Development Of a Heater for Thermal Management of Forklift Used in Cold Storage

Sunil Shinde[1], Aditya Navale[2], Eshita Nalawade[3], Atharva Nikam[4], Mohit Ohal[5], Om Rakshe[6], Parth Lambe[7]
[1,2,3,4,5,6,7]*Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune*

***Abstract*—Fogging of forklift windshields in refrigerated warehouses reduces operator visibility, productivity, and safety. This study presents the design, fabrication, and testing of a compact Positive Temperature Coefficient (PTC) forced-air heater developed specifically for defogging applications in low-temperature warehouse environments. The system utilized a 1700 W PTC coil powered by a 48 V, 36 A supply, integrated with a SPAL 006 centrifugal blower driven by a 12 V high-speed motor. A polypropylene (PP) 40% glass-fiber-reinforced housing fabricated by thermoplastic injection molding provides mechanical stability and thermal insulation. The prototype was tested at a −30 °C warehouse ambient temperature, achieving an outlet air temperature of 20 °C, airflow of 85 CFM, and outlet velocity of 4.5 m/s. Electrical safety was ensured using an NC thermostat and a relay-based switching system. The prototype demonstrated a practical and reliable solution for visibility improvement in cold chain industrial operations and was fully functional.**

***Index Terms*—Cold Storage, Forced-Air Heating, Forklift Defogger, PTC Heater, Thermal Safety.**

I. INTRODUCTION

Cold chain logistics is a critical component of modern supply chain infrastructure, with the global cold storage market projected to experience substantial growth driven by the pharmaceutical, food processing, and perishable goods sectors [1]. Forklifts operating in refrigerated warehouses routinely encounter ambient temperatures ranging from −20 to −35°C, creating challenging conditions for equipment operation and worker safety [2].

One of the most persistent operational challenges in these environments is the formation of fog and frost on the windshields of forklift cabins. This phenomenon occurs because of the temperature differential between the relatively warmer cabin interior (heated by the operator's body heat and residual equipment warmth) and the extremely cold exterior surfaces. When moisture-laden air contacts a cold windshield surface, condensation and subsequent frost formation occur rapidly, severely reducing operator visibility [3].

The consequences of impaired visibility in warehouse operations are significant:

- Safety hazards: Increased risk of collisions with personnel, equipment, and infrastructure
- Operational inefficiency: Reduced travel speeds and frequent stops for manual defrosting
- Productivity loss: Estimated 15–25% reduction in material handling throughput [4]
- Regulatory compliance: Occupational safety requirements mandate clear operator sightlines

The objective of this research was to design and build a safe, low-maintenance, forced-air heating system for rapid defogging in −30 °C warehouse conditions. This study focused on material selection, heat generation, airflow control, and electrical safety.

II. LITERATURE REVIEW

Traditional approaches to windshield defogging in cold environments include:

A. Resistance Wire Heaters

These systems use nichrome or similar resistive elements to generate heat. Although simple in design, they suffer from high power consumption with poor efficiency, risk of thermal runaway and overheating, requirement for complex temperature control circuitry, and limited lifespan due to thermal cycling stress [5].

B. Hot Air Systems

Engine coolant-based heating systems are common in automotive applications but present challenges in the case of electric forklifts: not applicable to battery-electric vehicles without combustion engines, slow warm-up time in extreme cold, and complex plumbing and maintenance requirements [6].

C. Electrically Heated Glass

Transparent conductive coatings can provide direct windshield heating but involve high installation and replacement costs, limited retrofit applicability, and potential optical distortion [7].

D. PTC Thermistors

Positive Temperature Coefficient (PTC) thermistors offer unique advantages for heating applications in harsh environments. PTC materials, typically barium titanate-based ceramics doped with rare-earth elements, exhibit a sharp increase in electrical resistance above their Curie temperature [8]. This intrinsic property provides: self-regulation (as temperature increases, resistance rises, automatically limiting current flow), safety against thermal runaway, solid-state reliability, rapid thermal response, and resistance to thermal cycling and mechanical shock [9]. PTC heaters have been successfully applied in automotive cabin heating [10], appliance defrosting [11], and industrial process heating [12]; however, limited research exists on their application in extreme cold warehouse environments for forklift defogging systems.

III. METHODOLOGY

The methodology adopted in this study involved the systematic design, development, and experimental validation of a compact forced-air heating system based on PTC technology for forklift windshield defogging applications. This approach integrates principles of heat transfer, fluid mechanics, and electrical system design to achieve a rapid and controlled thermal response under extremely low-temperature conditions (−30 °C).

The design process begins with the selection of a suitable heat generation mechanism capable of delivering a consistent thermal output without complex control systems. This was followed by the development of an optimized airflow pathway to ensure effective convective heat transfer from the heating element to the target surface. Material selection and structural design considerations were incorporated to ensure mechanical stability, thermal insulation, and electrical safety. Finally, a complete system was fabricated and experimentally evaluated to validate its performance under real operating conditions.

The system was designed as a compact forced-air heating unit, consisting of three primary subsystems: (i) heat generation using a PTC heating element, (ii) airflow generation using a centrifugal blower, and (iii) an insulated housing to guide and contain the airflow.

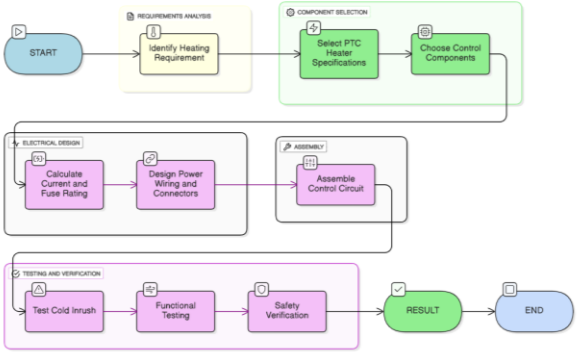

Fig. 1. Methodology of Project

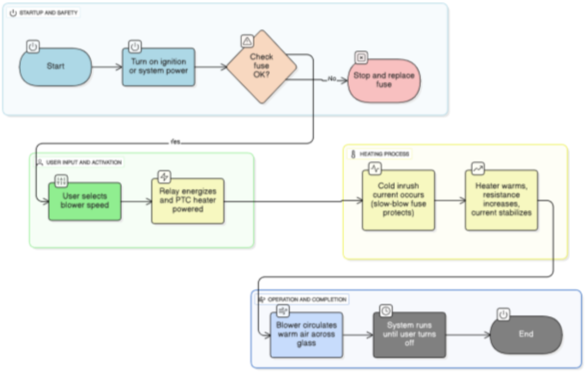

Fig. 2. Operational Flow of PTC Heater and Blower Circuit

A. Heating System

A PTC heating element rated at 48 V, 36 A, and 1700 W was selected to provide a rapid thermal output without an external temperature control circuit. A Normally Closed (NC) 85 °C thermostat was used for the thermal cutoff in series with a 30/87 relay for safe switching.

B. Airflow System

A SPAL 006 Series single centrifugal blower with a 12 V high-speed motor was used to supply forced convection via the heater fins. The manufacturer ratings indicate an airflow of 230 m³/h, with measured outlet conditions of 85 CFM and 4.5 m/s velocity.

C. Housing Material

The heater enclosure was fabricated using polypropylene (PP) reinforced with 40% glass fibers (GF) via thermoplastic injection molding. PP-GF40 exhibits high stiffness, dimensional stability, good heat resistance, and electrical insulation. This material selection minimizes deformation under thermal cycling while maintaining a low mass and durability.

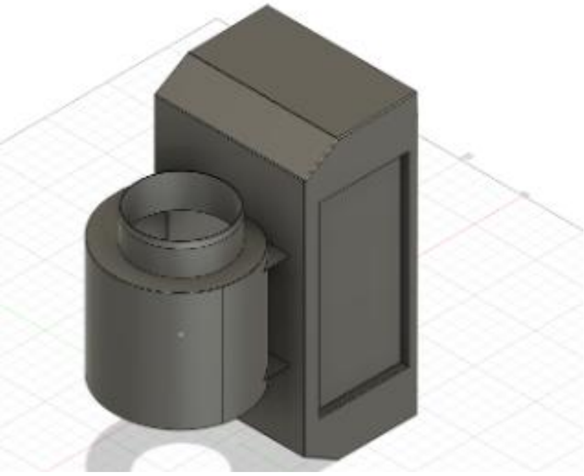

Fig. 3. CAD Model of Housing

D. Electrical Circuit

The circuit comprises a 4-position blower switch (Low/Medium/High/Battery), relay-controlled power path, PTC heater fused input, and thermostat protection. Only passive components were used in this study.

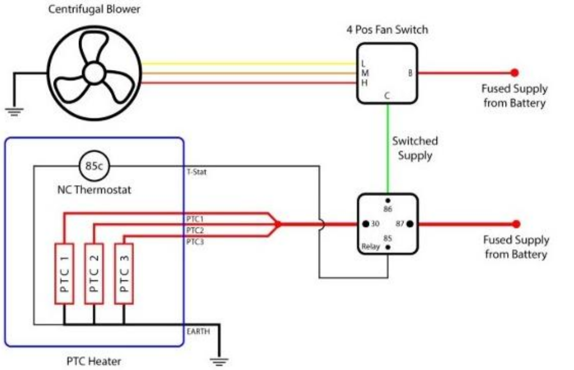

Fig. 4. Electric Circuit for Heater

IV. PROTOTYPE ASSEMBLY

The prototype was assembled using the following components:

- Injection molded top and bottom housing
- Mounted PTC heating array
- Separated air channel and wiring path
- SPAL blower mounted for direct heating flow path
- Relay and thermostat secured on chassis plate
- Automotive grade wiring, lugs, and connectors

All components were selected based on industry standards from the company.

V. ANALYSIS

A. Thermal and Fluid Flow Analysis

To evaluate the performance of the developed forced-air PTC heating system, a steady-state thermodynamic analysis was conducted based on energy balance and fluid flow principles. The heat transfer rate delivered to the airflow is expressed as:

$$\dot{Q} = \dot{m}\ Cp\ (Tout - Tin) \qquad (1)$$

The volumetric flow rate of 85 CFM corresponds to 0.0401 m^3/s. At an ambient temperature of −30 °C, the density of air is approximately 1.45 kg/m^3. Therefore, the mass flow rate is:

$$\dot{m} = \rho \cdot Q = 1.45 \times 0.0401 = 0.058\ kg/s \qquad (2)$$

Substituting into the energy equation with a measured temperature rise of 50 K, $\dot{Q} \approx 2915$ W. The discrepancy between the experimental and predicted results was attributed to non-uniform airflow distribution, measurement uncertainties in the volumetric flow rate, and localized heating effects within the PTC fin structure. This also indicates that the actual effective airflow interacting with the heating surface may be lower than the nominal blower rating.

B. Convective Heat Transfer Estimation

The heat transfer process is dominated by forced convection:

$$Q = h\ A\ \Delta T \qquad (3)$$

Assuming an effective heat transfer surface area of 0.15 m^2 and a temperature difference of 50 K, the convective heat transfer coefficient is estimated as $h \approx 226\ W/m^2K$. This value indicates a strong forced convection regime, consistent with compact finned heat exchanger configurations under high-velocity airflow.

C. Flow Regime Characterization

The Reynolds number was calculated to determine the nature of the airflow within the heater duct:

$$Re = (\rho\ V\ D) / \mu \approx 2.17 \times 10^4 \qquad (4)$$

The Reynolds number confirmed turbulent flow conditions, which enhanced mixing and significantly improved convective heat transfer efficiency.

D. Electrical and Thermal Behavior of PTC Heater

The PTC heating element operates based on the positive temperature coefficient characteristic, where the electrical resistance increases with temperature: R(T) ↑ as T ↑. At startup under cold conditions, the heater exhibits a low resistance, resulting in a high inrush current and rapid heat generation. As the temperature approaches the Curie point, the resistance increases sharply, reducing the current flow and stabilizing the heat output. This inherent self-regulating behavior eliminates the need for external electronic controllers such as PID or PWM systems.

E. Transient Thermal Response

The thermal response of the system can be characterized using the lumped capacitance approach:

$$\tau = (m\,C_p) / (h\,A) \qquad (5)$$

where τ is the thermal time constant. Owing to the low thermal mass of the PTC element and high convective heat transfer coefficient, the system exhibits a low time constant, enabling a rapid temperature increase. This characteristic is critical for defogging applications, where immediate heat delivery is required to restore visibility.

F. Defogging and Frost Removal Mechanism

The defogging process is governed by heat and mass transfer interactions on the windshield surface. Fog formation occurs when moist cabin air contacts a surface below the dew point temperature, resulting in the condensation of water vapor. At subzero temperatures, this condensation further transitions into frost.

The forced-air heating system mitigates this through raising the windshield surface temperature above the dew point, increasing local air temperature to reduce relative humidity, and enhancing evaporation through high-velocity airflow. The convective heat flux supplied to the glass surface can be expressed as:

$$q'' = h\,(T_{air} - T_{glass}) \qquad (6)$$

Sustained convective heating ensures the continuous removal of condensed moisture and prevents the reformation of frost, thereby maintaining clear visibility for the operator.

VI. RESULTS

The developed PTC-based forced-air heating system was experimentally evaluated under controlled cold storage conditions at an ambient temperature of −30 °C. The system demonstrated stable and repeatable thermal performances across multiple test cycles. The heater achieved an outlet air temperature of 20 °C, corresponding to a temperature increase of approximately 50 K. The airflow delivered by the centrifugal blower was measured at 85 CFM, producing an average outlet velocity of 4.5 m/s. The electrical input power remained consistent at 1700 W (48 V, 36 A), indicating a stable electrical operation without fluctuations or overloads.

Thermal safety testing confirmed that the Normally Closed (NC) thermostat was activated reliably at 85 °C, interrupting the heater circuit via relay switching. No thermal degradation, deformation, or material softening was observed in the PP-GF40 housing. The system exhibited a rapid thermal response, with noticeable warm airflow generation within a few seconds of activation. No evidence of electrical instability, excessive current draw, or blower performance degradation was observed during continuous operation.

VII. DISCUSSION

The results demonstrate that the integration of a PTC heating element with a centrifugal blower provides an effective solution for defogging in extreme cold environments. The system benefits from the inherent self-regulating nature of PTC materials, which eliminates the need for complex control systems while ensuring thermal stability. The observed temperature increase of 50 K under forced convection confirmed efficient heat transfer, supported by turbulent airflow conditions within the duct. The calculated Reynolds number ($\approx 2.17 \times 10^4$) indicated a fully turbulent regime, which enhanced convective heat transfer and improved thermal uniformity across the airflow.

The discrepancy between the theoretical heat transfer (~2900 W) and electrical input (1700 W) suggests that the nominal airflow rating may not fully represent the effective airflow interacting with the heating surface. This highlights the importance of duct design, flow distribution, and fin geometry in optimizing heat transfer efficiency. The use of PP-GF40 as the enclosure material proved advantageous because of its high stiffness, dimensional stability, and electrical insulation properties.

Compared to conventional resistance wire heaters, PTC-based systems offer superior safety owing to their intrinsic resistance-temperature feedback mechanism. The absence of coolant-based heating systems makes it particularly suitable for battery-operated forklifts. An airflow velocity of 4.5 m/s was sufficient to disrupt the boundary layer on the windshield surface, thereby enhancing convective heat transfer and accelerating defogging.

VIII. CONCLUSION

A compact, energy-efficient, and safe forced-air heating system based on PTC technology was successfully designed, fabricated, and experimentally validated for forklift windshield defogging applications in extreme cold storage environments. The system demonstrated reliable performance under −30 °C ambient conditions, achieving a consistent outlet air temperature of 20 °C and an airflow of 85 CFM. The integration of a self-regulating PTC heating element eliminates the need for active control systems, significantly simplifying the design and enhancing operational safety.

The use of a glass-fiber-reinforced polypropylene housing ensures structural integrity, thermal resistance, and electrical insulation, making the system suitable for industrial deployment. The inclusion of passive safety components, such as a thermostat and relay, provides an additional layer of protection against overheating and electrical faults. The prototype confirmed that effective defogging can be achieved through a combination of controlled heat generation and high-velocity airflow without relying on complex or maintenance-intensive systems.

ACKNOWLEDGMENT

The authors thank the Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, for providing laboratory facilities and support for this work.

REFERENCES

[1] Global Cold Chain Alliance, “Global Cold Storage Capacity Report 2024,” Alexandria, VA, USA: GCCA, 2024.

[2] S. A. Tassou, G. De-Lille, and Y. T. Ge, “Food transport refrigeration: Approaches to reduce energy consumption and environmental impacts of road transport,” *Applied Thermal Engineering*, vol. 29, no. 8–9, pp. 1467–1477, 2009.

[3] Y. Zhang, H. Chen, J. Wang, and Q. Liu, “Windshield fogging and defogging: Mechanisms and solutions,” *SAE International Journal of Passenger Cars – Mechanical Systems*, vol. 11, no. 4, pp. 345–358, 2018.

[4] G. Richards, *Warehouse Management: A Complete Guide to Improving Efficiency and Minimizing Costs in the Modern Warehouse*, 3rd ed. London, U.K.: Kogan Page Publishers, 2017.

[5] F. P. Incropera, D. P. DeWitt, T. L. Bergman, and A. S. Lavine, *Fundamentals of Heat and Mass Transfer*, 7th ed. Hoboken, NJ, USA: John Wiley & Sons, 2011.

[6] R. Farrington and J. Rugh, “Impact of vehicle air-conditioning on fuel economy, tailpipe emissions, and electric vehicle range,” NREL/CP-540-28960, National Renewable Energy Laboratory, Golden, CO, USA, 2000.

[7] P. Buelow and D. Ingram, “Electrically heated transparent windows,” *Thin Solid Films*, vol. 491, no. 1–2, pp. 323–331, 2005.

[8] A. Feteira, “Negative temperature coefficient resistance (NTCR) ceramic thermistors: An industrial perspective,” *Journal of the American Ceramic Society*, vol. 92, no. 5, pp. 967–983, 2009.

[9] J. Moulson and J. M. Herbert, *Electroceramics: Materials, Properties, Applications*, 2nd ed. Chichester, U.K.: John Wiley & Sons, 2003.

[10] H. S. Lee and M. Y. Kim, “Development of PTC heater for automotive HVAC systems,” *SAE International Journal of Passenger Cars – Mechanical Systems*, vol. 5, no. 2, pp. 1023–1029, 2012.

[11] Y. H. Shin, J. Y. Sim, and S. C. Kim, “Performance characteristics of modular PTC heating system for electric vehicles,” *Energies*, vol. 9, no. 10, p. 813, 2016.

[12] W. Jiang, X. Zeng, F. Zhang, H. Zhao, and L. Li, “A review on PTC heaters: Structures,

characteristics, and applications," *Applied Thermal Engineering*, vol. 165, p. 114596, 2019.

[13] Huybrechts, K. Ishizaki, and M. Takata, "Positive temperature coefficient of resistivity in barium titanate," *Journal of Materials Science*, vol. 30, no. 11, pp. 2463–2474, 1995.

[14] M. Völcker and J. Hausselt, "PTC effect of barium titanate," *Journal of the European Ceramic Society*, vol. 7, no. 5, pp. 299–311, 1991.

[15] F. P. Bleier, *Fan Handbook: Selection, Application, and Design*. New York, NY, USA: McGraw-Hill Education, 2019.

[16] L. W. McKeen, *The Effect of Temperature and Other Factors on Plastics and Elastomers*, 3rd ed. Oxford, U.K.: William Andrew Publishing, 2014.

[17] Society of Automotive Engineers, "SAE J902: Passenger Car Windshield Defrosting Systems," Warrendale, PA, USA: SAE International, 2018.

[18] ASHRAE, *ASHRAE Handbook – HVAC Systems and Equipment*, Atlanta, GA, USA: ASHRAE, 2020.

[19] Y. A. Çengel and A. J. Ghajar, *Heat and Mass Transfer*, 5th ed. New York, NY, USA: McGraw-Hill, 2015.

[20] ISO, "ISO 13732-1: Ergonomics of the thermal environment," Geneva, Switzerland: International Organization for Standardization, 2006.

[21] IEEE, "IEEE Std 141: Electric Power Distribution for Industrial Plants," New York, NY, USA: IEEE, 1993.