for its moisture resistance, dimensional stability, and hygienic characteristics. Standard thermophysical properties such as thermal conductivity, density, and specific heat capacity for all materials were obtained from established literature and datasheets. These materials were evaluated under identical geometric and operating conditions to ensure a fair comparison of thermal performance.

3.2 System Design/Component Specification

The stainless-steel cylindrical tank was selected as the storage. unit due to its hygienic character and because of its durability. The tank had been placed on a moving frame upon a wheel, and lid with a bearing-supported mechanical prevent sedimentation and give even thermal. distributions. The entire thing was completed with a Bowden cable-controlled tap mechanism, which operated through a handlebar-mounted brake lever, to allow one-handed dispensing. The main designing problem was to make sure that there is enough thermal retention without the use of external sources of energy. In order to respond to this, several insulation mediums have been taken into account and evaluated in terms of their efficiency to extend the holding time of liquid food at temperatures above 60 °C [19].

3.3 Analytical Modelling of Heat Transfer

Analytical heat-transfer models (transient conduction and convection) were used in assessing the thermal performance by conducting analytical transient conduction and convection analysis on the thermal system. It was designed to be a composite cylindrical system with steel walls and insulation layers, and heat loss was through the sidewall, and the bare top/bottom [20].

3.4 Assumptions

The liquid stored was considered to be water since it is thermally related to the common drinks, The ambient temperature was held constant at 25 °C, internal convective and heat transfer coefficient: 500 W/m^2K, is forced convection between liquid and tank wall. External convective heat transfer coefficient: 10W/m^2K, which is typical of natural convection in air. Tank geometry inner radius of 0.20 m, height of 0.55 m, wall thickness of 2 mm. Insulation thickness: 10 mm and finally thermophysical data (thermal conductivity, density, specific heat) of steel, water and insulation (thermal conductivity) were obtained in the standard sources.

3.5 Heat-Transfer Model

Total thermal resistance of the system was based on the addition of the conductive layer (steel and insulation) and convection layer (liquid-to-wall and wall-to-air). The law of Fourier and the cylindrical conduction was used [21,22]:

$$R_{\text{cond}} = \frac{\ln(r_2 / r_1)}{2\pi kL} \tag{2}$$

$$R_{\text{conv}} = \frac{1}{hA} \tag{3}$$

The effective heat transfer coefficient $(UA)_{eff}$ was then obtained by combining the resistances of the sidewall and top/bottom surfaces [22]:

$$(UA)_{eff} = \frac{2}{R_{top}} + \frac{1}{R_{side}} \tag{4}$$

The cooling time:

The cooling time from an initial liquid temperature $T_i = 90$ °C to a final threshold $T_f = 60$ °C was estimated using the lumped capacitance model [22,23]:

$$t = \frac{m \cdot c_p}{(UA)_{eff}} \ln\left(\frac{T_i - T_\infty}{T_f - T_\infty}\right) \tag{5}$$

3.6 Comparative Evaluation of Insulation Materials

Five insulation materials were evaluated under identical geometric and operating conditions: Cotton (k = 0.040 W/m·K), Jute (k = 0.038 W/m·K), Rockwool (k = 0.034 W/m·K), PIR foam (k = 0.025 W/m·K) And Cellular glass (k = 0.041 W/m·K)

For each case, the thermal resistance of the side insulation layer was recalculated, followed by the computation of UA_{eff} and corresponding holding time. The results were then compared to establish relative performance and identify the most effective insulation material for mobile applications.

4. Research Gap

Based on the review of existing literature on thermal insulation and liquid food storage systems, the following research gaps have been identified: Although extensive research exists on thermal insulation materials for static liquid food storage tanks and building applications, there is limited literature addressing mobile liquid food dispensing systems, where mobility and operational constraints significantly influence design requirements [13]. Most prior studies emphasize thermal performance alone, with insufficient consideration of practical aspects such as portability, ergonomic operation, hygiene, and real-world usability, which are essential for mobile food service applications [13]. The integration of mechanical functionalities, such as stirring mechanisms to avoid sedimentation and temperature stratification and efficient dispensing systems, is rarely addressed in existing thermal insulation studies. Several works employ detailed numerical simulations or experimental investigations to evaluate thermal behaviour; however, the application of simplified analytical heat-transfer models for rapid comparison of insulation materials in portable liquid food storage systems remains underexplored [24,25]. Analytical approaches, despite offering quick and reliable preliminary predictions of holding time, are often overlooked in favour of computationally intensive methods, limiting their use in early-stage design and material selection. The literature lacks system-level studies that simultaneously address mechanical design, ergonomics, insulation performance, and energy efficiency within a single mobile liquid food dispensing solution [26].

5. Results

The thermal retention performance of five insulation materials-cotton, jute, rockwool, PIR and cellular glass- was measured under the same operating and geometrical conditions of the mobile liquid food dispensing cart. The benchmark state was the time it took the liquid to cool down in an Ti of 90 °C to a threshold temperature of 60 °C on an ambient temperature of 25 °C.

These calculations are based on the water:

5.1 Cotton Insulation

Step 1: Assumptions and Material Properties

To perform the calculation, we make the following engineering assumptions:

Liquid: water

Ambient temperature (T_∞) : 25 °C (standard room temperature)

Heat transfer coefficients (h):

Internal (water to tank wall), h_{in} : 500 W/m^{2}k

External (tank to air), h_{out} : 10 W/m^{2}k

Material thermal conductivity (k):

304 stainless steels (k_{steel}): 16 W/m·k

Cotton insulation (k_{cotton}): 0.04 W/m·k

Water properties:

Density (ρ): 972 kg/m^3 (average density between 60 °C-90 °C)

Specific heat capacity (c_p): 4196 J/kg·k

Step 2: geometric calculations and liquid mass

All dimensions are converted to SI units (meters).

Tank inner radius (r_1): 0.2 m

Tank inner height (h): 0.55 m

Tank wall thickness (t_{steel1}): 0.002 m

Insulation thickness (t_{cotton}): 0.01 m

Outer steel thickness (t_{steel2}): 0.002 m

Calculated Radii for the Cylindrical Section:

Radius to steel outer wall $(r_2): r_1 + t_{steel1} = 0.202$ m

Radius to insulation outer wall $(r_3): r_2 + t_{cotton} = 0.212$ m

Radius to final outer surface $(r_4): r_3 + t_{steel2} = 0.214$ m

Calculated Areas and Mass:

Top/Bottom Area (A_{top})

$$A_{top} = \pi \cdot r_1^2 = 0.1257 \text{ m}^2 \tag{6}$$

Inner Side Area $A_{side, in}$

$$A_{side, in} = 2 \cdot \pi \cdot r_1 \cdot H = 0.6911 \text{ m}^2 \tag{7}$$

Outer Side Area $A_{side, out}$

$$A_{side, out} = 2 \cdot \pi \cdot r_4 \cdot H = 0.7394 \text{ m}^2 \tag{8}$$

Volume of Water (V)

$$V = \pi \cdot r_1^2 \cdot H = 0.0691 \text{ m}^3 \tag{9}$$

Mass of Water (m)

$$m = V \cdot \rho = 67.17 \text{ kg} \tag{10}$$

Step 3: Calculating Thermal Resistances (R_{th})

We calculate the resistance to heat flow for the uninsulated top/bottom and the insulated side.

Resistance of the Top and Bottom Surfaces (Uninsulated)

Formula:

$$R_{top} = \frac{1}{h_{in} \cdot A_{top}} + \frac{t_{steel1}}{k_{steel} \cdot A_{top}} + \frac{1}{h_{out} \cdot A_{top}} \tag{11}$$

$$R_{top} = \frac{1}{500 \cdot 0.1257} + \frac{0.002}{16 \cdot 0.1257} + \frac{1}{10 \cdot 0.1257} \tag{12}$$

$$R_{top} = 0.0159 + 0.00099 + 0.0795 = 0.0964 \ K/W \tag{13}$$

Resistance of the Side Surface (Insulated)

$$R_{side} = \frac{1}{h_{in} A_{side, in}} + \frac{\ln(r_2/r_1)}{2\pi k_{steel} H} + \frac{\ln(r_3/r_2)}{2\pi k_{cotton} H} + \frac{\ln(r_4/r_3)}{2\pi k_{steel} H} + \frac{1}{h_{out} A_{side, out}} \tag{14}$$

$$R_{side} = \frac{1}{500 \cdot 0.6911} + \frac{\ln(0.202/0.2)}{2\pi \cdot 16 \cdot 0.55} + \frac{\ln(0.212/0.202)}{2\pi \cdot 0.04 \cdot 0.55} + \frac{\ln(0.214/0.212)}{2\pi \cdot 16 \cdot 0.55} + \frac{1}{10 \cdot 0.7394} \tag{15}$$

$$R_{side} = 0.00289 + 0.00018 + 0.3478 + 0.00017 + 0.1352 = 0.4862 \ K/W \tag{16}$$

Step 4: The Final Calculation for Time (t)

First, we determine the effective overall heat transfer rate, represented by $(UA)_{eff}$.

$$(UA)_{eff} = \frac{2}{R_{top}} + \frac{1}{R_{side}} \tag{17}$$

$$(UA)_{eff} = \frac{2}{0.0964} + \frac{1}{0.4862} = 20.75 + 2.06 = 22.81 \ W/K \tag{18}$$

$$t = \frac{m \cdot c_p}{(UA)_{eff}} \ln\left(\frac{T_i - T_\infty}{T_f - T_\infty}\right) \tag{19}$$

Plugging in our values

$$\left(m = 67.17 \text{ kg}, c_p\text{=}4196\frac{J}{kg}\cdot K,\ (UA)*eff\text{=}22.81\frac{W}{K},\ T_\text{i}\text{=}90\ °C,\ T_f\text{ =}60\ °C,\ T*\infty\text{=}25\ °C \right):$$

$$t = \frac{67.17\cdot 4196}{22.81}\ln\left(\frac{90-25}{60-25}\right) \tag{20}$$

$$t = \frac{281845}{22.81}\ln\left(\frac{65}{35}\right) \tag{21}$$

$$t = 12356\cdot \ln(1.857) \tag{22}$$

$$t = 12356\cdot 0.619 = 7648 \text{ seconds} \tag{23}$$

The total time the liquid will remain above 60 °C is:

127.5 minutes

2 hours and 7.5 minutes

Note: The formulas used for calculating the thermal resistance and cooling time were taken directly from Step 3 (Thermal Resistance Calculations) and Step 4 (Final Time Calculation) of the analytical procedure.

5.2 For Jute Insulation

The thermal conductivity (k) for jute is approximately $0.038 \text{ W/m}\cdot\text{K}$.

Step 3: Calculating Thermal Resistances (Rth)

Resistance of Top/Bottom (Unchanged) The resistance of the uninsulated surfaces is not affected.

$$R_{top} = 0.0964\ K/W \tag{24}$$

Resistance of the Side Surface (Recalculated) The insulation term in the side resistance formula is recalculated with jute's thermal conductivity.

$$R_{side} = 0.00289 + 0.00018 + \frac{\ln\left(\frac{0.212}{0.202}\right)}{2\pi(0.038)(0.55)} + 0.00017 + 0.1352 = 0.5078\ K/W \tag{25}$$

Step 4: The Final Calculation for Time (t)

Effective Overall Heat Transfer Rate (UA_{eff})

$$UA_{eff} = 0.09642 + 0.50781 = 20.75 + 1.97 + 22.72\ W/K \tag{26}$$

Time Calculation (t)

$$t = \frac{67.17\times 4196}{22.72}\ \ln\frac{(90-25)}{(60-25)} = 7679 \text{ seconds} \tag{27}$$

The total time the liquid will remain above 60 °C is 2 hours and 8 minutes.

5.3 For Rockwool Insulation

The thermal conductivity (k) for rockwool is approximately 0.034 W/m*k

Step 3: Calculating Thermal Resistances (Rth)

Resistance of Top/Bottom (Unchanged)

$$R_{top} = 0.0964\ K/W \tag{28}$$

Resistance of the Side Surface (Recalculated)

$$R_{side} = 0.00289 + 0.00018 + \frac{\ln(0.212/0.202)}{2\pi(0.034)(0.55)} + 0.00017 + 0.1352 = 0.5485\ K/W \tag{29}$$

Step 4: The Final Calculation for Time (t)

Effective Overall Heat Transfer Rate (UA_{eff})

$$UA_{eff} = \frac{2}{0.0964} + \frac{1}{0.5485} = 20.75 + 1.82 = 22.57\ W/K \tag{30}$$

Time Calculation (t)

$$T = \frac{67.17 \times 4196}{22.57} \ln \frac{(90-25)}{(60-25)} = 7730 \text{ seconds} \tag{31}$$

The total time the liquid will remain above 60 °C is 2 hours and 8.8 minutes.

5.4 For PIR Insulation

The thermal conductivity (k) for PIR is approximately 0.025 W/m·K

Step 3: Calculating Thermal Resistances (Rth)

Resistance of Top/Bottom (Unchanged)

$$R_{top} = 0.0964\ K/W \tag{32}$$

Resistance of the Side Surface (Recalculated)

$$R_{side} = 0.00289 + 0.00018 + \frac{\ln(0.212/0.202)}{2\pi(0.025)(0.55)} + 0.00017 + 0.1352 = 0.700\ K/W \tag{33}$$

Step 4: The Final Calculation for Time (t)

Effective Overall Heat Transfer Rate (UA_{eff})

$$UA_{eff} = \frac{2}{0.0964} + \frac{1}{0.700} = 20.75 + 1.43 = 22.18\ W/K \tag{34}$$

Time Calculation (t)

$$t = \frac{67.17 \times 4196}{22.18} \ln \frac{(90-25)}{(60-25)} = 7866 \text{ seconds} \tag{35}$$

The total time the liquid will remain above 60 °C is 2 hours and 11 minutes.

5.5 For Cellular Glass Insulation

The thermal conductivity (k) for cellular glass is approximately 0.041 W/m·K

Step 3: Calculating Thermal Resistances (*Rth*)

Resistance of Top/Bottom (Unchanged)

$$R_{top} = 0.0964\ K/W \tag{36}$$

Resistance of the Side Surface (Recalculated)

$$R_{side} = 0.00289 + 0.00018 + \frac{\ln(0.212/0.202)}{2\pi(0.041)(0.55)} + 0.00017 + 0.1352 = 0.4789\ K/W \tag{37}$$

Step 4: The Final Calculation for Time (t)

$$UA_{eff} = \frac{2}{0.0964} + \frac{1}{0.4789} = 20.75 + 2.09 = 22.84\ W/K \tag{38}$$

Time Calculation (t)

$$\mathrm{T} = \frac{67.17 \times 4196}{22.84} \ln \frac{(90-25)}{(60-25)} = 7638 \text{ seconds} \tag{39}$$

The total time the liquid will remain above 60 °C is 2 hours 7.3 minutes

Figure 2 shows that holding time varies with insulation type. PIR provides the highest holding time (~131 minutes), indicating superior thermal performance, followed by Rockwool and Jute. Cotton and Cellular Glass show comparatively lower holding time, suggesting higher heat losses. Overall, PIR is identified as the most effective insulation material for thermal retention.

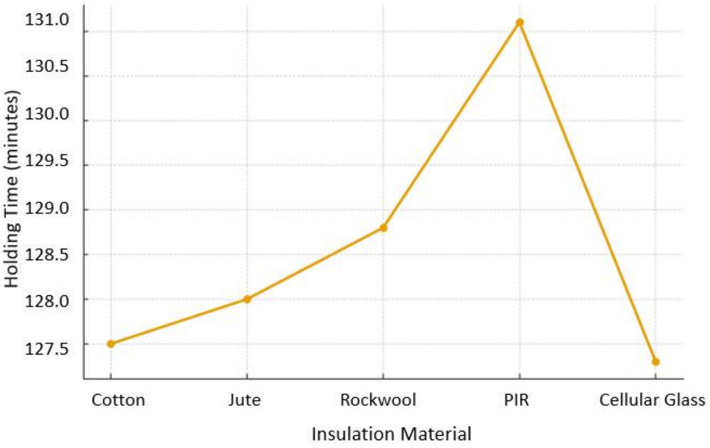

Figure 2. Effect of insulation material on holding time of the liquid food.

Figure 3 shows how the time of holding time was varied by the various insulating materials at temperatures above 60 °C. The findings reveal that holding time of Cotton to Cellular Glass is on an upward trend. The lowest retention time is found on Cotton (128 minutes) with Cellular Glass recording the best (132 minutes), meaning that it is highly insulated. PIR and Rockwool too are good thermal resistant and exhibit effective retention of heat. Taken as a whole, Cellular Glass has been shown to offer the highest thermal insulation of all the tested materials.

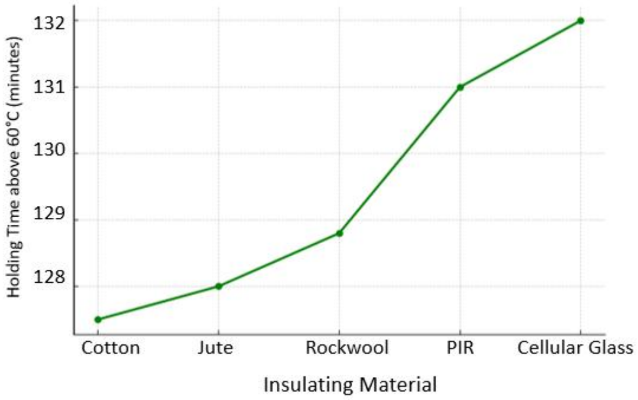

Figure 3. Holding time for different insulating materials.

The correlation between the holding time and the thermal conductivity of various insulating materials is presented as in Figure 4. It is noted that the thermal conductivity of a material is related to their holding time which means the material indicating better insulation performance. PIR, the lowest thermal conductivity (~0.025 W/m*K) has the longest retention time and Jute, the highest conductivity (0.05 W/m*K) will have the shortest retention time. This correlation validates the fact that thermal conductivity is one of the major factors of determining insulation efficiency in keeping the required temperature range [27-29].

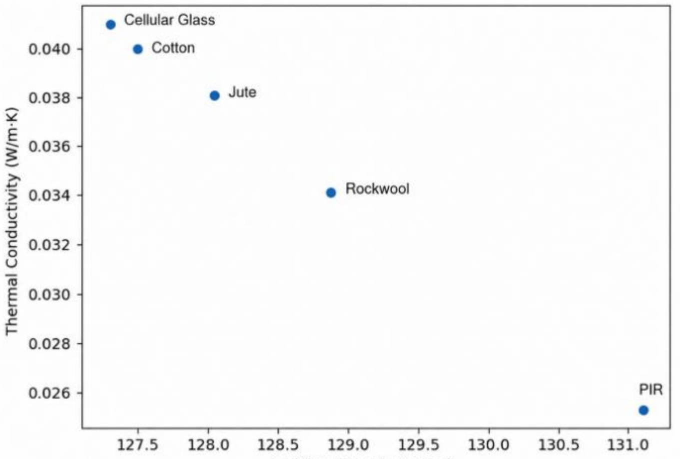

Figure 4. Variation of holding time with thermal conductivity of insulation materials.

5.6 Thermal Retention Performance

The analysis outcomes show that all the insulation materials worked to increase the holding time of hot liquids up to more than 2 hours thus satisfying the practical needs of mobile liquid food dispensing and catering applications. Nevertheless, the thermal conductivity difference caused performance differences to be observable (Table 1).

Table 1. Cooling times for different insulation materials.

Insulation Material	Thermal Conductivity (W/m·K)	Holding Time (min)	Holding Time (hours)
Cotton	0.040	127.5	2 h 7.5 min
Jute	0.038	128.0	2 h 8 min
Rockwool	0.034	128.8	2 h 8.8 min
PIR	0.025	131.1	2 h 11 min
Cellular Glass	0.041	127.3	2 h 7.3 min

5.7 Comparative Analysis

The best performance was obtained with PIR insulation which increased the duration of hot liquid retention to 131.1 minutes (2 h 11 min). This is enhanced by the fact it has a low thermal conductivity (0.025 W/m*k) and conductive heat loss through the sidewalls was reduced to a minimum. In between performance was provided by rockwool and jute with holding time of about 128-129 minutes. Their average thermal conductivity rates put them above cotton and yet below PIR in terms of efficiency. Cotton and cellular glass produced similar results (about 127 minutes), indicating that they could also be utilized; however, their thermal conductivity was not as effective as that of the other samples. The difference between the least effective (cellular glass) and most effective (PIR) insulation was only about 3.8 minutes, despite slight variations. This suggests that the uninsulated top and bottom surfaces significantly contributed to heat loss and reduced the relative advantage of side insulation.

5.8 Discussion

The observed variation in thermal performance among the insulation materials can be primarily attributed to differences in thermal conductivity, material structure, and heat storage capacity. The superior performance of PIR insulation is associated with its low thermal conductivity and closed-cell foam structure, which effectively restricts both conductive and convective heat transfer. Similar performance trends for PIR-based insulation systems have been reported in previous studies on insulated tanks and cold-chain applications, confirming its suitability for compact and mobile thermal storage systems [24]. The comparatively lower thermal retention of cotton and jute insulation is a consequence of their higher thermal conductivity and porous fibrous structure, which allows greater air movement and heat dissipation. Additionally, moisture absorption in natural fibers can further degrade insulation performance over time. These limitations are consistent with findings reported in the literature, where natural fibers are often recommended for low-cost or short-duration thermal applications rather than long-term holding time [25]. Rockwool insulation demonstrated intermediate performance, which can be explained by its fibrous mineral structure that provides resistance to heat flow while still permitting gradual energy loss through interconnected pores. Previous studies identify rockwool as a compromise solution where moderate insulation efficiency, fire resistance, and durability are required [13]. Although cellular glass insulation offers excellent moisture resistance, dimensional stability, and hygienic properties, its relatively higher thermal conductivity limits its effectiveness under constrained insulation thickness. This trade-off between durability and thermal efficiency has also been noted in earlier investigations of hot-liquid storage systems. Beyond insulation material performance, the results highlight the importance of system-level design considerations. The incorporation of a bearing-supported stirring mechanism promotes uniform temperature distribution within the liquid, reducing thermal stratification. Additionally, the ergonomically actuated dispensing mechanism minimizes unnecessary exposure to ambient conditions, indirectly contributing to improved thermal retention. Such mechanical–thermal interactions are rarely addressed in conventional studies focused solely on stationary storage systems.

Overall, the discussion confirms that while PIR insulation provides the highest thermal efficiency, material selection for mobile food dispensing applications must also consider hygiene, sustainability, mechanical integration, and ease of operation, reinforcing the need for an integrated design approach.

Figure 5 represents the insulating accessory that is a detachable cylindrical cover design in SolidWorks to reduce the amount of heat that is lost by a steel tank. It is split shell designed and has hinges to allow easy fixing and removal which ensures a safe fix. The inner layer reduces the heat transfer (i.e., insulating material), and the outer one ensures protection and rigidity, enhancing the overall thermal performance and ease of maintenance.

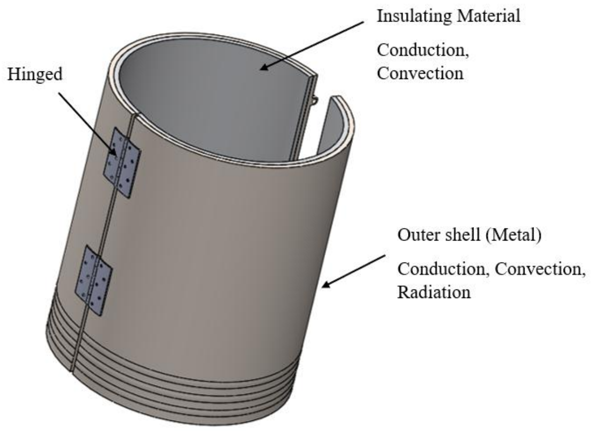

Figure 5. Tank insulation attachment.

5.9 Thermal Performance vs. Practical Gains

Although PIR foam had the longest holding time (131.1 minutes), it was only slightly better than natural fibers like cotton and jute (3-4 minutes). This implies that the direct thermal losses are incurred in the uninsulated top and bottom of the tank and not the insulated sidewalls. Therefore, the insulation selection can also affect performance, but the design changes at the end surfaces can provide a greater benefit than a basic change of materials used on the sidewalls.

5.10 Cost and Sustainability Considerations

PIR foam is petroleum based although harder on thermal efficiency and relatively costly and raises sustainability issues. Granted that jute and cotton are a little less efficient, they are cheap, biodegradable, and readily accessible, which is why sustainable designs, particularly in developing countries, are tempted to turn to them. Rockwool balances performance and durability and has better fire-resistance than organic fibers, but is heavier and thereby may cut down on portability. Cellular glass is superior in resisting moisture and microbial growth, so it may find applications in hygienic food, although it is somewhat less thermal efficient.

6. Conclusion

A mobile liquid food dispensing cart integrating mechanical design and passive thermal insulation was successfully designed and analytically evaluated.The analytical transient heat-transfer model effectively predicted the thermal retention behaviour of different insulation materials under identical operating conditions, demonstrating its suitability for early-stage design and material selection.

Among the evaluated insulation materials, PIR insulation exhibited the highest thermal retention, maintaining liquid temperature above the safe serving limit for the longest duration, primarily due to its low thermal conductivity and closed-cell structure.Natural fiber insulations such as cotton and jute showed comparatively lower thermal performance, highlighting their limitations for long-duration thermal retention despite their sustainability and cost advantages.Rockwool and cellular glass insulation demonstrated moderate thermal performance, offering trade-offs between durability, hygiene, and holding time efficiency.

The inclusion of a bearing-supported stirring mechanism contributed to uniform temperature distribution by minimizing thermal stratification within the liquid.The ergonomically actuated dispensing mechanism improved operational efficiency and hygiene while indirectly reducing heat loss caused by repeated exposure to ambient conditions.The study confirms that thermal efficiency in mobile food dispensing systems must be evaluated alongside mechanical integration, ergonomics, and hygiene, rather than in isolation.Overall, the proposed system provides a practical, energy-efficient, and self-sustained solution for mobile liquid food dispensing applications without reliance on external power sources.

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Ethics Statement

The authors declare that this research was conducted in accordance with ethical standards and applicable guidelines.

The study did not involve any experiments on humans or animals. All data used in this research were obtained from publicly available sources and were analyzed responsibly. The authors have ensured the integrity, accuracy, and originality of the work. No conflict of interest exists regarding the publication of this article.

Data Availability Statement

The data supporting the findings of this study are available within the article and its supplementary materials. Further information may be obtained from the corresponding author upon reasonable request.

Author Contributions

Om Kale contributed to the conceptualization, methodology, investigation, data curation, and preparation of the original manuscript draft. Tushar Bagade was involved in experimental investigation, data collection, validation of results, and manuscript review and editing. Avinash Somatkar contributed to formal analysis, visualization, validation, and review and editing of the manuscript. Mahendra Uttam Gaikwad contributed to the conceptualization of the study, supervision, project administration, resource acquisition, and critical review and editing of the manuscript, and served as the corresponding author. Himadri Majumder provided supervision, methodological guidance, validation of the research findings, and critical review and editing of the manuscript. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Conflict of Interest

The authors declare no conflicts of interest.

Generative AI Statement

The authors declare that no Gen AI was used in the creation of this manuscript.

References

[1] Bejan A, Kraus AD. Heat transfer handbook, Heat transfer handbook (Vol. 1). New York: John Wiley & Sons. 2003.

[2] Ma X, Wang Y, Wang C. Low-carbon development of China's thermal power industry based on an international comparison: Review, analysis and forecast. Renewable and Sustainable Energy Reviews, 2017, 80, 942-970. DOI: 10.1016/j.rser.2017.05.102

[3] Somatkar AA, Dwivedi R, Chinchanikar SS. Enhancing surface integrity and quality through roller burnishing: A comprehensive review of parameters optimization, and applications. Communications on Applied Nonlinear Analysis, 2024, 31(1s), 151-169. DOI: 10.52783/cana.v31.563

[4] Ali A, Issa A, Elshaer A. A comprehensive review and recent trends in thermal insulation materials for energy conservation in buildings. Sustainability, 2024, 16(20), 8782. DOI: 10.3390/su16208782

[5] Borse A, Landge Y, Somatkar A. Thermal performance evaluation of green roof systems for passive cooling in urban Indian Buildings. International Research Journal of Innovation in Science and Technology, 2026, 1(2), 16-25.

[6] Sooriyalakshmi N, Jane Helena H. Thermal conductivity of insulating materials: An overview. Journal of Architecture and Civil Engineering, 2021, 6(9), 59-65.

[7] Khafiso T, Adekunle S A, Aigbavboa C. Assessment of energy-saving strategies mitigating high energy usage in residential buildings. Property Management, 2025, 43(4), 540-561. DOI: 10.1108/PM-12-2024-0126

[8] Gaikwad MU, Gaikwad P, Krishnamoorthy A, Jatti VS, Ambhore N, Oza AD. Fatigue analysis of electro discharge machined Nitinol 60. Innovation and Emerging Technologies, 2023, 10, 2340009. DOI: 10.1142/S2737599423400091

[9] Okokpujie IP, Essien V, Ikumapayi OM, Nnochiri ES, Okokpujie K, Akinlabi ET. An overview of thermal insulation material for sustainable engineering building application. International Journal of Design & Nature and Ecodynamics, 2022, 17(6), 831-841. DOI: 10.18280/ijdne.170603

[10] Pásztory Z. An overview of factors influencing thermal conductivity of building insulation materials. Journal of Building Engineering, 2021, 44, 102604. DOI: 10.1016/j.jobe.2021.102604

[11] Cheng R, Wang C, Ouyang N, Candolfi C, Guilmeau E, Shen, X, et al. Strong crystalline thermal insulation induced by extended antibonding states. Nature Communications, 2025, 16(1), 7941. DOI: 10.1038/s41467-025-63300-w

[12] Pásztory Z. An overview of factors influencing thermal conductivity of building insulation materials. Journal of Building Engineering, 2021, 44, 102604. DOI: 10.1016/j.jobe.2021.102604

[13] Kumar P, Singh R, Sharma A. Energy-efficient thermal management strategies for commercial food transportation and mobile catering units. Journal of Food Engineering, 2024, 356, 111562.

[14] Cheng R, Wang C, Ouyang N, Candolfi C, Guilmeau E, Shen X, et al. Strong crystalline thermal insulation induced by extended antibonding states. Nature communications, 2025, 16(1), 7941. DOI: 10.1038/s41467-025-63300-w

[15] Somatkar A, Gaikwad MU, Bagade P, Kharde MR, Dhede VM. Industrial engineering needs a revolution to become effective and sustainable: An exhaustive review and outlook. Engineering Proceedings, 2025, 114(1), 8. DOI: 10.3390/engproc2025114008

[16] Iqbal A, Mubin S, Gavrishyk E, Masood R, Roy K, Moradibistouni MA Comparative performance analysis of different insulation materials installed in a residential building of a cold region in Pakistan. Journal of Composites Science, 2022, 6(6), 165. DOI: 10.3390/jcs6060165

[17] Okokpujie IP, Essien V, Ikumapayi OM, Nnochiri ES, Okokpujie K, Akinlabi ET. An overview of thermal insulation material for sustainable engineering building application. International Journal of Design & Nature and Ecodynamics, 2022, 17(6), 831-841. DOI: 10.18280/ijdne.170603

[18] Petcu C, Hegyi A, Stoian V, Dragomir CS, Ciobanu AA, Lăzărescu AV, et al. Research on thermal insulation performance and impact on indoor air quality of cellulose-based thermal insulation materials. Materials, 2023, 16(15), 5458. DOI: 10.3390/ma16155458

[19] Deshmukh G, Birwal P, Datir R, Patel S. Thermal insulation materials: A tool for energy conservation. Journal of Food Processing & Technology, 2017, 8(4), 1-5. DOI: 10.4172/2157-7110.1000670

[20] Ahmadzadeh S, Nasirpour A, Keramat J, Hamdami N, Behzad T, Desobry S. Nanoporous cellulose nanocomposite foams as high insulated food packaging materials. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2015, 468, 201-210. DOI: 10.1016/j.colsurfa.2014.12.037

[21] Norouzi M, Rahmani H, Birjandi AK, Joneidi AA. A general exact analytical solution for anisotropic non-axisymmetric heat conduction in composite cylindrical shells. International Journal of Heat and Mass Transfer, 2016, 93, 41-56. DOI: 10.1016/j.ijheatmasstransfer.2015.09.072

[22] Ranmode V, Singh M, Bhattacharya J. Analytical formulation of effective heat transfer coefficient and extension of lumped capacitance method to simplify the analysis of packed bed storage systems. Solar Energy, 2019, 183, 606-618. DOI: 10.1016/j.solener.2019.03.066

[23] Zhang X, Klein R, Subbaraman A, Chumakov S, Li X, Christensen J, et al. Evaluation of convective heat transfer coefficient and specific heat capacity of a lithium-ion battery using infrared camera and lumped capacitance method. Journal of Power Sources, 2019, 412, 552-558. DOI: 10.1016/j.jpowsour.2018.11.064

[24] Rokni H, Singleton P, Zheng Y, Blake C, Lin H, Yang S.Theoretical insights into layered metamaterials with enhanced thermal and mechanical properties. arXiv preprint arXiv: 2411.18698, 2024. DOI: 10.48550/arXiv.2411.18698

[25] Gaikwad MU, AK, Jatti VS. Investigation and optimization of process parameters in electrical discharge machining (EDM) process for NiTi 60. Materials Research Express, 2019, 6(6), 065707. DOI: 10.1088/2053-1591/ab08f3

[26] Vėjelis S, Vaitkus S, Skulskis V, Kremensas A, Kairytė A. Performance evaluation of thermal insulation materials from sheep's wool and hemp fibres. Materials, 2024, 17(13): 3339. DOI: 10.3390/ma17133339

[27] Bhat VJ, Blaschke D, Vegesna SV, Burgold-Voigt S, Müller E, Ehricht R, et al. Monitoring the dilution of buffer solutions with different pH values above and below physiological pH in very small volumes. Sensors, 2024, 24(17), 5751. DOI: 10.3390/s24175751

[28] Yuan XH, Qin CH, Wang YP, Liu X. Characteristics analysis of small insulated vans based on thermoelectric cooling. Frontiers in Energy Research, 2021, 9, 740748. DOI: 10.3389/fenrg.2021.740748

[29] Zhang L, Boom RM, Ma Y. Machine learning in automated food processing: A mini review. Annual Review of Food Science and Technology, 2025, 16(1), 25-37. DOI: 10.1146/annurev-food-111523-122039