ISSN: 3048-9563

KT Journal of Mechanical Engineering

Key Tech Services Publication, India

http://www.ktjme.com
https://doi.org/10.64188/3048956326204

Vol.: 3, No. 2, 2026, Pages: 37-42

A Modular Semi-Rigid Thermal-Management Bag for Last-Mile Transportation of Temperature-Sensitive Medical Products

Dattatray S. Galhe[1], Nishigandh B Gorade[2], Borade Tanuja[3], Gunjal Sanskar[4], Nighot Madhura[5]

[1-5]Department of Mechanical Engineering, Jaihind College of Engineering, Kuran, Pune 410511

Abstract

ThermaVault is a modular semi-rigid thermal-management bag proposed for the last-mile transportation of temperature-sensitive medical products. The project focuses on a practical balance between thermal protection, portability, structural support and flexible internal storage. The proposed bag uses a protective outer layer, semi-rigid HDPE/PP panels, reflective foil, polyurethane (PU) foam, removable phase change material (PCM) sleeves and a removable modular tray. Product-specific inserts are proposed for insulin pens, pharmaceutical vials and blood/sample tubes. Published studies show that insulation, PCM arrangement, container geometry and ambient temperature strongly affect passive cold-storage performance. The present work therefore investigates these factors within a compact semi-rigid bag rather than claiming the individual technologies as new. A target capacity of 8–10 L is considered, with a preliminary internal chamber of 330 × 200 × 140 mm (9.24 L) and approximately 25 mm PU insulation. CAD modelling, heat-transfer calculations and temperature-retention testing will be used to evaluate the design. Temperature monitoring is included for testing, while active cooling and IoT functions are considered future extensions

1. Introduction

Temperature-sensitive medical products require suitable thermal conditions during storage and transportation. Insulin, pharmaceutical preparations and biological samples may be affected by excessive heat, freezing or long exposure to uncontrolled ambient conditions. The last-mile stage is difficult because transport can involve high ambient temperature, repeated handling, delays and limited access to powered refrigeration. Conventional cold boxes, vaccine carriers and insulated bags already use insulation and coolant packs for passive thermal protection. PCM-based systems are also established. Research shows that PCM arrangement, insulation performance, container geometry and ambient temperature can strongly affect storage duration

Received: 05.04.2026 Revised: 08.05.2026 Accepted:17.06.2026 Published Online: 10.07.2026

Keywords: Thermal management, PCM, cold chain, medical transport, modular storage, PU insulation
*Corresponding author name and email: Nishigandh B Gorade, nishigandh1992@gmail.com
How to cite this article: Dattatray Shankar Galhe, Nishigandh B Gorade, Borade Tanuja, Gunjal Sanskar, Nighot Madhura, A Modular Semi-Rigid Thermal-Management Bag for Last-Mile Transportation of Temperature-Sensitive Medical Products, KT Journal of Mechanical Engineering, 3 (2) 2026, 37-42. https://doi.org/10.64188/3048956326204

and temperature uniformity [1-5]. ThermaVault is therefore proposed as an engineering integration study. The focus is a common semi-rigid thermal enclosure with removable PCM sleeves and interchangeable product-specific inserts. Portable medical carriers are often designed around a particular product type, container geometry or cooling method. A carrier may provide thermal protection but limited internal organization or structural support. Active cooling and connected electronics can also increase weight, cost and power requirements. The problem addressed in this work is to develop a compact carrier that combines passive thermal protection, structural support and adaptable internal storage. The objectives of the study is to investigate PCM quantity and placement, to develop a semi-rigid bag with a removable modular tray, to design interchangeable inserts for insulin pens, vials and sample tubes, to prepare CAD models and preliminary thermal calculations and to evaluate temperature retention and thermal uniformity.

2. Literature Review

Ray et al. (2022) studied portable PCM cold-storage boxes and compared different geometries. Their results showed that configuration and heat transfer influence cooling duration. They developed a PCM-based portable cold box, focusing on optimized geometry to enhance thermal retention during transit, demonstrating the feasibility of compact passive cooling units for field applications. Devrani et al. (2021) studied a vaccine carrier using CFD, insulation R-value measurements, PCM selection and temperature monitoring; the redesigned carrier showed about 16% higher R-value and about 17% higher retention time. They investigated the role of insulation materials, PCM selection, and tray arrangement within cold storage units, and validated their design through experimental testing, highlighting how internal configuration significantly influences cooling duration and temperature uniformity. Nadimuthu and Victor (2022) investigated micro cold storage for last-mile vaccine logistics. Extending this concept to logistics, Nadimuthu and Victor [3] proposed a last-mile micro cold storage solution, addressing the critical gap in maintaining cold chain integrity during final-stage delivery in resource-constrained settings. Schmit et al. (2024) studied PCM development for vaccine transport without dry ice and showed that PCM selection must match the required temperature range and thermal cycling conditions. Schmit et al. (2024) focused specifically on PCM formulation for vaccine transport, emphasizing the development of materials with phase transition temperatures suited to strict pharmaceutical storage requirements, thereby improving reliability in medical cold chain logistics. Zhou et al. (2026) investigated modular passive cold devices using different PCMs, layouts and packing configurations. Their work confirms that PCM layout, insulation and ambient temperature are important design variables. Phase change material (PCM) based passive cooling systems have gained significant attention for cold chain and vaccine transport applications due to their ability to maintain temperature without continuous power input. More recently, Zhou et al. [5] explored modular passive cold devices with varied PCM layout configurations, demonstrating that modularity and layout optimization can further improve thermal performance and scalability of passive cooling systems. Collectively, these studies indicate a clear research trend toward compact, energy-independent, and application-specific PCM-based cooling solutions, with growing emphasis on geometry, material selection, and modular design for last-mile and vaccine cold chain applications.

3. Proposed Product and Specifications

The following values are preliminary engineering specifications for the prototype. Final dimensions and PCM quantity is confirmed after CAD fit checks, thermal calculations and testing. Table 1 shows the preliminary product specification and Table 2. For proposed layer arrangement

Table 1. Preliminary product specification

Parameter	**Proposed specification**
Product type	Semi-rigid modular thermal-management bag
Target capacity	8–10 L
Preliminary internal chamber	330 × 200 × 140 mm
Internal volume	9.24 L
Approx. external body	390 × 260 × 200 mm
Insulation	PU foam, approximately 25 mm
Structural panels	2–3 mm HDPE/PP
Reflective layer	Aluminium reflective foil
PCM system	Removable PCM sleeves; quantity to be finalized
Modular tray	Approx. 310 × 180 × 120 mm; CAD fit to be verified
Insert types	Insulin pen, pharmaceutical vial, blood/sample tube
Closure	U-shaped zipper opening
Carrying	Top handle + adjustable shoulder strap
Monitoring	Temperature sensors/data logger for testing
Cooling method	Passive thermal management

Table 2. Proposed layer arrangement

Layer	**Material / component**	**Function**
1	Outer fabric	Protection and handling
2	HDPE/PP sheet	Semi-rigid structural support
3	Reflective foil	Reduces radiant heat transfer
4	PU foam	Main thermal insulation
5	Removable PCM sleeve	Thermal energy storage
6	PP/HDPE divider	Separates PCM from product
7	Modular tray	Product organization
8	Medical product	Insulin pen / vial / sample tube

4. System Architecture

ThermaVault has four main parts: the outer semi-rigid enclosure, the insulation and PCM system, the modular storage system and the monitoring system. The outer enclosure provides structural protection. Insulation limits heat flow from the surroundings. PCM sleeves provide thermal buffering. The removable tray and product-specific inserts organize and protect the contents. A common tray interface allows one insert to be replaced by another without changing the complete thermal enclosure. PCM sleeves are removable so they can be conditioned and serviced separately.

4.1 Thermal Design and Analysis

The preliminary heat gain through an insulated wall can be estimated using:

$$\dot{Q} = kA\,(T_a - T_i) / L \tag{1}$$

where $\dot{Q}$ is heat-transfer rate, k is thermal conductivity, A is heat-transfer area, T_a is ambient temperature, T_i is internal temperature and L is insulation thickness.

4.2 PCM Thermal Storage

$$Q\_PCM = m\_PCM \times L\_PCM \tag{2}$$

where m_PCM is PCM mass and L_PCM is latent heat. Sensible heat effects can also be included when required. The final PCM mass will be selected from the required temperature range, desired transport duration, ambient condition and experimental results. This approach is supported by recent studies showing that PCM layout and ambient temperature have a major effect on passive cold-storage performance [1, 5]. Table 3 shows the modular insert specifications

Table 3. Modular insert specifications

Insert	Preliminary arrangement	Purpose
Insulin pen	Horizontal grooves, approximately 22–24 mm diameter	Prevents rolling and allows quick access
Pharmaceutical vial	Vertical cylindrical pockets	Keeps vials upright and separated
Blood/sample tube	Vertical filleted compartments with soft support	Reduces movement and contact damage

Exact insert dimensions will be finalized after measuring the actual products used for the prototype. Clearance will be provided for easy insertion and removal.

4.3 Material Selection

Table 5 shows the material selection for the setup and Table 6 shows the experimental evaluation plan

Table 5. Material selection

Component	Candidate material	Reason
Structural panels	HDPE / PP	Lightweight, rigid and moisture resistant

Insulation	PU foam	Good thermal insulation
Reflective layer	Aluminium foil laminate	Reduces radiant heat transfer
Outer cover	Durable fabric	Flexible protection
Inner divider	PP / thin HDPE	Lightweight and cleanable
Tray	PP / ABS / HDPE	Reusable and easy to fabricate
PCM enclosure	Sealed polymer sleeve	Prevents direct product contact

Table 6. Experimental evaluation plan

Test	Parameter	Measurement
Empty-bag test	Internal stability	Temperature vs. time
Loaded test	Performance with representative load	Temperature vs. time
PCM layout test	Side / bottom / combined placement	Retention and uniformity
Insulation test	Different thicknesses	Heat-gain comparison
Ambient test	Different surrounding temperatures	Temperature response
Handling test	Opening/closing and carrying	Temperature disturbance usability

Sensors should be placed at representative points such as the centre, upper region and lower region of the chamber. Testing will identify thermal gradients and support final selection of PCM quantity and placement. The expected results are functional prototype close to 8–10 L capacity, better product organization through interchangeable inserts, reduced heat transfer through PU insulation and reflective layer, measured influence of PCM quantity and placement, temperature-retention data for comparison with analytical calculations and reusable carrier architecture adaptable to different product geometries.

4.4 Sustainability and Practical Impact

The basic system is passive and does not require continuous electrical power for cooling. A reusable outer enclosure and replaceable inserts can reduce the need to manufacture a complete carrier for every product type. Modular components can also simplify repair and replacement. The prototype is intended for research and short-duration last-mile applications. It should not be treated as validated medical cold-chain equipment. Real medical use would require product-specific qualification, temperature mapping, validation and compliance with applicable requirements.

5. CONCLUSION

ThermaVault proposes a practical modular architecture for passive thermal management during last-mile transportation of temperature-sensitive medical products. Published research confirms that insulation, PCM arrangement, geometry and ambient temperature are important factors in portable cold-chain performance. The proposed design combines these established principles with a semi-rigid outer structure and interchangeable product-specific inserts. The initial target is an 8–10 L carrier with a 9.24 L internal chamber and approximately 25 mm PU insulation. Final PCM quantity, thermal performance and detailed dimensions will be established through calculation, CAD development and experimental testing.

REFERENCES

[1] A. K. Ray, S. Singh, D. Rakshit, and Udayraj, “Comparative study of cooling performance for portable cold storage box using phase change medium,” Thermal Science and Engineering Progress, vol. 27, art. 101146, 2022. doi: 10.1016/j.tsep.2021.101146.

[2] S. Devrani, R. Tiwari, N. Khan, K. Sankar, S. Patil, and K. Sridhar, “Enhancing the insulation capability of a vaccine carrier box: An engineering approach,” Journal of Energy Storage, vol. 36, art. 102182, 2021. doi: 10.1016/j.est.2020.102182.

[3] L. P. R. Nadimuthu and K. Victor, “Environmental friendly micro cold storage for last-mile Covid-19 vaccine logistics,” Environmental Science and Pollution Research, 2022. doi: 10.1007/s11356-021-17584-2.

[4] H. Schmit et al., “Development of a phase change material for vaccine transport without dry ice,” Energy Storage, vol. 6, no. 1, e557, 2024. doi: 10.1002/est2.557.

[5] Z. Zhou, Y. Zhang, A. Rahbari, B. Chalermsinsuwan, X. Zhai, and X. Wang, “Modularized passive cold devices with phase change materials for efficient vaccine delivery in remote areas,” International Communications in Heat and Mass Transfer, vol. 172, art. 110428, 2026. doi: 10.1016/j.icheatmasstransfer.2025.110428.

[6] M. M. Farid et al., “A review on phase change energy storage: Materials and applications,” Energy Conversion and Management, vol. 45, nos. 9–10, pp. 1597–1615, 2004. doi: 10.1016/j.enconman.2003.09.015.

[7] A. Sharma, V. V. Tyagi, C. R. Chen, and D. Buddhi, “Review on thermal energy storage with phase change materials and applications,” Renewable and Sustainable Energy Reviews, vol. 13, no. 2, pp. 318–345, 2009. doi: 10.1016/j.rser.2007.10.005.

[8] D. Das, R. K. Sharma, P. Saikia, and D. Rakshit, “An integrated entropy-based multi-attribute decision-making model for phase change material selection and passive thermal management,” Decision Analytics Journal, vol. 1, art. 100011, 2021.