Development of a Thermal Insulated AC Cabin for Extreme Temperature Conditions

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ABSTRACT

This paper presents the design, development, and performance evaluation of an insulated air-conditioned (AC) cabin capable of maintaining interior temperatures between 25°C and 30°C under extreme ambient conditions up to 80°C. The system was designed for use in automotive, industrial, and defense environments, where thermal comfort and energy efficiency are essential. A dual-layer insulation system consisting of 30–40 mm of polyurethane foam (PUF) and 8 mm of reflective bubble foil was implemented. Thermal load analysis, including conduction, radiation, and occupant heat gain, was conducted to determine the cooling requirement. Experimental testing under a polycarbonate shed environment showed that the insulation reduced the total cooling load to approximately 0.6 kW, enabling the use of a compact 1 TR rooftop AC unit. The insulated cabin achieved interior comfort within the desired range with a low compressor duty cycle of 25–35%, confirming high thermal efficiency. The study demonstrates a practical approach to integrating insulation materials with optimized HVAC design for maintaining comfortable conditions in high-temperature environments.

KEYWORDS

Polyurethane Foam (PUF), Reflective Insulation, Air Conditioning, Thermal Load, HVAC Design, High Ambient Temperature.

1. INTRODUCTION

Thermal management in enclosed spaces operating under high ambient temperatures has become a critical engineering challenge across the automotive, industrial, and defense sectors. Maintaining interior thermal comfort is essential not only for human safety but also for equipment reliability and operational efficiency. When ambient temperatures exceed 70°C, heat ingress through metallic surfaces and glazing rapidly raises internal temperatures, leading to overheating and reduced HVAC efficiency.

Traditional air-conditioning systems experience significant performance losses under such extreme conditions due to reduced condenser efficiency and elevated cooling demands. Therefore, combining advanced insulation systems with appropriately sized HVAC units is a promising solution for achieving energy-efficient thermal control.

Polyurethane foam (PUF) insulation and reflective bubble foil have emerged as effective materials for minimizing conductive and radiant heat transfer. Their integration into cabin design allows for significant reduction in cooling load, making compact air-conditioning systems feasible. This research aims to develop and experimentally validate an insulated AC cabin capable of maintaining comfortable conditions (25°C–30°C) under external temperatures up to 80°C.

2. LITERATURE REVIEW

Polyurethane foam (PUF) is widely recognized for its low thermal conductivity (0.022–0.028 W/m·K) and lightweight cellular structure, making it a preferred insulation material for enclosures exposed to high temperatures. Studies by Saha et al. (2019) and Yadav and Kumar (2018) confirmed that 30–40 mm of PUF can reduce heat ingress by more than 60% in vehicle cabin applications. Reflective bubble foil insulation complements PUF by targeting radiant heat; Sharma et al. (2020) showed that reflective foil can reduce solar heat gain by up to 95% when properly installed.

High ambient temperature conditions significantly degrade AC system performance, as noted by Patil et al. (2018) and Abdullah et al. (2016). Combining effective insulation with optimized HVAC sizing is therefore critical to maintain efficiency. Comparative studies (Ravi et al., 2021; Kandpal and Singh, 2020) found PUF to offer the best thermal performance-to-cost ratio, while aerogels and vacuum insulation panels, though superior in performance, remain cost-prohibitive.

The literature consistently identifies integrated insulation and HVAC design as the most practical approach for achieving reliable and efficient thermal control in compact enclosures.

3. OBJECTIVE AND METHODOLOGY

3.1 Objectives

The primary objective is to design and evaluate an insulated air-conditioned cabin that maintains 25°C–30°C internal temperature under ambient heat conditions up to 80°C. Specific aims include:

- Selection of suitable insulation materials that minimize conduction and radiation.
- Determination of total thermal load under steady-state conditions.
- Optimization of air-conditioning system capacity for efficient energy use.

- Experimental validation of insulation and HVAC performance under simulated high-temperature environments.

3.2 Methodology

The study followed a structured experimental and analytical methodology. Cabin and Insulation Design: The cabin was designed as a closed metallic structure with a total surface area of approximately 6 m². It was insulated using a dual-layer configuration of 35–40 mm PUF and 8 mm reflective bubble foil. The reflective layer minimized radiant heat, while the PUF provided resistance against conduction and convection. Laminated glass with solar-control film was used for glazing to reduce solar gain.

Thermal Load Estimation: Total heat ingress was determined using the relation:
$Q_{total} = Q_{glass} + Q_{sheet} + Q_{occupant}$
where each component was evaluated using respective U-values and surface areas.

For the insulated sheet metal section,
$U = 1 / R_{total}$, with $R_{total} = R_{PUF} + R_{foil}$.
Based on thermal conductivity and thickness, the overall U-value was found to be approximately 0.67 W/m²·K.

AC System Sizing: The total cooling load was estimated at 0.62 kW (~2100 BTU/hr), leading to the selection of a 1 TR (3.5 kW) rooftop AC unit to ensure capacity under peak heat conditions.

Performance Testing: The system was evaluated experimentally under a polycarbonate shed, simulating 38°C–57°C ambient temperatures. Multiple thermocouples measured surface and air temperatures, and power consumption was recorded to assess energy efficiency.

4. EXPERIMENTAL SETUP

The insulated cabin was constructed using composite sheet metal panels incorporating PUF insulation and reflective foil. The AC unit was mounted on the roof to ensure optimal airflow and ease of maintenance. A polycarbonate shed provided controlled high-temperature test conditions while shielding the setup from direct rainfall and excessive solar glare.

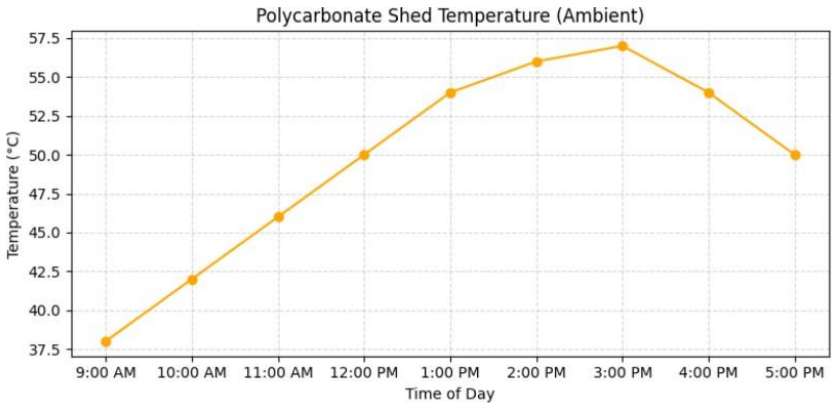
Instrumentation: Temperature and humidity sensors were placed inside and outside the cabin to record variations. Surface thermocouples were attached to the inner and outer walls, glass panels, and insulation layers. A wattmeter was used to measure AC power input.

Testing Procedure: The AC system was operated continuously until steady-state was achieved, defined as temperature fluctuations less than ±0.5°C over 10 minutes. Data were logged at one-minute intervals for analysis.

5. RESULTS AND DISCUSSION

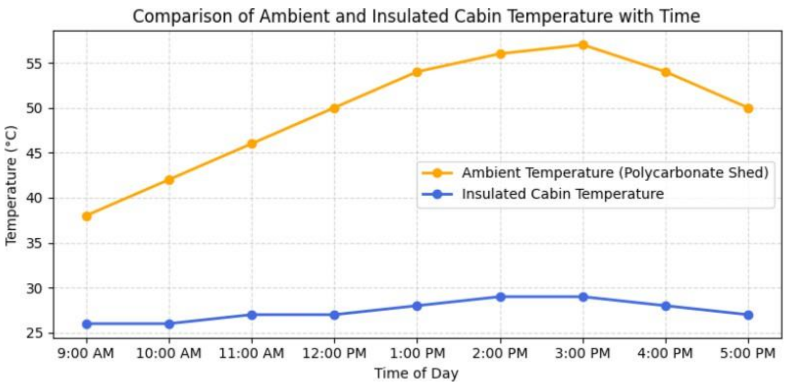
Thermal Performance: The total heat gain through the cabin structure was calculated as: Q_{glass} = 459 W, Q_{sheet} = 60 W, $Q_{occupant}$ = 100 W, giving a total cooling load of 619 W. This equated to approximately 2112 BTU/hr, confirming that the designed 1 TR system provided adequate capacity with significant margin for stability.

Experimental Observations: During testing, ambient temperatures ranged from 38°C to 57°C. The insulated cabin maintained interior air temperatures between 26°C and 29°C consistently. In contrast, the uninsulated control cabin exceeded 100°C under similar conditions, highlighting the insulation's effectiveness.



Polycarbonate Shed Temperature Vs Time

The graph illustrates the ambient temperature profile recorded beneath the polycarbonate shed during testing. The temperature increased steadily from approximately 38°C at 9:00 AM to a peak of about 57°C at 3:00 PM, followed by a gradual decline toward evening. This pattern reflects the natural diurnal heating behavior within a semi-enclosed environment, where the polycarbonate roof allows solar radiation transmission while restricting convective heat dissipation. These conditions effectively simulated high-ambient thermal exposure for evaluating the performance of the insulated air-conditioned cabin.



Ambient Temperature Vs insulated Ac Cabin

The temperature-time graph clearly showed a sharp rise in ambient temperature between 9:00 AM and 3:00 PM, while the insulated cabin maintained a nearly constant internal temperature. The stabilization period for cooling from initial conditions to steady-state was observed to be approximately 10–15 minutes after the AC was switched on.

Energy Consumption: Average compressor power was between 0.8 and 1.0 kW, with a 25–35% duty cycle. Daily energy consumption was approximately 2–3 kWh for eight hours of operation, demonstrating the energy-saving benefit of insulation.

Comparison with Analytical Predictions: Analytical predictions estimated a cooling load of 0.62 kW under 80°C ambient conditions. Experimentally measured values under 57°C ambient showed a 0.59 kW load—less than 5% deviation. This validates the accuracy of the thermal model and the insulation design approach.

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6. CONCLUSION

The development and testing of the insulated air-conditioned cabin successfully demonstrated that integrating PUF and reflective bubble foil insulation significantly reduces cooling requirements while maintaining interior comfort under extreme heat. The optimized dual-layer insulation achieved a thermal gradient of nearly 30°C, allowing a compact 1 TR AC unit to operate efficiently with low power consumption. The results confirm the system's feasibility for industrial, automotive, and defense applications operating in high-temperature environments.

The experimental outcomes closely matched analytical predictions, verifying the reliability of the design methodology. The proposed configuration offers a lightweight, energy-efficient, and cost-effective solution for thermal management in harsh climates.

7. FUTURE SCOPE

Further research will focus on advanced insulation materials such as aerogel composites, vacuum panels, and phase change materials for enhanced thermal resistance. The integration of variable-speed compressors and smart control systems may further reduce energy consumption. Long-term outdoor testing under varying climatic conditions will also be conducted to evaluate durability and performance over time.

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