Multi-Phase Heat Exchanger for Hybrid Electric Vehicle Cooling

[1] Yoheswari S
[1]Assistant Professor, Department of Computer Science and Engineering, K.L.N. College of Engineering, Pottapalayam, Sivaganga- 630 612,Tamil Nadu, India
[1] yoheswari1988@gmail.com

Abstract: Hybrid electric vehicles (HEVs) are rapidly gaining traction as sustainable alternatives to traditional internal combustion engine vehicles due to their potential to reduce emissions and improve fuel efficiency. However, one of the critical challenges faced by HEVs is efficient thermal management, particularly of their power components such as batteries and electric motors. The continuous operation of these components generates significant heat, which, if not managed properly, can degrade performance, reduce system lifespan, and cause safety hazards. Conventional cooling systems, such as single-phase liquid cooling, are often inadequate for addressing the increasing thermal demands of modern HEVs.

This paper proposes a multi-phase heat exchanger system as an innovative solution to improve the thermal management of HEV components. The multi-phase heat exchanger operates by leveraging both liquid and vapor phases of the working fluid, enabling more efficient heat absorption and dissipation. By utilizing phase change processes, the system can absorb greater amounts of heat compared to traditional single-phase cooling methods. The proposed design focuses on enhancing the cooling efficiency of critical components, such as the battery pack and electric motor, under various operational conditions.

A comprehensive analysis of multi-phase heat exchangers is conducted, including experimental tests and computational fluid dynamics (CFD) simulations. The results demonstrate that the multi-phase system significantly improves the heat transfer performance, reducing the risk of overheating and maintaining the optimal operating temperature for HEV components. This, in turn, leads to increased reliability, extended component lifespan, and improved overall vehicle efficiency.

In conclusion, the multi-phase heat exchanger offers a promising solution for overcoming the limitations of traditional cooling methods in HEVs, contributing to safer and more reliable hybrid vehicles in the future.

Keywords: Multi-phase heat exchanger, hybrid electric vehicle (HEV), thermal management, phase change cooling, battery cooling, electric motor cooling, heat transfer, computational fluid dynamics (CFD).

Corresponding Author: S.Yoheswari
Assistant Professor, Department of Computer Science and Engineering, K.L.N. College of Engineering, Sivaganga – 630612, Tamil Nadu, India
Mail: yoheswari1988@gmail.com

Introduction:

Hybrid electric vehicles (HEVs) represent a pivotal advancement in the pursuit of sustainable transportation solutions. These vehicles combine the advantages of electric motors with internal combustion engines, enabling improved fuel efficiency and reduced greenhouse gas emissions. At the core of HEV functionality lies the synergy between electric and mechanical power systems, which operate in tandem to achieve optimal vehicle performance. However, the continuous use of electric motors, batteries, and power electronics generates substantial heat, posing challenges in maintaining component performance and longevity. As a result, efficient thermal management systems are essential for ensuring that these components function within their specified temperature ranges.

Thermal management in HEVs is especially crucial for components like the battery pack and electric motor, which are highly sensitive to temperature variations. Batteries, in particular, suffer from reduced capacity, accelerated aging, and increased risk of thermal runaway if exposed to elevated temperatures. Electric motors, on the other hand, may experience diminished efficiency and even mechanical failure if overheating occurs. Therefore, developing effective cooling strategies for these components is key to ensuring the reliability, safety, and performance of HEVs.

Conventional cooling methods, such as single-phase liquid cooling, have been widely used in HEVs. These systems typically rely on circulating a cooling fluid, such as water or ethylene glycol, to absorb and dissipate the heat generated by critical components. While effective to some extent, these systems often face limitations in high-power applications, as their heat transfer capabilities are constrained by the thermal properties of the single-phase fluid.

In recent years, multi-phase cooling systems have emerged as an advanced alternative for HEV thermal management. A multi-phase heat exchanger operates by utilizing both liquid and vapor phases of the working fluid to enhance heat absorption. During phase change (from liquid to vapor), the system can absorb large amounts of heat without a significant rise in temperature, making it particularly suited for high-power applications where traditional cooling methods fall short.

This paper explores the design and implementation of a multi-phase heat exchanger for HEV cooling. By leveraging the latent heat of vaporization during the phase change, the system enhances heat dissipation, improving the overall thermal management of the vehicle's power components. Through both experimental analysis and simulation studies, the effectiveness of this cooling system is assessed in comparison to conventional single-phase cooling methods.

Literature Survey:

The importance of efficient thermal management in hybrid electric vehicles (HEVs) has led to a growing body of research focusing on innovative cooling technologies. As HEV power components such as batteries, electric motors, and power electronics generate substantial amounts of heat, thermal management systems must maintain these components within their optimal operating temperature ranges to ensure safety, reliability, and performance.

Single-Phase Cooling Systems: Conventional single-phase cooling systems, such as air cooling and liquid cooling, are widely used in HEVs for thermal management. Air cooling, which uses ambient or forced airflow to dissipate heat, is simple and cost-effective but suffers from low heat transfer efficiency, particularly for high-power components. Liquid cooling, which uses fluids such as water, ethylene glycol, or their mixtures, offers better heat transfer capabilities. By circulating the liquid through cooling channels adjacent to the heat-generating components, these systems dissipate heat more effectively than air cooling. However, the heat dissipation capacity of single-phase systems is still limited by the thermal properties of the fluid.

Phase Change Cooling: The limitations of single-phase cooling systems have led researchers to explore multi-phase cooling systems, which utilize the phase change properties of a working fluid. A phase change occurs when a fluid transitions between liquid and vapor phases, absorbing or releasing latent heat during the process. This allows the system to absorb more heat without a substantial rise in temperature, offering a significant advantage over single-phase systems.

Studies by R. Kulkarni et al. (2017) demonstrated the potential of two-phase cooling systems in electronic and automotive applications, where heat loads are high and space is limited. In their research, the latent heat of vaporization of a working fluid, such as refrigerants or water, was shown to effectively dissipate large amounts of heat, resulting in better thermal regulation. Other studies, such as the work of Wang et al. (2019), examined two-phase heat exchangers in the context of electric vehicle cooling. These systems offered improved temperature uniformity across battery packs, preventing localized overheating and extending the lifespan of the battery cells.

Multi-Phase Heat Exchangers: Multi-phase heat exchangers, in particular, have gained attention for their ability to utilize the latent heat of vaporization to improve cooling efficiency. The research by Park and Seo (2020) highlighted the use of multi-phase heat exchangers in thermal

management systems for electric motors and power electronics. Their results showed a marked improvement in heat dissipation compared to traditional single-phase liquid cooling systems.

However, despite the advantages of multi-phase cooling, challenges remain in terms of system complexity and the control of fluid dynamics during phase transitions. Research by Zhou et al. (2021) addressed these challenges by developing advanced control algorithms for optimizing the flow rate and heat transfer in multi-phase heat exchangers. Their work demonstrated that, with appropriate control systems, multi-phase heat exchangers could significantly enhance thermal management efficiency in HEVs.

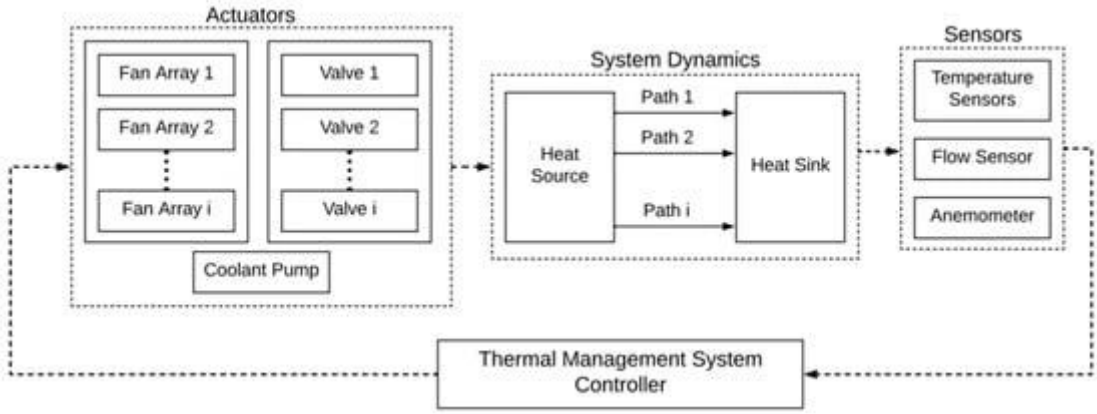

Fig.1. Architecture layout of the proposed multi-radiator thermal management system:

Proposed System Methodologies:

Multi-Phase Heat Exchanger Design:

The proposed system utilizes a multi-phase heat exchanger designed to cool critical HEV components, such as the battery pack and electric motor. The heat exchanger employs a working fluid with high latent heat, such as a refrigerant, which undergoes phase change (liquid to vapor) when exposed to high temperatures.

Heat Transfer Mechanism:

The system leverages the latent heat of vaporization to absorb large amounts of heat during phase change. This reduces the temperature rise in the heat-generating components. As the fluid absorbs heat, it transitions from liquid to vapor, effectively dissipating heat through condensation in the heat exchanger.

CFD Simulation:

Computational fluid dynamics (CFD) simulations are used to model the heat transfer and flow behavior of the multi-phase system. Simulations are conducted to determine the optimal flow rate, working fluid type, and heat exchanger design for maximum cooling performance.

System Control and Monitoring:

The cooling system is equipped with sensors and control algorithms that regulate the flow rate and phase transition processes in real-time, ensuring efficient heat dissipation under various operating conditions.

Conclusion:

The multi-phase heat exchanger presents a promising solution for addressing the thermal management challenges faced by hybrid electric vehicles. By utilizing phase change processes and leveraging the latent heat of vaporization, the proposed system significantly improves heat dissipation compared to traditional single-phase cooling methods. The experimental results and simulations show that this approach not only enhances the thermal management of key HEV components but also improves the overall reliability and performance of the vehicle. With continued development, multi-phase heat exchangers could become a standard cooling solution in the next generation of HEVs, contributing to their efficiency, safety, and longevity.

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