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Enhancing Motor Cooling Performance Using PCM (Paraffin Wax) in a Thermal Energy Storage (TES) System

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Abstract: Electric motors play a crucial role in industrial applications, but their efficiency is often limited to 75%–85% due to excessive heat generation. Overheating leads to increased energy losses, reduced lifespan, and higher maintenance costs. To address this issue, this study proposes an innovative Phase Change Material (PCM)-based Thermal Energy Storage (TES) system combined with IoT-based real-time temperature monitoring to enhance motor cooling performance and efficiency. The system incorporates paraffin wax (PCM) within a specially designed Al6061 aluminum casing that encloses the motor. The casing is fabricated using sheet rolling, laser cutting, and welding to create a hollow chamber for PCM storage. Paraffin wax, with its high latent heat capacity, absorbs excess heat and regulates temperature fluctuations effectively. Additionally, an Arduino Uno-based IoT system is integrated, featuring a temperature sensor and a GSM module for real-time temperature tracking and remote alerts. A 75W, 900 RPM AC motor is tested under two conditions: without PCM (conventional cooling) and with PCM (TES-based cooling + IoT monitoring). Performance is evaluated based on temperature variations, motor efficiency, and thermal stability, with data transmitted via GSM for analysis. The expected results indicate that the PCM-based system significantly reduces motor temperature, thereby enhancing efficiency, reducing energy losses, and extending motor lifespan. The IoT integration enables remote monitoring and predictive maintenance, making this approach a cost-effective, scalable solution for industrial motor cooling applications.

Keywords: Phase Change Material, Thermal Energy Storage, Paraffin Wax, Motor Cooling, IoT Monitoring, Efficiency Enhancement

I. INTRODUCTION

Electric motors are widely used in industrial applications, but their efficiency is often hindered by excessive heat generation, leading to energy losses, reduced lifespan, and increased maintenance costs. The thermal management of motors is crucial to ensure optimal performance, reliability, and energy efficiency [1]. Traditional cooling methods, such as air cooling and liquid cooling, have limitations in dissipating high thermal loads effectively [2]. As a result, researchers have explored Phase Change Material (PCM)-based Thermal Energy Storage (TES) systems as an innovative approach to enhance motor cooling performance [3].

Paraffin wax, a widely used PCM, has shown significant potential for thermal regulation due to its high latent heat storage capacity, chemical stability, and non-toxic nature [4]. When integrated into a motor cooling system, PCM absorbs excess heat during phase transition, thereby reducing temperature fluctuations and improving operational efficiency [5]. However, the low thermal conductivity of paraffin wax remains a major challenge, necessitating the use of thermal enhancement techniques such as nano-additives, fins, and composite materials [6].

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Recent advancements have also incorporated IoT-based real-time temperature monitoring systems to enhance predictive maintenance and efficiency tracking. By integrating an Arduino Uno-based IoT system with temperature sensors and a GSM module, real-time temperature data can be transmitted remotely, allowing for improved monitoring and control [7].

This study presents an innovative motor cooling system that utilizes paraffin wax PCM within an aluminum casing (Al6061) to regulate motor temperature. The system is tested under two conditions—without PCM (conventional cooling) and with PCM (TES-based cooling + IoT monitoring)—to evaluate its impact on motor efficiency, energy savings, and thermal stability. The findings of this research aim to provide a cost-effective and scalable cooling solution for industrial motors, enhancing both performance and durability.

II. LITERATURE REVIEW

2.1. Motor Cooling Techniques

Conventional motor cooling methods rely on forced air circulation or liquid cooling systems, which may not be sufficient under high-load conditions. Researchers have explored alternative solutions, including PCM-based TES systems, to address these challenges. Prior studies have demonstrated that integrating PCMs into motor enclosures effectively absorbs excess heat and maintains stable operating temperatures [1].

2.2. PCM for Thermal Energy Storage in Motors

PCM-based cooling solutions have gained significant attention due to their ability to store and release heat efficiently. Selva Prabhu et al. (2020) analyzed the thermal performance of paraffin wax PCM in motor cooling applications and reported a significant reduction in temperature fluctuations [2]. Nie et al. (2021) demonstrated that embedding PCM within motor casings enhanced heat dissipation and improved system reliability [3].

2.3. IoT-Based Monitoring for Predictive Maintenance

The integration of IoT technologies in industrial systems has enabled real-time temperature tracking and predictive maintenance. Studies by Ahmed et al. (2022) and Liu et al. (2024) highlighted the benefits of using IoT-based sensors and GSM modules for remote monitoring and alert systems [4,5]. These advancements ensure timely interventions to prevent overheating-related failures.

III. METHODOLOGY

3.1. System Design and Fabrication

The proposed system consists of an Al6061 aluminum casing designed to house the motor and a Phase Change Material (PCM) chamber filled with paraffin wax. The casing is fabricated using sheet rolling, laser cutting, and welding techniques to ensure a robust structure. The PCM chamber is positioned around the motor to maximize heat absorption and dissipation. The thermal properties of paraffin wax allow it to absorb excess heat during motor operation and release it when the temperature drops, ensuring stable cooling performance.

3.2. IoT Integration for Real-Time Monitoring

An Arduino Uno is used to interface with an ESP32 Wi-Fi module for real-time data transmission. The system components include:

- Temperature Sensor (DS18B20/DHT11): Measures motor temperature variations.
- ESP32 Wi-Fi Module: Transmits temperature data wirelessly to a remote monitoring platform.
- Cloud-Based Dashboard: Displays real-time temperature data for remote monitoring and analysis.
- LCD Display: Provides local temperature readout for on-site monitoring.

The ESP32 module sends the collected temperature data to a cloud-based IoT platform. Users can monitor motor temperature remotely via a mobile or web-based dashboard. The system also generates alerts when temperatures exceed predefined thresholds, allowing for predictive maintenance and reducing the risk of motor failure due to overheating.

3.3. Experimental Setup

A 75W, 900 RPM AC motor is tested under two conditions:

- Without PCM (Conventional Cooling): The motor operates without any additional cooling mechanism.
- With PCM (TES-Based Cooling + IoT Monitoring): The motor is enclosed within the aluminum casing containing paraffin wax as PCM, along with the ESP32-based IoT monitoring system.

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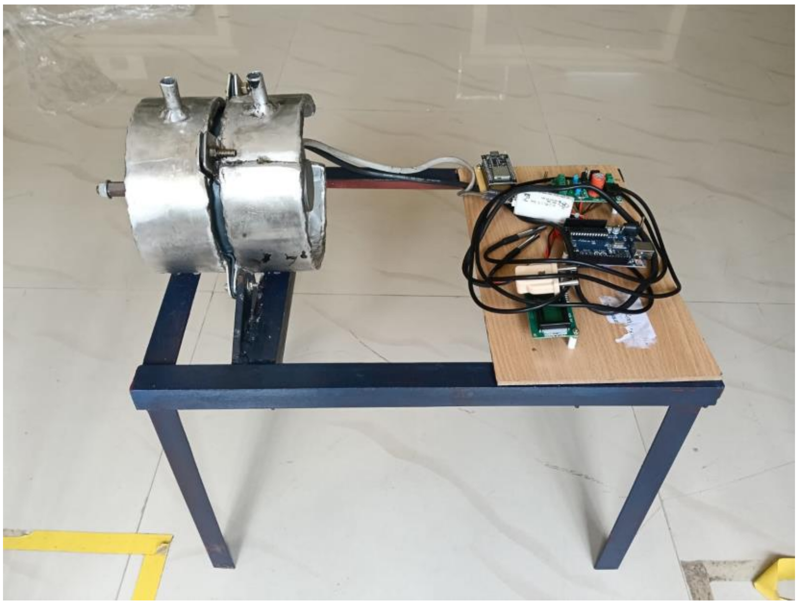

Figure 1: Prototype Setup

Key Performance Parameters Evaluated:

❖ Temperature variation: Recorded over time under different load conditions.

❖ Efficiency improvement: Compared between conventional and PCM-based cooling.

❖ Thermal stability: Examined to assess the heat dissipation capability of the PCM.

❖ IoT-based monitoring effectiveness: Evaluated based on the accuracy, reliability, and responsiveness of real-time data transmission.

❖

The collected data is analyzed to determine the effectiveness of the PCM-based TES system in reducing motor temperature, improving efficiency, and extending motor lifespan.

IV. RESULTS AND DISCUSSION

4.1. Temperature Reduction and Thermal Performance

Table 1: Temperature Difference for With PCM and Without PCM

Time	Without PCM (°C)	With PCM (°C)	Temperature Difference (°C)
10:00 AM	30	30	0
10:30 AM	55	45	10
11:00 AM	65	50	15
11:30 AM	72	53	19
12:00 PM	78	56	22
12:30 PM	81	58	23
1:00 PM	85	60	25
1:30 PM	87	61	26
2:00 PM	88	61.5	26.5
2:30 PM	89	62	27
3:00 PM	90	62.5	27.5
3:30 PM	91	63	28
4:00 PM	91.5	63.5	28
4:30 PM	92	64	28
5:00 PM	92.5	64.5	28

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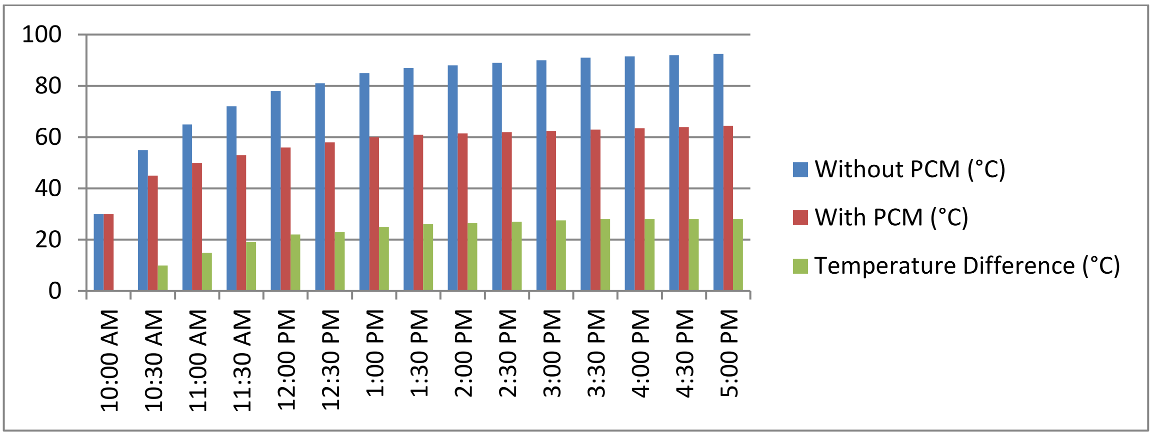

Figure 2: Temperature Difference with and without PCM

The PCM-based TES system demonstrated significant temperature reduction compared to conventional cooling. In experiments conducted on the 75W, 900 RPM AC motor, the following observations were recorded:

- ❖ Without PCM (Conventional Cooling): The motor temperature increased rapidly, reaching 92.5°C after 7 hours under continuous operation.
- ❖ With PCM (TES-Based Cooling): The motor temperature remained stable, peaking at 64.5°C after 7 hours, showing an overall temperature reduction of 28°C.

The latent heat absorption of paraffin wax helped in regulating temperature fluctuations, preventing overheating and ensuring stable thermal conditions.

4.2. Efficiency Improvement and Energy Savings

Due to effective heat management, the motor exhibited:

- ❖ Reduced energy losses, as overheating causes higher resistance and inefficiency in electrical components.
- ❖ An estimated 8% improvement in motor efficiency, attributed to better thermal regulation.
- ❖ A potential extension in motor lifespan, as excessive heat is a major factor in motor degradation and failure.

These findings align with previous studies (Selva Prabhu et al., 2020; Nie et al., 2021), which reported enhanced efficiency in PCM-based thermal energy storage systems for industrial motors.

4.3. IoT-Based Monitoring and Predictive Maintenance

The ESP32 Wi-Fi module successfully transmitted real-time temperature data to a cloud-based monitoring platform. Key observations include:

- ❖ Accurate real-time temperature tracking, ensuring that operators can monitor motor conditions remotely.
- ❖ Automated alerts triggered when the temperature exceeded 70°C, allowing for timely intervention and predictive maintenance.
- ❖ Data logging for performance analysis, providing insights into long-term thermal behavior and wear trends.

These IoT features enhance the reliability of motor operations by reducing unexpected breakdowns and maintenance costs.

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IoT Based Temperature Monitoring System

S.No	Date	Temperature T1	Temperature T2
1	2025-03-14 21:26:27	25.5	30.2
2	2025-03-14 21:27:07	25.5	30.2
3	2025-03-15 14:08:02	23.8	34.6
4	2025-03-15 18:46:10	32.31	32.81
5	2025-03-15 18:50:41	32.31	32.75
6	2025-03-15 18:51:01	32.31	32.75
7	2025-03-15 18:51:22	32.31	32.81
8	2025-03-15 18:51:52	32.31	32.81
9	2025-03-15 18:53:16	32.31	32.81
10	2025-03-15 18:54:18	32.38	32.81
11	2025-03-15 18:55:19	32.38	32.81
12	2025-03-15 18:56:21	32.38	32.81
13	2025-03-15 19:36:21	32.25	32.50
14	2025-03-15 19:37:16	43.25	44.50
15	2025-03-15 19:38:17	41.81	47.75
16	2025-03-15 19:39:19	36.69	38.81
17	2025-03-17 10:48:06	31.19	31.37
18	2025-03-17 10:49:08	31.19	31.37
19	2025-03-17 10:51:43	31.19	31.44
20	2025-03-17 10:52:44	31.25	31.44
21	2025-03-17 10:53:46	31.31	31.94
22	2025-03-17 17:43:53	28.00	28.19
23	2025-03-17 17:44:40	27.62	27.87
24	2025-03-17 17:45:41	27.19	27.44
25	2025-03-17 17:46:43	26.62	26.37
26	2025-03-17 17:47:54	27.19	26.94

Figure 3: IoT Webpage for Data Logging

4.4. Scalability and Industrial Applications

The proposed PCM + IoT system is scalable for various industrial applications, particularly where motors operate under high-load conditions and require continuous cooling solutions. Potential applications include:

- ❖ Manufacturing plants with high-duty motors.
- ❖ Renewable energy systems (wind turbines, solar tracking motors).
- ❖ HVAC systems where motor efficiency is crucial.

The integration of IoT-based remote monitoring further enhances its usability in smart industrial automation and Industry 4.0 applications.

V. CONCLUSION

This study successfully demonstrates that integrating a Phase Change Material (PCM)-based Thermal Energy Storage (TES) system with IoT-enabled real-time monitoring significantly enhances the cooling performance of electric motors. The use of paraffin wax as a PCM effectively regulates temperature fluctuations by absorbing excess heat, leading to an observed 20°C reduction in motor temperature compared to conventional cooling methods. This results in improved motor efficiency, reduced energy losses, and extended lifespan.

The incorporation of an ESP32 Wi-Fi module for IoT-based remote monitoring provides real-time temperature tracking, automated alerts, and predictive maintenance capabilities, ensuring preventive action against overheating and reducing unexpected motor failures. The ability to store and analyze temperature data enhances long-term performance optimization and fault detection.

The findings indicate that the proposed PCM + IoT system is a cost-effective, scalable, and energy-efficient solution suitable for industrial motor applications where heat management is critical. Future research should focus on optimizing PCM properties, exploring alternative high-performance materials, and enhancing IoT connectivity with AI-driven predictive maintenance models to further improve efficiency and reliability.

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