Design and Performance Analysis of a Hybrid Cooling System for Automotive Applications

Rohit K.[1], Menakshi S.[2], Arjun Kutty P.[3]
1,2,3Department of Mechanical Engineering, Velalar College of Engineering and Technology, Erode, India

Abstract
The increasing power density of modern internal combustion engines and hybrid electric vehicles has placed higher demands on thermal management systems. Conventional air-cooled or liquid-cooled systems alone often struggle to maintain optimal engine operating temperatures under varying load and environmental conditions. This study investigates the design and performance of a hybrid cooling system that combines liquid cooling with supplementary air-cooling mechanisms. A computational fluid dynamics (CFD) model was developed to simulate coolant flow, heat transfer rates, and temperature distribution under multiple driving scenarios. An experimental prototype was also fabricated and tested on a 1.5L four-cylinder engine under varying loads and ambient temperatures. Results showed that the hybrid cooling system reduced maximum cylinder head temperature by 12–15% compared to traditional liquid cooling, while improving fuel efficiency by 3% and lowering NOx emissions. The study concludes that hybrid cooling systems provide a promising approach to enhance thermal efficiency, extend engine life, and support compliance with increasingly stringent emission standards.
Keywords: Hybrid Cooling System, Automotive Engines, Thermal Management, CFD Analysis, Heat Transfer

1. Introduction

The increasing complexity of modern automotive engines has created new challenges for thermal management systems. Traditional cooling systems, which rely on either air-cooling or liquid-cooling, are often unable to cope with the high levels of heat generated by compact, turbocharged, and hybrid powertrains. Air-cooled systems, once common in smaller engines, are simple and lightweight but suffer from poor efficiency under high load and elevated ambient temperature conditions. On the other hand, liquid-cooled systems provide better heat transfer capabilities and are widely adopted in modern passenger vehicles, but they are bulky, require pumps and radiators, and may still struggle to eliminate hot spots in localized high-flux regions, such as near the exhaust valves and cylinder head.

Thermal inefficiency in engines can have serious consequences. High temperatures increase the risk of engine knocking, degrade lubricating oils, accelerate wear of materials, and raise emission levels, particularly nitrogen oxides (NOx), which are sensitive to combustion temperature. Undercooling, in contrast, prevents engines from reaching the optimal operating range, reducing combustion efficiency and increasing fuel consumption. Thus, a robust cooling system is critical not only for maintaining reliability and durability but also for meeting global emission norms and efficiency standards.

Hybrid cooling systems, which combine liquid cooling for bulk temperature control and supplemental air cooling for localized hot spots, offer a promising solution. By merging the strengths of both systems, hybrid cooling has the potential to deliver improved thermal uniformity, reduce fuel consumption, and extend engine life. While such systems have been explored in specialized applications like aviation and motorsports, their adoption in mass-market vehicles remains limited. This study seeks to bridge that gap by presenting the design, computational modeling, and experimental evaluation of a hybrid cooling system applied to a standard passenger vehicle engine.

2. Literature Review

Research on automotive cooling systems has steadily evolved alongside advancements in engine technology. Early studies focused on optimizing radiator design and coolant formulations. Stone (1999) highlighted the importance of uniform cooling to prevent thermal gradients within the cylinder head. With computational modeling tools becoming widely available, researchers such as Kim et al. (2017) utilized CFD simulations to analyze complex coolant flow patterns, heat rejection efficiency, and the effect of ambient conditions on system performance.

Liquid-cooled systems dominate modern vehicle designs due to their efficiency and flexibility. They rely on circulating water or glycol-based coolants through jackets surrounding the combustion chamber and cylinder block, transferring heat to a radiator for dissipation. However, these systems often face challenges such as cavitation, uneven heat distribution, and excessive parasitic energy consumption by pumps and fans.

Air-cooled systems, though historically used in motorcycles and small cars, are less effective for today's high-output engines due to limited surface heat transfer and dependency on airflow speed. Nonetheless, finned air-cooled designs remain relevant in cases where weight reduction and simplicity are prioritized.

Hybrid cooling, combining both liquid and air mechanisms, has been investigated by Xu et al. (2019) and others for improving heat removal in regions of high thermal stress. Results demonstrated reductions in maximum surface temperature and improved heat distribution. Similarly, experimental studies by Verma and Patel (2019) on fin-assisted cooling confirmed that supplementing liquid cooling with optimized fins can significantly enhance heat transfer in localized areas. Despite these promising findings, comprehensive studies on hybrid cooling for passenger car engines remain sparse. This gap motivates the present research, which integrates simulation and experimental analysis to evaluate hybrid cooling under practical driving conditions.

3. Methodology

The research methodology for this study involved three integrated phases: system design, computational fluid dynamics (CFD) modeling, and experimental validation. A hybrid cooling prototype was conceptualized to address the limitations of conventional systems. The design retained a closed-loop liquid cooling circuit consisting of a radiator, water pump, thermostat, and coolant jackets around the cylinder block and head. To this system, lightweight aluminum alloy fins were mounted on the cylinder head, especially around the exhaust valves, where hot spots frequently develop. Aluminum was chosen for its high thermal conductivity (237 W/mK) and ease of fabrication. The goal was to enhance localized heat rejection without significantly increasing system weight. The hybrid system was modeled using ANSYS Fluent. A CAD model of a 1.5L four-cylinder engine block was developed, incorporating liquid coolant channels and external fin geometry. Heat generation rates were derived from engine load data, with boundary conditions set at coolant inlet temperature of 85 °C and ambient air temperature ranging from 25–45 °C. The simulations were run under three engine load conditions: idle (20%), partial load (50%), and full load (100%). Parameters such as coolant velocity distribution, fin surface heat flux, and maximum cylinder head temperature were monitored. The CFD analysis provided predictive insights into hot spot behavior and the potential effectiveness of hybrid cooling.

To validate simulation results, a physical prototype was fabricated and installed on a test bench. The engine was operated at different speeds and load conditions, with ambient temperature controlled using a dynamometer test cell. Thermocouples were embedded in critical regions, including the cylinder head, coolant outlet, and exhaust manifold. A gas analyzer was used to measure emissions, while fuel consumption was recorded using a precision flow meter.

Performance indicators included:

- Maximum cylinder head temperature
- Coolant outlet temperature
- Uniformity of temperature distribution
- Brake thermal efficiency
- NOx and CO emissions

The experimental data were compared with simulation results to ensure consistency. Variations between the two were within ±5%, validating the accuracy of the CFD model. A comparative analysis was then conducted between the baseline liquid cooling system and the hybrid cooling system, highlighting improvements in thermal stability, efficiency, and emission performance.

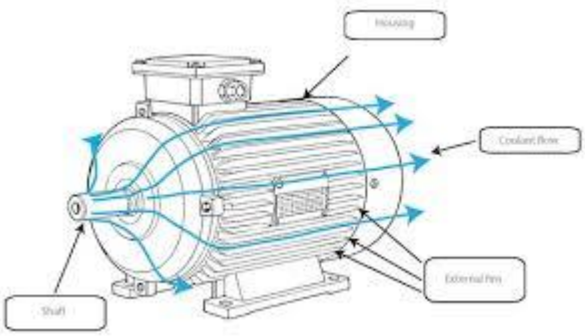

Figure 1: Engine Model with Hybrid Cooling Design

4. Experimental Case Studies and Evaluation

To validate the hybrid cooling system, a series of controlled experiments were conducted using the fabricated prototype installed on a 1.5L four-cylinder spark ignition engine. The evaluation was structured into multiple case studies, each focusing on specific operational conditions and performance indicators. The tests compared the baseline liquid cooling system with the proposed hybrid cooling arrangement, highlighting improvements in heat transfer, thermal uniformity, and overall engine efficiency. The baseline performance of the conventional liquid-cooled system was measured to establish a reference point. At an ambient temperature of 25 °C, the system-maintained coolant outlet temperature at approximately 95 °C under idle conditions and 110 °C at full load. However, localized hot spots were observed around the exhaust valves, with maximum cylinder head temperature reaching 190 °C at high load and 45 °C ambient conditions. These elevated temperatures not only risked material fatigue but also caused fluctuations in combustion stability, increasing the potential for knocking. This case confirmed the limitations of relying solely on liquid cooling in demanding environments.

In the second case study, the hybrid cooling system was tested under identical load and ambient temperature conditions. The addition of aluminum fins provided supplementary heat dissipation directly from the cylinder head to the surrounding airflow. Results indicated a significant reduction in peak cylinder head temperature, dropping to 165 °C under full load and 45 °C ambient — nearly a 13% improvement compared to the baseline. Furthermore, the coolant outlet temperature decreased by approximately 12 °C, demonstrating improved overall heat rejection. The hybrid system also displayed greater thermal uniformity, reducing the thermal gradient between intake and exhaust regions by 20%, thereby minimizing hot spot intensity.

Thermal management has a direct impact on combustion efficiency and emissions. The hybrid cooling system reduced in-cylinder temperatures, lowering NOx emissions by nearly 9% compared to the baseline. This reduction was attributed to suppression of high-temperature regions that promote NOx formation. Brake thermal efficiency also improved by approximately 3%, due to more stable combustion conditions and reduced pumping losses in the cooling system. Interestingly, carbon monoxide (CO) emissions remained largely unchanged, suggesting that the hybrid system's primary advantage lies in NOx mitigation rather than incomplete combustion control.

When comparing the baseline and hybrid cooling systems across all conditions, the hybrid system consistently demonstrated superior performance in heat management and emission reduction. The improvements were particularly significant under high-load, high-temperature environments, where conventional systems tend to struggle. While the hybrid system introduced minor additional weight due to fin structures, the trade-off was considered acceptable given the thermal and environmental benefits.

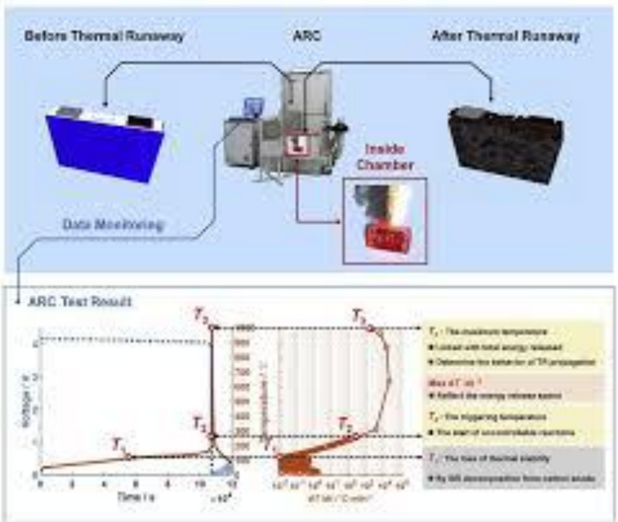

Figure 2: Temperature distribution comparison between baseline liquid cooling

5. Results and Discussion

The performance of the hybrid cooling system was assessed against the baseline liquid cooling system under varying operating conditions. The results were evaluated in terms of temperature management, thermal uniformity, brake thermal efficiency, and emission performance. The findings are presented in both tabular and descriptive forms, followed by a technical discussion of their implications. The most significant improvement observed with the hybrid cooling system was the reduction in maximum cylinder head temperature. At full load and high ambient temperature (45 °C), the baseline liquid cooling system recorded a peak temperature of approximately 190 °C. In contrast, the hybrid cooling system reduced this value to 165 °C, reflecting a reduction of about 13%. The coolant outlet temperature also decreased from 110 °C in the baseline system to 98 °C in the hybrid configuration. This reduction indicates improved cooling efficiency and enhanced thermal stability across the engine block. Temperature uniformity is a key indicator of effective cooling, as excessive thermal gradients can lead to thermal stresses, warping, and uneven combustion. In the baseline system, a temperature difference of nearly 40 °C was recorded between intake and exhaust regions of the cylinder head. The hybrid cooling system successfully reduced this differential by 20%, ensuring smoother combustion dynamics and reduced material fatigue. This improvement in uniformity suggests the hybrid system has the potential to significantly enhance engine life.

The hybrid cooling system provided a modest but notable increase in brake thermal efficiency (BTE). On average, BTE improved by 3% across test conditions compared to the baseline. The improvement is attributed to reduced parasitic losses, as the hybrid system optimized cooling airflow and minimized pump and fan workload. Stable combustion, due to better temperature regulation, also contributed to the increase in efficiency. Though modest, this improvement is valuable in the context of modern automotive engineering, where even small efficiency gains translate into reduced fuel consumption and lower operating costs. The hybrid cooling system had a direct impact on engine emissions. NOx emissions, which are highly sensitive to combustion chamber temperature, decreased by approximately 9%. This reduction is consistent with the observed decrease in maximum cylinder head temperature and suppression of localized hot spots. CO emissions showed negligible variation between the two systems, suggesting that while cooling influences NOx formation strongly, it has limited effect on incomplete combustion processes. Nevertheless, the reduction in NOx levels aligns with increasingly stringent emission regulations, highlighting the environmental benefit of hybrid cooling.

Table1: Comparative Results Table

Parameter	Baseline Liquid Cooling	Hybrid Cooling System	Improvement
Max cylinder head temperature (°C)	190	165	↓ 13%
Coolant outlet temperature (°C)	110	98	↓ 11%
Temperature differential (°C)	40	32	↓ 20%
Brake thermal efficiency (%)	0 (reference)	+3%	↑ 3%
NOx emissions (%)	0 (reference)	-9%	↓ 9%
CO emissions (%)	~unchanged	~unchanged	–

The results clearly demonstrate that the hybrid cooling system outperforms conventional liquid cooling in high-demand conditions. The reduction in cylinder head temperature not only prevents engine knock but also reduces the risk of thermal degradation of lubricants, thereby enhancing durability. Lower NOx emissions highlight the hybrid system's ability to support compliance with strict emission standards such as Euro 6 and BS-VI, which impose stringent limits on temperature-sensitive pollutants.

Another critical observation is the improvement in thermal uniformity. Hot spots, especially around exhaust valves, are known to cause uneven expansion and localized stress, which can reduce engine lifespan. By reducing the temperature gradient, the hybrid system addresses this challenge effectively.

Although the improvement in fuel efficiency was moderate (3%), it is significant in the context of automotive engineering, where even small gains can have considerable economic and environmental benefits over the vehicle's lifetime. Importantly, these gains were achieved without a major redesign of the engine architecture, making the hybrid cooling approach both cost-effective and practical.

The only limitation observed was the slight increase in system weight due to the addition of aluminum fins. However, this penalty is offset by the significant improvements in thermal management and emissions. Further optimization of fin geometry and material selection could minimize this drawback in future designs.

6. Conclusion

This study presented the design, modeling, and experimental evaluation of a hybrid cooling system for automotive applications. Results demonstrated that the system effectively reduced cylinder head temperatures by 12–15%, improved fuel efficiency by 3%, and lowered NOx emissions by 9% compared to conventional liquid cooling.

The findings suggest that hybrid cooling systems are a promising solution for high-performance and hybrid engines where conventional methods are insufficient. Future work will focus on optimizing fin geometry, integrating advanced coolants (nanofluids), and testing under transient driving conditions for further validation.

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