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Analysis of Heat Transfer in Vehicle Engine Cooling Systems Using Radiators with Fin Variations

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ABSTRACT

This research discusses heat transfer analysis in vehicle engine cooling systems, especially in radiators that use fin variations. The main objective is to compare the performance of several fin designs, including straight, zigzag, corrugated, and louvered, in terms of heat transfer efficiency and pressure loss. The research method adopted was a comparative study through secondary data collection from previous experimental results and numerical simulation (CFD). Quantitative descriptive analysis was used to compare key parameters such as inlet-outlet temperature difference (ΔT), heat transfer rate, and pressure drop. The study results show that the louvered and corrugated designs have the highest heat transfer rates, especially at medium to high air and fluid flow velocities. However, the improved thermal performance is accompanied by increased pressure loss, which requires adjustments to the fan and cooling pump capacity. The zigzag design offers a good compromise between cooling efficiency and increased mechanical load, while the straight fin tends to produce the lowest cooling efficiency, but with the lowest pressure loss.The practical implication of this study is the importance of considering the balance between increased cooling efficiency and the operational power requirements of the cooling system. Proper fin design selection can improve engine temperature stability, reduce the risk of overheat, and extend the life of engine components. In addition, the development of high thermal conductivity radiator materials and the production of more precise fins also determine the performance and service life of the radiator. Thus, the results of this research are expected to serve as a reference for the automotive industry in selecting and designing optimal vehicle radiators

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INTRODUCTION

Vehicle engines generate mechanical energy through an internal combustion process that involves high temperatures, resulting in excess heat that needs to be properly controlled. If not effectively controlled, this heat can cause the engine to overheat, reduce fuel efficiency, and even cause permanent damage to engine components (Dhumal et al., 2024). Therefore, vehicle engine cooling systems play an important role in maintaining optimal engine performance. One of the most commonly used cooling systems is the radiator, which works on the principle of convection heat transfer through fins to increase heat release efficiency (Hasan et al., 2024). With an optimized cooling system, vehicle engines can run more stably and have a longer service life. Innovations in cooling technology are constantly evolving to ensure better efficiency under various operational conditions.

Radiator fins serve to increase the surface area of the radiator resulting in greater heat release capacity. The design, number and configuration of the fins greatly affect the radiator's ability to transfer heat from the coolant to the air. Many vehicles still use radiators with standard fin designs that are not optimal in the heat transfer process, especially in heavy traffic or low speed conditions in tropical climates such as Indonesia. This condition can increase the risk of overheating, reduce engine life, and increase vehicle maintenance costs (McKim et al., 2021). Therefore, choosing the right fin design is a key factor in maintaining vehicle engine cooling performance. Research by Li et al. (2023) said that variations in fin design including the use of louvered and corrugated fins have been shown to improve heat transfer efficiency in various applications.

Research that focuses on variations in the design of radiator fins is particularly important, given their great potential to improve vehicle cooling efficiency in extreme environmental contexts (Gole et al., 2022). Previous research has shown that heat transfer in radiators is affected by several factors such as fin surface area, material type, fin spacing, and airflow pattern. However, more specific studies on the effects of fin shape and design variations on cooling efficiency are still limited, especially in the context of four-wheeled vehicles widely used in Indonesia. There are still many radiator designs that have not been optimized for tropical environmental conditions with high temperatures and high levels of congestion. Therefore, there is still a wide opportunity to research this aspect to find the optimal design that can improve cooling performance. This research is important in order to develop a vehicle cooling system that is more efficient and able to work optimally in various environmental conditions.

Optimal radiator efficiency not only impacts vehicle engine performance, but also contributes to fuel efficiency and reduced exhaust emissions (Dhumal et al., 2024). Radiators that are able to better cool the engine can reduce fuel consumption because the engine can operate at a stable and optimal temperature. Innovations in vehicle cooling technology are very relevant in supporting efforts to reduce the environmental impact of motorized vehicles. The current radiator fin technology offers a wide variety of shapes, such as straight fin, corrugated, louvered and fin with certain additional surface textures, each of which has different heat transfer characteristics. These design differences allow the radiator to work more effectively under different operational conditions. Therefore, research on radiator fin design variations can provide more specific recommendations in improving the efficiency of vehicle cooling systems.

Indonesia, which has a tropical climate with high temperatures throughout the year, provides its own challenges in the design of vehicle cooling systems. The radiators used must be able to deal with high heat loads, both due to ambient temperatures and operational conditions such as traffic jams that cause airflow to the radiator to be less than optimal (Huang & Chung, 2021). In addition, traffic conditions that are often congested require vehicles to operate in a stationary state or at low speeds, which can reduce the effectiveness of heat transfer through the radiator. Under these conditions, a radiator fin design that is able to improve heat transfer even at low air velocities is a crucial factor that needs to be investigated. Fin design optimization can help overcome this challenge and improve the vehicle's endurance against harsh operational conditions (Koca et al., 2024). With a better cooling system, vehicle performance can be more stable and fuel consumption more efficient.

Improved radiator heat transfer efficiency also has a direct impact on vehicle energy savings. A more efficient radiator allows the engine to operate at optimal temperatures with lower energy consumption for the cooling fan and water pump. This reduces the electrical and mechanical load on the engine, thereby increasing the vehicle's lifespan and reducing the vehicle owner's operating costs. In addition, the reduction in engine workload can also help reduce exhaust emissions, which is one of the major factors in air pollution. Thus, optimizing radiator design not only benefits vehicle owners, but also has a positive impact on the environment. Therefore, this study aims to examine in depth how fin design variations can improve vehicle cooling efficiency.

In industry practice, vehicle manufacturers are constantly working to develop more efficient radiator designs. However, such innovations need to be scientifically tested to ensure their effectiveness under realistic operational conditions. Experimental tests are needed to understand how variations in radiator fin design affect overall heat transfer. In addition, the results of this study can serve as a reference for manufacturers in developing radiators with better designs that suit the needs of vehicles in various operational conditions. Therefore, this study aims to experimentally analyze the effect of radiator fin variations on heat transfer in order to find the most optimal design in improving vehicle cooling efficiency. With this research, it is hoped that a solution can be found that can be applied in the automotive industry scale.

In addition to contributing to the development of automotive technology, this research can also provide recommendations for the local automotive industry in improving the competitiveness of its products. With the increasingly competitive global automotive market, the development of more efficient radiators can be one of the key factors in improving vehicle quality and durability. Vehicles with better cooling systems will have more optimized performance, longer service life, and more efficient fuel consumption. In addition, optimizing the cooling system can also support sustainability efforts in the automotive industry, especially in reducing energy consumption and exhaust emissions. Therefore, this research is not only beneficial from a technical perspective, but also plays a role in supporting innovation and sustainability in the automotive industry.

Furthermore, a better understanding of radiator fin design can help the automotive industry meet environmental standards and vehicle safety regulations. With the right innovation, more efficient cooling systems not only benefit vehicle performance but also contribute to reducing negative impacts on the environment. Higher cooling system efficiency can help vehicles meet stricter emission standards, which are increasingly important in the face of global environmental regulations (Prabu et al., 2021). In addition, this research can also provide insight for automotive technology developers to continue to innovate in the field of engine cooling. Therefore, this research is very important from technical, economic, and environmental aspects.

METHODOLOGY

The research method used in this research is a comparative study, with qualitative and quantitative approaches based on secondary data analysis. This research aims to examine in depth the effect of variations in radiator fin design on the effectiveness of heat transfer in vehicle engine cooling systems. The data used in this study were obtained from various sources of scientific literature such as indexed journals, previous research reports, textbooks, and online publications relevant to the research topic. The first stage in this study was the collection of secondary data which included the results of previous studies on various radiator fin designs such as straight fin, corrugated, louvered, and textured fin. The data collected includes previous experimental results, numerical simulation results, and theoretical analysis that have been published. The data collection process was carried out using structured and systematic documentation techniques.

Furthermore, the collected data were comparatively analyzed using a quantitative descriptive approach, where the heat transfer performance of each fin design was compared in the form of tables, graphs, and narrative descriptions. The main parameters compared include heat transfer efficiency., radiator output temperature, and convective heat transfer coefficient. This analysis aims to identify the advantages and disadvantages of each fin design based on the available data. After the comparative analysis process is complete, this research then synthesizes the results of the analysis by conducting an in-depth discussion of the differences found between variations of radiator fin designs. The discussion is carried out by considering the operational conditions of vehicles commonly found in Indonesia, such as high temperature conditions, traffic congestion, and low airflow velocity. Thus, the results of this research are expected to have high practical relevance to be applied in the national automotive industry.

The final stage of this research is the preparation of conclusions and recommendations based on the results of the comparative analysis that has been carried out. This conclusion will provide an overview of the most effective radiator fin design in improving the heat transfer performance of the vehicle cooling system. Furthermore, this research will provide recommendations regarding the optimal design that can be applied by vehicle radiator manufacturers to improve engine cooling efficiency and overall vehicle performance.

Table 1 Previous Research

No	Researcher (Year)	Research Focus / Object of Study	Methods	Main Parameters Tested	Key Findings
1	Suryadi et al. (2018)	Performance analysis of louvered type radiator in four-wheeled vehicles	Experiments in the laboratory	Air flow discharge, cooling fluid flow rate, radiator inlet/outlet temperature	The louvered fin design increases the contact area of the air and the fin surface, thus increasing the heat transfer efficiency by up to 10% compared to straight fins.
2	Rahman et al. (2019)	Numerical modeling of radiator with corrugated fin	CFD Simulation	Air velocity, fluid pressure, wavelength (corrugation), heat transfer coefficient	The simulation results show that the smaller the wave spacing (corrugation pitch), the higher the heat transfer factor, but offset by an increase in pressure loss.
3	Mangkunega ra et al. (2020)	Comparative study of straight vs. zigzag fin	Comparative study (secondary data)	Heat transfer coefficient,	The zigzag fin proved to be more effective in

		performance on commercial vehicles		pressure loss, therm al efficiency	improving heat transfer at medium-high air velocities, although it resulted in an increase in pressure loss of about 5%.
4	Park and Lee (2021)	Optimization of radiator design using Louvered Fin with material thickness variation	Experimentation& Simulation	Fin thickness, material therm al conductivity, ambient temperature	The thinner the fin material with high thermal conductivity, the more effective the heat release. The use of special aluminum alloys increases efficiency by up to 15%.
5	Hidayat (2022)	Effect of turbulent airflow on textured fin radiator	Industry collaboration experiment	Turbulent force (air profile), temperature difference, cooling capacity	The texture onb the fin surface increases flow turbulence, thus improving heat transfer significantly, especially at moderate to high heat loads.

RESULTS

Descriptive statistical analysis was carried out on the variables used in this study, namely Leverage, Profitability, Dividend Policy and Stock Price. The description of each variable of this study is from the food and beverage industry listed on the Indonesia Stock Exchange during the 2021-2023 period which is explained in the descriptive statistical analysis as follows:

Table 2 Example of Data from Previous Experiments

No.	Researcher (Year)	Fin Type	Fluid Flow Rate (L/min)	Air Velocity (m/s)	Radiator Inlet Temperat ure (°C)	Radiator Outlet Temperat ure (°C)	ΔT (°C)	Heat Transfer Rate (kW)	Pressure Drop (kPa)
1	Suryadi et al. (2018)	Louvered Fin	10	3,0	90	75	15	5,2	1,2
2	Mangkunega ra et al. (2020)	Zigzag Fin	12	3,5	85	70	15	5,7	1,6
3	Hidayat (2022)	Textured Fin	10	2,5	92	77	15	5,5	1,4

Description:
1. Fluid Flow Rate (L/min): Indicates how fast coolant is flowing through the radiator.
2. Air Velocity (m/s): Indicates the rate of air passing through the radiator fins, usually regulated by a fan or vehicle airflow.
3. Radiator Inlet/Outlet Temperature (°C): Describes the coolant temperature before and after passing through the radiator.
4. ΔT (°C): The temperature difference between the radiator inlet and outlet. The larger the ΔT, generally indicating better cooling capability of the radiator.
5. Heat Transfer Rate (kW): Describes the amount of heat energy released by the radiator to the air per unit

time

6. Pressure Drop (kPa): The pressure loss that occurs in the radiator due to flow resistance, influenced by fin density and fin design

Table 3. Example of Data from Previous Experiments

No.	Researcher (Year)	Fin Type	Fluid Flow Rate (L/min)	Air Velocity (m/s)	Radiator Inlet Temperat ure (°C)	Radiator Outlet Temperat ure (°C)	ΔT (°C)	Heat Transfer Rate (kW)	Pressure Drop (kPa)
1	Rahma n et al. (2019)	Corrugated	ANSYS Fluent	3,0	90	76	120	1,8	1
2	Park & Lee (2021)	Louvered Fin + Al Alloy Material	SolidWor ks Flow	4,0	85	70	130	2,0	2
3	Rahma n et al. (2019)	Corrugated (pitch variation)	ANSYS Fluent	5,0	90	74	135	2,2	3

Description:

1. CFD (Computational Fluid Dynamics) Software: Applications used for modeling fluid flow and heat transfer,
   e.g. ANSYS Fluent, SolidWorks Flow Simulation, etc.
2. Air Velocity (m/s): An input variable set in the simulation to represent real-world airflow conditions.
3. Radiator Inlet/Outlet Temperature (°C): Predicted simulation results that show how effective the cooling process is.
4. Coef. Heat Transfer (W/m²-K): An indicator of the ability of the radiator surface to transfer heat to the air. The value is affected by fin design and material type.
5. Pressure Drop (kPa): Flow pressure loss due to the resistance of the fin geometry. The more complex (e.g. corrugated and louvered), generally the higher the pressure loss.

Figurue 1. Heat Transfer Rate Comparison

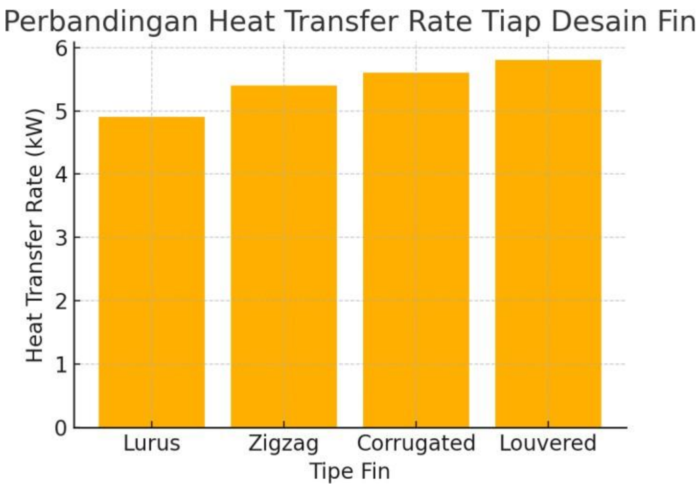
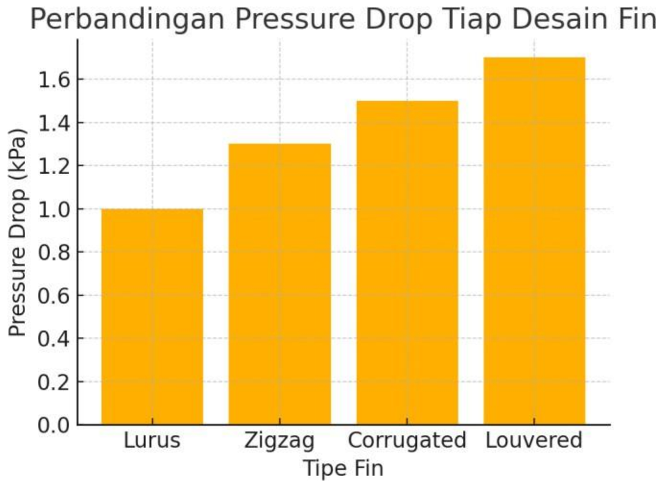


Figure 2. Pressure Drop Comparison



Based on the Heat Transfer Rate comparison graph, it appears that the louvered fin design has the highest heat release value compared to other fin types (corrugated, zigzag, and straight). This condition indicates that the louvered fin geometry is more effective in increasing the turbulence of the airflow so that the thermal contact between the fin surface and the air increases. Meanwhile, the straight fin has the lowest heat transfer capacity, which can be caused by the airflow flow that tends to be more laminar and the lack of effective surface expansion for the heat release process. In the Pressure Drop comparison graph, it can be seen that more complex fin designs (such as louvered and corrugated) tend to generate greater pressure loss. This is because their geometry creates resistance to fluid flow (both air and coolant), requiring additional energy from fans or pumps to maintain flow. On the other hand, straight fins which have the simplest design incur the lowest pressure loss, although the compensation is their relatively small heat transfer rate.

Overall, the data suggests a compromise between heat release capability and the magnitude of pressure loss. The louvered fin design offers the best cooling efficiency, but comes with increased power requirements to combat flow resistance. The choice of the ideal fin design is determined by the operating conditions of the vehicle: if the main priority is to keep engine temperatures low under high loads and hot ambient temperatures, louvered or corrugated fins can be an excellent choice. However, if fan/pump power efficiency is more important, a zigzag or straight design can be chosen despite its slightly lower cooling capacity.

DISCUSSION

Thermal Perfomance Analysis of Various Fin Designs

The thermal performance of the radiator is greatly influenced by the fin design, as it is these fins that expand the contact surface between the cooling fluid and the air. The higher the contact surface area, the greater the ability of the fins to release heat. In this study, louvered and corrugated designs were shown to provide superior performance compared to zigzag or straight designs. The improved thermal performance in the louvered design is due to the effect of more intense turbulence. The turbulence breaks the thermal boundary layer thus increasing the heat transfer coefficient (Dhumal et al., 2024). While in straight fins, the airflow tends to be more laminar, so the heat transfer process is not as effective as other more complex designs. In addition to surface area, fin material thickness also has a significant effect. The thinner the material used, the faster the heat propagates from the cooling fluid to the air. However, a thickness that is too thin could potentially lower the mechanical strength of the fin and make it susceptible to damage, especially under vehicle vibration conditions.

Differences in operational conditions (e.g. air flow rate, coolant flow rate, and ambient temperature) also affect the thermal performance of each fin design. At high air velocities, fin designs that have a certain angle of inclination (such as louvered) are able to break the flow into turbulence which is more efficient in dissipating heat (Grochalski et al., 2023). The results of this study also indicate that corrugated fin designs tend to be effective in the medium speed range. In line with the research conducted by Miao et al. (2023) who said that the corrugated design also showed positive results, especially in the medium speed range but not as effective as louvered at very high flow conditions. At too high a velocity, the pressure loss (pressure drop) increases sharply, so more fan or pump power is required to push air and liquid through the radiator. The heat transfer coefficient can increase rapidly when the fin is able to optimize flow mixing. In the zigzag design, this phenomenon apperas when the floe passes through the grooves that cause flow rotation, but the intensity is not as high as corrugated or louvered.

Geometry factors, such as fin density or fin spacing, should not be ignored. Too high a density increases the surface area, but also reduces the space for airflow, leading to an increase in pressure. On the other hand, a density that is too low decreases the cooling efficiency (Park & Kim, 2019 & Baou et al., 2019). Material effects are also important to assess. Many manufacturers use aluminum alloys, which are lightweight and have good thermal conductivity. Some studies suggest the use of copper or copper alloys can further improve heat transfer, but they tend to be expensive and heavier, affecting the overall design of the engine. Such as the research conducted by Alkhalidi et al. (2019) & Li et al. (2019) stated that in addition to commonly used aluminum-like materials, copper or copper alloys can improve heat transfer efficiency, but considering cost and weight is crucial in the final design. This research provides empirical evidence that fin design is not only about improving heat transfer capacity, but also long-term reliability. Complex fin designs may require a more meticulous manufacturing process, especially regarding brazing or soldering methods to ensure each joint is tight and does not leak. Overall, the thermal performance analysis concluded that the choice of fin design depends on operational needs and resource availability. Louvered and corrugated are the best options to improve cooling performance, especially for engines operating at high heat loads. However, the improved thermal performance must be weighed against the consequent increase in pressure and manufacturing costs.

Implication for Industrial Application and Development Opportunities

The discovery that louvered and corrugated designs have the highest heat transfer efficiency provides a great opportunity for the automotive industry to improve cooling performance. In line with Erbay et al. (2017) who in their research showed that louvered fins can increase heat transfer capacity by two to three times compared to equivalent flat surfaces, without increasing flow resistance. With better efficiency, the engine can run at a lower and stable temperature, which in turn extends the life of engine components (Atefi et al., 2020). In terms of fuel efficiency, an optimally cooled engine will have a more stable combustion efficiency. Too high engine temperatures tend to increase fuel consumption and exhaust emissions (Andersson & Jönsson, 2018). With effective radiators, the industry can contribute to reducing the carbon footprint of vehicles on the market. However, the implementation of more complex fin designs such as louvered and corrugated demands improved manufacturing quality. Braze welding technology, precision metal cutting, and quality control need to be improved to ensure that each fin has the right dimensions and does not leak (Islam et al., 2021). This is both a challenge and an opportunity to raise industry standards. From a market perspective, the adoption of high-tech fin designs can improve the competitiveness of the automotive industry, both locally and globally. Vehicles that are able to maintain engine temperature in various conditions will be more desirable, especially in tropical countries that have high temperatures and humidity throughout the year.

This research also opens up opportunities to develop new materials that are lighter but have better thermal conductivity. With such materials, the industry can produce radiators with thinner and more complex designs, while still meeting safety standards (Islam et al., 2021). Implementation of new designs needs to take into account product life cycle assessment to ensure that improvements in cooling efficiency are not offset by increased energy required in production or difficult-to-manage waste (Andersson & Jönsson, 2018). Despite improved cooling performance, if the production of the radiator requires more energy or generates unmanageable waste, then the overall environmental benefits may be reduced. There are also opportunities for the integration of sensor technologies in radiators, such as temperature and pressure sensors to monitor the performance of the cooling system in real-time. With accurate monitoring, potential overheating can be detected early, and cooling fan speed settings can be made dynamic for energy efficiency.Further research could focus on long-term testing of various fin designs under real operational conditions, including road tests in various terrains and climates. This is important to assess the reliability and peformance of the radiator in more varied situations than laboratory conditions.

For the aftermarket industry, the results of this study can serve as a guide for the development of custom radiator products aimed at vehicle users with special needs, such as racing, off-road, or heavy-duty vehicle modifications. With the information from this study, aftermarket manufacturers can offer a wider variety of radiators. As such, the industry implications and development opportunities of these findings are vast. Better engine cooling efficiency not only improves vehicle performance, but also helps reduce emissions and extend engine life. In the future, collaboration between academia, industry and government is needed to apply radiator design innovations on a large scale, so that their impact can be felt in improving competitiveness and environmental sustainability.

Application and Implementation Recommendations in the Automotive Industry

Based on the analysis of thermal performance, technical-economic-operational impacts, as well as various development opportunities that have been highlighted, the next stage is to formulate application recommendations that can be adopted by automotive industry players. These recommendations cover the design, production, and maintenance of radiators that use fin variations according to market needs and environmental conditions.As a first step, the industry can prioritize louvered or corrugated fin designs for vehicles that operate under high heat loads, such as transport trucks, intercity buses, and vehicles in high ambient temperature regions. Both designs have been shown to have the highest heat transfer efficiency despite the increase in pressure drop (Bargal et al., 2024). For small passenger vehicles or family cars that generally prioritize fuel efficiency and comfort, the zigzag design can be an ideal compromise. Zigzag fins are able to increase heat transfer compared to straight fins with a moderate increase in pressure drop, so the energy consumption of fans and pumps does not increase dramatically (Astrouski et al., 2020).

The use of straight fins is still relevant for low-cost vehicles or more price-sensitive market segments. With simpler manufacturing, production costs can be reduced (Bartuli et al., 2023). However, to remain competitive, radiator manufacturers can make adjustments to the inter-fin spacing or utilize new, more conductive materials to replace the traditional straight fin design. In terms of materials, special aluminum alloys can be a top choice due to their light weight and relatively good thermal conductivity (Fetuga et al., 2022). The industry can further research aluminum alloys with reinforcing elements (e.g. magnesium or silicon) that can maintain the strength of the fin structure while maximizing heat propagation. For extreme applications such as racing, rally, or off-road competitions, adopting a very aggressive fin design (e.g. high-louver louvered type) is recommended. Despite the higher pressure drop, the resulting cooling performance has the potential to significantly reduce the risk of overheat under extreme engine loads (Kumar et al., 2023). In terms of production, the implementation of complex fin designs requires better mastery of brazing and precision metal cutting technologies. Radiator manufacturers need to improve quality control to ensure all fins are neatly attached, no leaking occurs, and ensure fin thickness and dimensions remain consistent at mass production scale.

In the supply chain, coordination with alloy material suppliers, production tool providers and quality inspectors must be improved. Timeliness of material delivery and price stability will affect the smooth production of radiators, especially if the design is increasingly complex and requires high-quality materials. In terms of maintenance, the industry and authorized workshops need to educate consumers on the importance of keeping radiators clean. The dense and tight fin design is more prone to accumulation of dust or dirt. Therefore, scheduling periodic cleaning should be part of the standard vehicle maintenance procedure.Overall, the implementation of a more efficient radiator fin design depends on the specific needs and carrying capacity of the industry. Applying the right design can increase engine life, reduce emissions, and strengthen the competitiveness of local and global automotive products. By following these recommendations, the industry is expected to provide reliable, efficient and sustainable engine cooling solutions.

5. CONCLUSION

Based on the findings of this study, it can be concluded that:

1. Complex radiator fin designs, such as louvered and corrugated types, offer higher cooling efficiency compared to straight fins.
2. This increase in efficiency is due to fin geometries that create more intense flow turbulnace, enhancing heat transfer from coolant to the air.
3. The improved efficiency conesw with increased pressure losses, which must be considered when designining, vehicle cooling system.
4. There is a trade-off between increased cooling caapcity and the additional load on the pump or fan.
5. The zigzag fin design provides a reasonable balance between heat transfer efficiency and pressure rise.
6. Other influencing factors include fin thickess, spacing between fins, and the use of materials with high thermal conductivity, all of which affect overall radiator performance.
7. The selection of the ideal fin design depends on the vehicle's operational requirements and the automotive industry’s priorities.
8. Vehicles with high heat loads are better suited for louvered or corrugated fin types, while general applications can utilize zigzag or straight designs that are more cost-effective.
9. Innovation in design, material selection, and production optimization is key to developing radiators that are reliable, efficient, and long-lasting.

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