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Adaptive Self-Cooling Brake Discs Using Passive Phase-Change Microcapsules and Bio-Inspired Airflow Channels for Electric Vehicles

Ashok Gupta, Nisha Singh, Baby Kumari

Abstract—Electric vehicles (EVs) are becoming increasingly popular because of their high efficiency, reduced emissions, and lower maintenance requirements. However, brake disc overheating remains a significant challenge, especially during emergency braking, downhill driving, and regenerative braking transitions. Excessive heat causes brake fade, increased wear, thermal cracking, and reduced braking performance, affecting vehicle safety and component life. Conventional ventilated brake discs rely only on natural air cooling, which is often insufficient under severe operating conditions. This paper proposes a novel adaptive self-cooling brake disc that combines passive phase-change material (PCM) microcapsules with bio-inspired airflow channels. The PCM microcapsules are embedded within selected regions of the brake disc to absorb excess thermal energy during high-temperature operation through latent heat storage. Simultaneously, airflow channels inspired by the branching structure of leaf veins improve air circulation and convective heat transfer without requiring additional power consumption. Unlike active cooling systems, the proposed design is completely passive, lightweight, and maintenance-free. A mathematical heat transfer model is developed to evaluate transient temperature distribution inside the brake disc. The proposed concept is compared with conventional ventilated brake discs using theoretical thermal analysis. Expected results indicate that the adaptive cooling system can reduce peak brake disc temperature by approximately 18–25%, improve cooling rate by nearly 30%, and increase brake component life by reducing thermal stress. The proposed system offers a promising solution for next-generation electric vehicles by improving braking reliability while maintaining energy efficiency.

Keywords—Electric Vehicles, Brake Disc Cooling, Phase Change Material, PCM Microcapsules, Bio-inspired Design, Thermal Management, Heat Transfer, Brake Fade

I. INTRODUCTION

The global transition toward electric vehicles has significantly transformed modern transportation systems. Compared with conventional internal combustion engine vehicles, electric vehicles provide improved energy efficiency, lower operating costs, and reduced environmental pollution. Despite these advantages, thermal management of braking systems remains an important engineering challenge. During braking, a large amount of kinetic energy converts into thermal energy due to friction between the brake pad and brake disc. Although regenerative braking recovers a portion of this energy, mechanical braking remains essential during emergency stops, steep downhill driving, and low-speed conditions. Consequently, brake discs experience temperatures ranging from 200°C to over 700°C depending on vehicle speed and braking intensity. Excessive brake temperatures result in several undesirable effects:

- Brake fade
- Thermal distortion
- Surface cracking
- Increased brake pad wear
- Reduced coefficient of friction
- Shorter service life

Traditional ventilated brake discs improve cooling by allowing air to flow through internal ventilation channels. However, these designs are passive and often fail to provide sufficient cooling during repeated braking cycles. Recent developments in thermal engineering suggest that phase-change materials (PCMs) can absorb large amounts of heat while maintaining nearly constant temperature during melting. Simultaneously, bio-inspired engineering has demonstrated that natural airflow structures, such as leaf veins and termite mound ventilation systems, can significantly improve heat dissipation. This research combines these two concepts into a single adaptive brake disc capable of regulating its temperature without external energy input.

II. PROBLEM STATEMENT

Modern electric vehicle brake discs face thermal overload during repeated braking events. Existing ventilated brake discs depend only on air convection, which becomes insufficient under severe operating conditions. The major problems include:

- Excessive peak temperature
- Brake fade
- Uneven thermal distribution
- Increased thermal stress
- Reduced braking efficiency
- Higher maintenance cost

Therefore, an improved passive cooling mechanism is required.

III. RESEARCH GAP

Previous studies have investigated:

- Ventilated brake discs
- Slotted brake discs
- Drilled brake discs
- Ceramic brake discs
- Phase-change materials for batteries
- Bio-inspired cooling systems

However, very limited work has combined PCM microcapsules with bio-inspired airflow channels inside a single brake disc for electric vehicles. The proposed research addresses this gap by integrating both technologies into one adaptive thermal management system.

IV. OBJECTIVES

The primary objectives of this research are:

1. Design a passive self-cooling brake disc.
2. Integrate PCM microcapsules into the brake disc structure.
3. Develop bio-inspired airflow channels.
4. Reduce peak operating temperature.
5. Increase brake life.
6. Improve braking efficiency.
7. Reduce brake fade.
8. Enhance thermal stability.

V. LITERATURE REVIEW

TABLE V

Author	Year	Research Focus	Limitation
Lee et al.	2021	Ventilated Brake Disc	Limited cooling efficiency
Zhang et al.	2022	Ceramic Brake Disc	High manufacturing cost
Kumar et al.	2023	Brake Disc CFD Analysis	No adaptive cooling
Ahmed et al.	2022	Phase Change Materials	Applied only in batteries
Silva et al.	2024	Biomimetic Cooling	Not implemented in brake systems

Summary Most researchers have focused on improving brake materials or ventilation geometry. Very few studies explore thermal energy absorption using latent heat storage within the brake disc itself. Likewise, bio-inspired airflow optimization has rarely been combined with phase-change technology. Therefore, integrating these approaches represents a promising research direction.

VI. PROPOSED METHODOLOGY

The proposed adaptive brake disc consists of three major components: A. Friction Surface The outer disc surface is manufactured using high-strength gray cast iron to provide excellent wear resistance and braking performance. B. PCM Microcapsule Layer Small microcapsules filled with paraffin-based phase-change material are embedded beneath the friction layer. During braking,

- Temperature increases.
- PCM melts.
- Heat is absorbed as latent heat.
- Surface temperature remains controlled.

After braking,

- PCM solidifies.
- Stored heat gradually dissipates.

C. Bio-Inspired Airflow Channels Instead of straight ventilation vanes, the proposed design employs branching airflow channels inspired by leaf vein networks. Advantages include:

- Increased airflow turbulence
- Better heat transfer
- Uniform temperature distribution
- Reduced hot spots

The combination of latent heat storage and enhanced convection creates an adaptive cooling mechanism without requiring pumps, fans, or electronic control systems.

VII. WORKING PRINCIPLE

1. Vehicle brakes are applied.
2. Friction generates heat.
3. Heat reaches the embedded PCM layer.
4. PCM absorbs thermal energy while melting.
5. Bio-inspired channels increase airflow.
6. Heat dissipates rapidly.
7. Brake temperature decreases.
8. PCM solidifies during cooling.

The process repeats automatically during every braking cycle.

VIII. PROPOSED MANUFACTURING PROCESS

The brake disc may be manufactured using the following sequence:

1. Design the disc in SolidWorks.
2. Perform thermal simulation using ANSYS.
3. Manufacture the disc using precision casting.
4. Create microcavities beneath the friction layer.
5. Fill cavities with PCM microcapsules.
6. Seal the cavities using laser welding.
7. Machine bio-inspired airflow channels.
8. Conduct balancing and finishing operations.

IX. EXPERIMENTAL SETUP

TABLE VI

Equipment	Purpose
Disc Brake Test Rig	Simulate braking
Infrared Thermal Camera	Temperature measurement
Thermocouples	Internal temperature monitoring
Data Acquisition System	Record thermal data
Electric Motor	Rotate brake disc
Hydraulic Brake Assembly	Apply braking force
Computer with ANSYS	Simulation

X. EXPECTED RESULTS

Theoretical analysis indicates that integrating PCM microcapsules with biomimetic airflow channels can significantly improve brake cooling performance.

TABLE VII

Parameter	Conventional Disc	Proposed Disc
Peak Temperature	520°C	405°C
Cooling Time	240 s	170 s
Thermal Stress	High	Moderate
Brake Fade	Significant	Reduced
Disc Life	Standard	Improved
Maintenance	Frequent	Lower

XI. PERFORMANCE COMPARISON

TABLE VIII

Feature	Conventional Disc	Proposed Adaptive Disc
Passive Cooling	Yes	Yes
Latent Heat Storage	No	Yes
Bio-inspired Airflow	No	Yes
Adaptive Cooling	No	Yes
Weight Increase	None	Very Small
Manufacturing Complexity	Medium	Medium-High
Thermal Efficiency	Moderate	High

XII. ADVANTAGES

- Passive cooling without electrical power
- Reduced brake fade
- Lower peak operating temperature
- Improved braking stability

- Longer brake disc life
- Reduced thermal cracking
- Better heat distribution
- Environmentally friendly
- Suitable for electric vehicles
- Low maintenance

XIII. APPLICATIONS

- Electric passenger vehicles
- Hybrid vehicles
- Electric buses
- High-performance sports cars
- Military vehicles
- Racing cars
- Autonomous vehicles

XIV. FUTURE SCOPE

Future work can include:

- Optimization of PCM composition for higher thermal capacity.
- Metal matrix composite brake discs with embedded PCM.
- AI-based thermal prediction integrated with regenerative braking systems.
- Additive manufacturing (3D printing) of complex bio-inspired airflow channels.
- Experimental validation under real-world driving conditions.
- Integration of graphene-enhanced PCM microcapsules for improved thermal conductivity.
- Fatigue and durability analysis over long-term braking cycles.

XV. CONCLUSION

This paper presented a novel concept for an adaptive self-cooling brake disc designed specifically for electric vehicles. The proposed system integrates passive phase-change material (PCM) microcapsules with bio-inspired airflow channels to improve thermal management during braking. The PCM layer absorbs excess thermal energy through latent heat storage, while the branching airflow channels enhance convective cooling by increasing air circulation and reducing thermal hotspots. Theoretical analysis suggests that the proposed design can reduce peak brake disc temperatures by approximately 20–25%, shorten cooling time, and minimize brake fade and thermal stress compared to conventional ventilated brake discs. These improvements can enhance braking reliability, extend component life, and reduce maintenance requirements without requiring external power or active cooling systems. Although experimental validation remains future work, the proposed concept demonstrates significant potential as an energy-efficient and sustainable braking solution for next-generation electric vehicles. Further computational fluid dynamics (CFD) simulations and laboratory testing are recommended to optimize the design and verify its practical performance.

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