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Advancements in Heat Exchangers for Improved Engine Cooling: A Comprehensive Literature Review

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Abstract

This literature review investigates the dynamic environment of heat exchangers employed in engine cooling systems, exploring advancements and innovations that have shaped the field. The increasing demand for enhanced engine performance, fuel efficiency, and environmental sustainability has propelled research into heat exchanger technologies. The review encompasses a comprehensive analysis of different types of heat exchangers, materials utilized, design considerations, and performance evaluations, with a keen focus on their respective applications in engines and radiators. The various kinds of heat exchangers belong to the most important themes, such as air-to-air, liquid-to-liquid, finned-tube, and plate heat exchangers, with a focus on their respective advantages, drawbacks, and applications. Design considerations encompass size, shape, and configuration, addressing the factors influencing design choices in modern engine cooling systems. A comprehensive evaluation of heat exchanger performance is carried out, taking into account variables including energy consumption, pressure drop, and heat transfer efficiency. The review incorporates insights from experimental methods and simulations used in assessing heat exchanger performance. Challenges in the field are discussed, providing a nuanced understanding of current limitations, and potential areas for improvement are explored. The literature review concludes with a synthesis of key findings, emphasizing the current state of knowledge in heat exchangers for engine cooling. The abstract aims to provide a concise overview of the multifaceted aspects covered in the literature review, offering valuable insights for researchers and engineers in the advancement of engine cooling systems.

Keywords

heat exchangers, engine cooling, heat transfer efficiency, radiators

1 Introduction

In the field of automotive engineering, engine cooling system dependability and efficiency are critical to ensuring longevity and high efficiency (Elmaihy et al., 2023). Unrecognized by these systems, heat exchangers can be found in many different shapes, each with special benefits. Their function in dissipating excess heat is crucial, and they can use anything from conventional shell and tube designs to cutting-edge plate heat exchangers (Erek et al., 2005). Efforts in the past few years have been grouped into two main areas: choosing the right fluids for the supercritical Rankin cycle and improving heat exchanger design. Studies in the field of optimizing design include (Salmon et al., 2017; Hussein et al., 2014a; Goudarzi and Keshtgar, 2017).

The engine cylinder produces hot gasses as a result of the fuel and air being burned. The coolant in a car serves as a conduit for heat transfer from the engine to the outside air. The engine cooling and exhaust gas systems are the two main sources of heat energy in an automobile, and they both transfer almost the same amount of heat energy. The heat exchangers play a significant role in cooling the engine, and numerous studies explore various techniques, such as design modifications and alternative fluids, that can potentially enhance the efficiency of heat exchangers (Sadhasivam et al., 2021; Hilo et al., 2018). Ikhtiar et al. (2023) explore the use of the Lamella Heat Exchanger (LHE) to cool intake air for a 1.5-liter naturally aspirated engine, addressing global warming and air pollution. According to experimental research, the LHE improves combustion efficiency, which lowers exhaust pollutants and helps restore some lost engine power and torque. This is accomplished through the use of recovered

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heat to warm the fuel or intake air, resulting in improved fuel usage and more thorough combustion. Umirov and Abdurokhmonov (2022) composed a piece that explains the rationale for the fluid flow's aeration and potential directions for two-phase liquid flows, both horizontally and vertically. Thermal efficiency is affected by the two-phase flow's movement patterns and the structural makeup in the radiator channels. The aeration of coolant in engine cooling systems is influenced by design features, load, engine conditions, and technical conditions. Two-phase flow structure and movement in radiator channels affect thermal efficiency. Lipnický et al. (2023) investigated how coolant and radiator mileage affect radiators' thermal-hydraulic properties. Different heat exchange regions were found in two types of car radiators. In terms of the number and placement of fans, radiator II was better suited for the engine under investigation when compared to radiator I. Using the old radiator II, it took 29 minutes and 30 seconds to heat the coolant until it reached its operating temperature of T^{th} = 80.64 °C, with a total mileage of 0 km. In addition, it only took five minutes to cool down. Majmader and Hasan (2023) investigated in a CFD research aiming at computationally evaluating the hydrothermal behavior of a hot water radiator under geometric change of the fin surfaces and addition of perforation to its heat transfer surfaces. The study revealed that altering fin geometries increases the heat transfer rate by up to 131%, perforating fins increases it up to 134%, and radiation heat transfer surpasses convection heat transfer by 60-180%. Lechowska and Guzik (2014) examined an equation that represented unsteady heat transfer in spaces with thin walls and sporadic heating. Each room's air capacity and hot water radiator capacity were factored into the air heat balance. The data showed reasonable agreement between radiator water and internal air, with root mean square errors for internal air and radiator water, which were 1.0K and 1.8K respectively suggesting a prior on-mode switch for light structures. Buonomo et al. (2019) analyzed the heat transfer and performance of an automotive radiator using aluminum nanofluids as a coolant, revealing that despite similarities with ethylene glycol/water (EG/W) coolant, nanofluids consistently demonstrated a superior heat transfer rate, surpassing EG/W by 2%. However, the performance index of nanofluids is smaller due to the higher pumping power demand. The study Elsaid (2019) examined the radiator's heat transfer efficiency and pressure drop properties in a car in Cairo, in Egypt's climatic conditions. When compared to alumina, cobalt oxide improves heat exchanger efficiency and reduces energy consumption. At higher concentrations, it raises the Nusselt number, pump power, and performance index. An elevated temperature of the nanofluid results in a higher Nusselt number. Furthermore, we may draw the conclusion that, under the conditions examined, using nanofluids in car radiators can help increase radiator performance since they enhance heat transfer mechanisms, which in turn enhance engine performance (Neves et al., 2022; Arora and Gupta, 2020). Increasing efficiency in heat transfer studies involves investigating hybrid nanofluid combinations of two nanoparticle types in a base fluid. This technique aims to enhance heat transfer, showcasing potential advancements in efficiency and performance (Allahyar et al., 2016; Xian et al., 2022; Ahmed et al., 2018; Jibhakate et al., 2023).

This review delves into the diverse realm of heat exchangers, examining efficiency factors and the intriguing domain of nanofluids. It offers insights into the evolving landscape of engine cooling technologies, analyzing prior experimental and numerical studies to present results that illuminate more efficient approaches for cooling systems. As shown in Fig. 1, the number of publications on 'engine radiator' has steadily increased over the years, highlighting growing research interest in this area.

2 Heat Exchangers (HXs)

Heat exchangers (HXs) are crucial in industrial fields, balancing surface area and pressure drop. They can be classified according to the transfer method, process nature, fluid flow, and compactness. Compact HXs have a large heat exchange surface per unit volume, making them popular in the aerospace and aeronautical sectors due to their low weight and high thermal efficiency (Careri et al., 2023). In particular, this part focuses on types of heat exchangers, as shown in Fig. 2, which represents the view of an analyzed plate fin and tube heat exchanger.

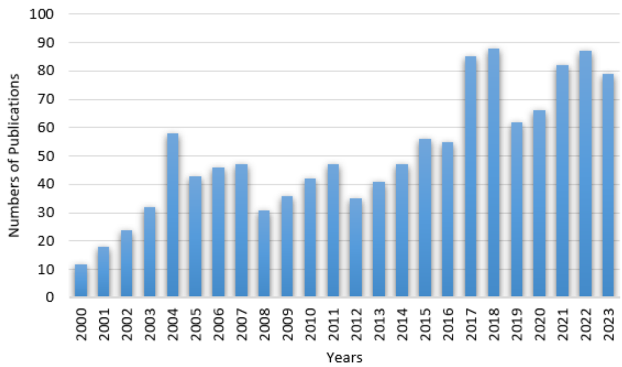

Fig. 1 Numbers of publications per year in Scopus on the keyword 'engine radiator'

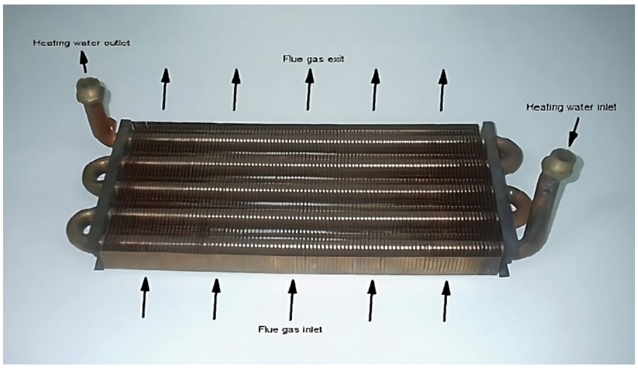

Fig. 2 View of an analyzed plate fin and tube heat exchanger (Erek et al., 2005)

2.1 Radiators

With its crucial role in dissipating excess heat produced during engine operation, a radiator is a component of the cooling system that is necessary for internal combustion engines. The radiator, which is usually found at the front of a car, uses a system of tubes and fins to help transfer heat from the engine coolant to the air around it (Borrajo-Peláez et al., 2010). Radiators come in a variety of forms, from contemporary aluminum constructions to conventional downflow and crossflow designs. When the radiator is working, coolant flows through it, and heat is transferred to the air as it travels over the tubes, allowing the coolant to return to the engine at a reduced temperature. Radiators are essential for maintaining engine performance, preventing overheating, and extending the life of the car.

2.1.1 Crossflow radiator

In car cooling systems, a particular type of radiator called crossflow radiator is used, in which coolant passes across the radiator core horizontally. These radiators, which are identified by side-mounted tanks, allow coolant to be distributed evenly. Coolant enters one tank and leaves the other through tubes or fins that run horizontally. This design ensures efficient heat dissipation by providing a longer flow path, which increases efficiency. Crossflow radiators are a popular option in many different types of vehicles due to their high efficiency and small size, which helps to regulate engine temperatures optimally and prevent overheating (Batista et al., 2022; Colgan et al., 2024; Gopinath and Poovazhagan., 2019).

2.1.2 Downflow radiator

A common radiator design used in automotive cooling systems is the downflow radiator. Downflow radiators have the coolant flowing vertically from the top to the bottom of the radiator core, in contrast to crossflow radiators. In most cases, two tanks are located at the top and bottom of the radiator in this design, through which coolant enters, travels through the radiator core's tubes or fins, and exits. When the coolant draws heat from the engine and releases it into the surrounding air, the vertical flow path facilitates effective heat exchange. Downflow radiators are widely used in a variety of automobiles because they provide an easy-to-use and efficient way to control engine temperatures and avoid overheating. Their dependability and ease of design make them a popular option for automotive applications (Delgado et al., 2020).

2.1.3 Aluminum radiator

Aluminum radiators, widely used in automotive applications, are a contemporary and effective development in cooling system technology. Because of its superior heat conductivity and lightweight nature, aluminum is used either entirely or predominantly in the construction of these radiators. An aluminum radiator's core is composed of aluminum alloy tubes and fins that efficiently transfer heat. When compared to conventional radiators, the use of aluminum reduces overall weight while improving durability. In high-performance and race vehicles, where effective heat dissipation is essential, this design is especially beneficial. Radiators made of aluminum are more resistant to corrosion and can withstand a wide range of operating environments. Their extensive use is indicative of a dedication to maximizing engine cooling efficiency and attaining improved thermal efficiency in a range of automotive environments (Witry et al., 2005; Strebkov et al., 2019; Palmer and Hindin. 1998).

2.2 Air Cooled Heat Exchangers (ACHE)

Air Cooled Heat Exchangers (ACHE) play a crucial role in industrial environments by providing an effective means of heat dissipation without relying on water-based cooling systems. In these systems, ambient air is utilized to cool equipment or process fluids circulating through finned tubes. The configurations, featuring forced and induced drafts, enhance adaptability to spatial constraints, making ACHEs widely utilized in sectors such as HVAC, power generation, and petrochemicals. The importance of ACHEs lies in their environmental compatibility, flexibility, and ease of maintenance, especially in scenarios with limited water availability (Wei et al., 2024). Within the broader context of ACHE, specific components are examined: Axial flow fans, recognized for their efficiency and reduced noise levels, play a crucial role in industrial processes, cooling systems, and ventilation, finding applications in electronic cooling systems, heat exchangers, and air conditioning units. Variations like tube-axial and vane-axial fans cater to specific industry needs (Czwielong et al., 2022). Multi-Fan Air Coolers, also known as swamp coolers, serve as environmentally responsible and energy-efficient alternatives, effectively lowering air temperatures through evaporative cooling in both commercial and residential settings, particularly thriving in dry climates (Yan et al., 2024). Furthermore, Fin-Fan Air Coolers, employed in industrial processes such as petrochemical, power generation, and oil and gas sectors, dissipate heat into the surrounding air to cool fluids. Their finned-tube design enhances cooling efficiency, making them ideal for dry or isolated areas where water usage is impractical (Zhang et al., 2020). The widespread use of ACHEs is rooted in their ability to offer efficient and adaptable heat dissipation solutions in diverse industrial applications.

3 Nano-fluids

Operating conditions, intended heat transfer characteristics, and particular application requirements all play a role in the choice of nanofluids used in engine radiators. Engineered fluids called nanofluids are made with suspended nanoparticles that are selected to improve thermal conductivity and the efficiency of heat transfer. The ability of the nanoparticles in nanofluids to dramatically change important characteristics like thermal conductivity gives them an advantage in efficiently dissipating heat. When selecting nanofluids for engine radiators, considerations such as compatibility with radiator materials, temperature stability, and the possibility of better cooling performance are taken into account. To guarantee that nanofluids continue to improve heat transfer in the radiator system, routine maintenance and monitoring are necessary (Sidik et al., 2015). Some of the experiments and studies on using nanofluids in radiators are summarized in Table 1.

4 Discussions

It is vital to research the flow characteristics of the nanofluids in addition to their heat transfer performance in order to use them in practical applications. More pumping power is typically needed for nanofluids than for their base fluid. An increase in the density of the working fluid relative to pure water results from a rise in the volumetric concentration of nanoparticles (ϕ), thereby indicating a rise in energy consumption. Moreover, when operating conditions rise, there is a decrease in the mass flow of refrigerant needed for engine cooling, which lowers the need for pumps (Fig. 3). Because of their higher density, it has been found that the addition of aluminum nanoparticles causes a drop in coolant pressure.

Figs. 4 and 5 demonstrate how changing the fin geometries for varying hot water flow rates affects the rate of heat transfer. The area exposed to heat transfer determines the rate of convective and radiation heat transfer. Because it has a smaller surface area than the other four modification cases, it has been discovered that the base radiator case has the lowest rate of heat transfer. Radiation effects show that the straight fin arrangement has the maximum heat transfer rate (1672 W at 7 L/min) among all flow rate scenarios, whereas the spike rib design has the lowest heat transfer rate. Including convection, the straight fin configuration shows a 46% higher maximum heat transfer rate than the semicircular fin arrangement.

Fig. 6 shows the cooling process with the fans switched on for both the old and new radiator II. The new radiator II finished in the shortest amount of time – 0 km of coolant mileage while the previous radiator II took one minute to complete. When radiators are operating, limescale and corrosion build up, which decreases cooling effectiveness and flow. The old radiator still does its job of cooling properly, though. The longest cooling process was accomplished using coolant mileages of 100,000 and 50,000 kilometers.

Fig. 7 illustrates the viscosity at various temperatures using different TiO_2 volume concentrations (0.1, 0.2, and 0.3%) to investigate how temperature affects nanofluid viscosity. It is evident that the viscosity of the nanofluid decreases as the inlet temperature rises. Consequently, in comparison to the base fluid, we may conclude that there is a direct correlation between temperature and viscosity for each study carried out under all circumstances.

The experimental thermal conductivity of the nanofluid agrees well with published values (Ahmed et al., 2018; Maxwell, 1873; Yu and Choi, 2003). Fig. 8 makes it abundantly evident that for every unit increase in volume fraction, thermal conductivity rises in a nearly linear fashion. The relationship between volume concentration and thermal conductivity is also depicted in the same figure.

The application of a helical coil with an aluminum-silver nanocomposite is the main topic of the study (Fig. 9). The nanofluid concentrations in the nanocomposite vary from 0.1 to 0.4 vol%, with 97.5% aluminum and 2.5% silver making up its composition. The findings demonstrate that rising Reynolds numbers and nanoparticle concentrations are related to rising Nusselt numbers. Particle migration

Table 1 Summary of experimental studies on radiators using nanofluids

Maximum HTC enhancement	Flow Regime (Reynolds number)	Nanofluid temperature (°C)	Nanoparticle concentration	Nanofluid	Researcher(s)
3.8% for 2 vol% of nanofluid	Turbulent (4,000–6,000)	70–95	2 vol%	Cu/EG	Leong et al. (2010)
45% for 1 vol% of nanofluid	Turbulent (9,000–23,000)	37–49	0.1–1 vol%	Al_2O_3/water	Peyghambarzadeh et al. (2011)
9% for 0.65 vol% of both nanofluids	Laminar (50–1,000)	50, 65 and 80	0.15, 0.4, and 0.65 vol%	CuO/water and Fe_2O_3/water	Peyghambarzadeh et al. (2013)
11% and 22.5% for TiO_2/water and SiO_2/water, respectively	Laminar (250–2,000)	60–80	1–2 vol%	TiO_2/water and SiO_2/water	Hussein et al. (2014b)
25.6% for 2.0 wt% of TiO_2 based nanofluid	Laminar (272–781)	80–95	0.5, 1.0, and 2.0 wt%	Al_2O_3/EG-water (50:50) and TiO_2/EG-water (50:50)	Nieh et al. (2014)
17% decrement for 0.16 wt% of nanofluid	Turbulent (22,000–50,000)	50, 60, 70 and 80	0.05, 0.08 and 0.16 wt%	MWCNT/water	Oliveira et al. (2017)
46.4% for 0.4 vol% of nanofluid	Turbulent (11,000–30,000)	50–80	0.15, 0.25 and 0.4 vol%	ZnO/(PG: water::60:40)	Tejes and Appalanaidu (2017)
196.3% for 0.5 vol% of nanofluid	Laminar; flow rate 2, 4 and 6 L/	80–120	0.1, 0.25, 0.5 vol %	MWCNT/(EG*: water::50:50)	M'hamed et al. (2016)

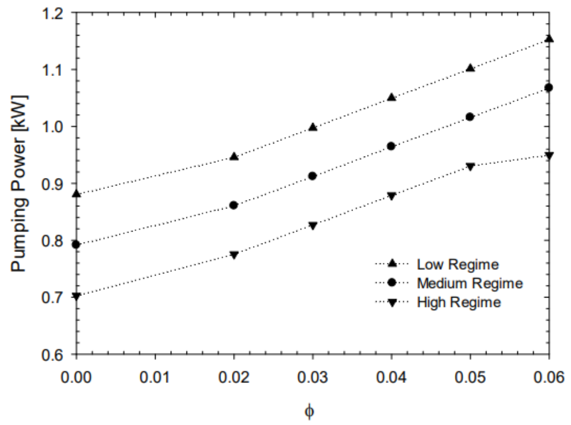

Fig. 3 Car radiator pumping power as a function of nanoparticle concentration (Buonomo et al., 2019)

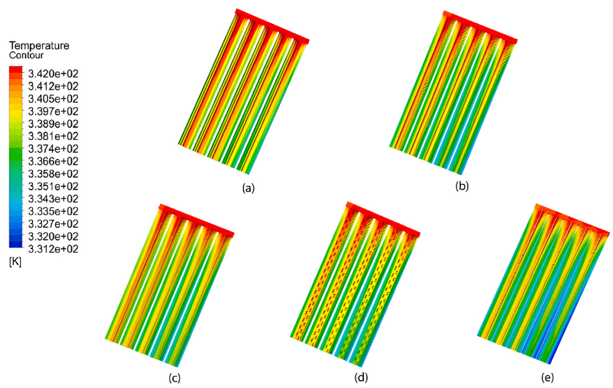

Fig. 5 Temperature contour of the fins of (a) semi-circle, (b) wavy, (c) spike-rib, (d) cut-section, (e) straight fin arrangements (Majmader and Hasan, 2023)

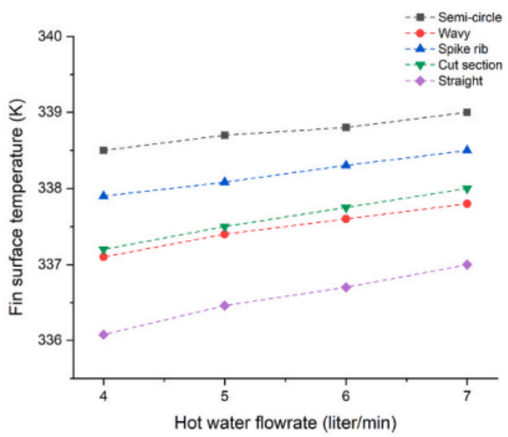

Fig. 4 Plot of fin surface temperature for various fin geometries in relation to water flow rate (Majmader and Hasan, 2023)

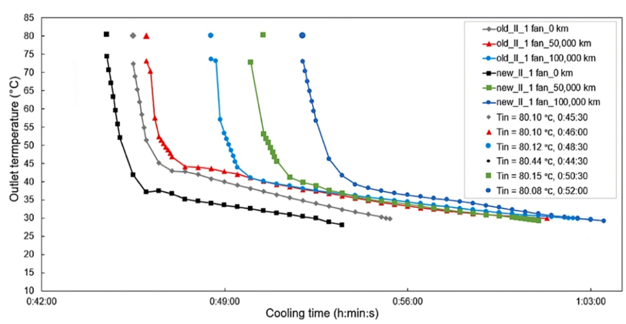

Fig. 6 The radiator's cooling time with a single fan, both new and old (Lipnický et al., 2023)

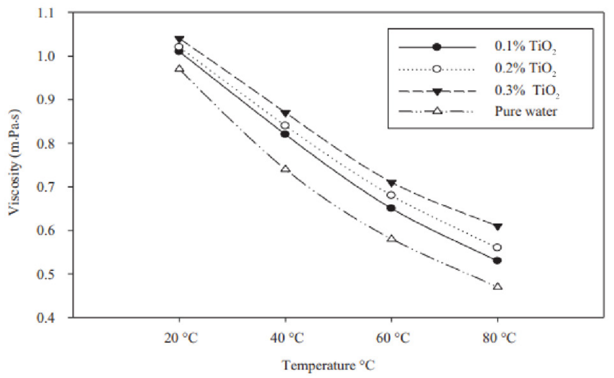

Fig. 7 TiO_2-water nanofluid viscosity at various temperatures (Ahmed et al., 2018)

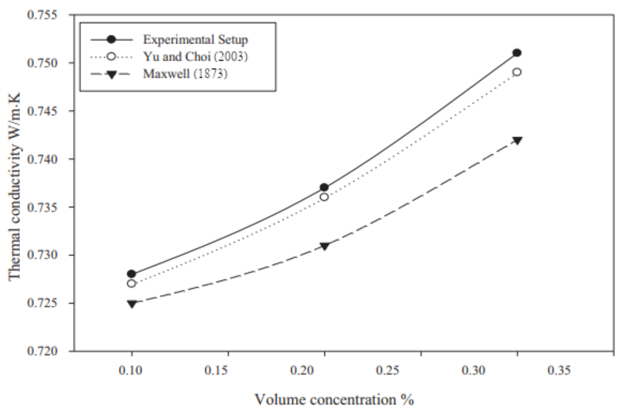

Fig. 8 The thermal conductivity of TiO_2 nanofluid at various volume fractions (Ahmed et al., 2018)

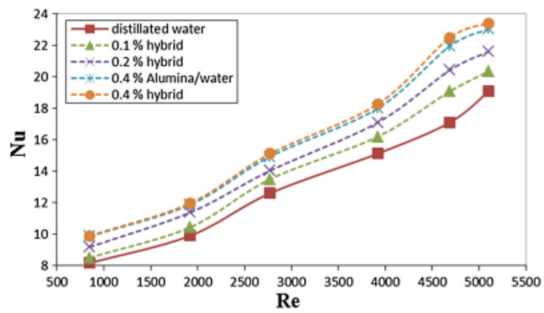

Fig. 9 Reynolds number with Nusselt number at various nano concentrations (Allahyar et al., 2016)

and Brownian movement cause nanoparticles to disperse and move proportionately near the pipe wall, which accelerates heat transmission. The boundary layer's thickness decreases as a result of the helical coil's secondary flow and centrifugal force. The helical coil's hybrid nanofluid accelerates heat transfer because of particle migration, Brownian movement, and a decrease in boundary layer thickness.

Heat transfer is enhanced in proportion to the concentration of nanoparticles. Nevertheless, as the Reynolds number rises, the enhancement of heat transfer decreases. For example, for Re = 5,000, the heat transfer enhancement increases by 32.7% when the concentration of Al_2O_3 increases up to 10%, while for Re = 20,000, the growth decreases slightly to 31.3%. The corresponding heat transfer enhancement increases by 32.4% and 31.0%, respectively, with increasing TiO_2 concentration. This may be due to the fact that, as shown in Fig. 10, when the concentration of nanoparticles increases, the Nusselt number increases more for lower Reynolds numbers than for higher Reynolds numbers.

4 Summary

The paper comprehensively examines heat exchange technologies, focusing on radiators, air-cooled heat exchangers (ACHE), and the application of nanofluids. Radiators, crucial in internal combustion engine cooling systems, are explored in various designs, including crossflow and downflow radiators, as well as contemporary aluminum

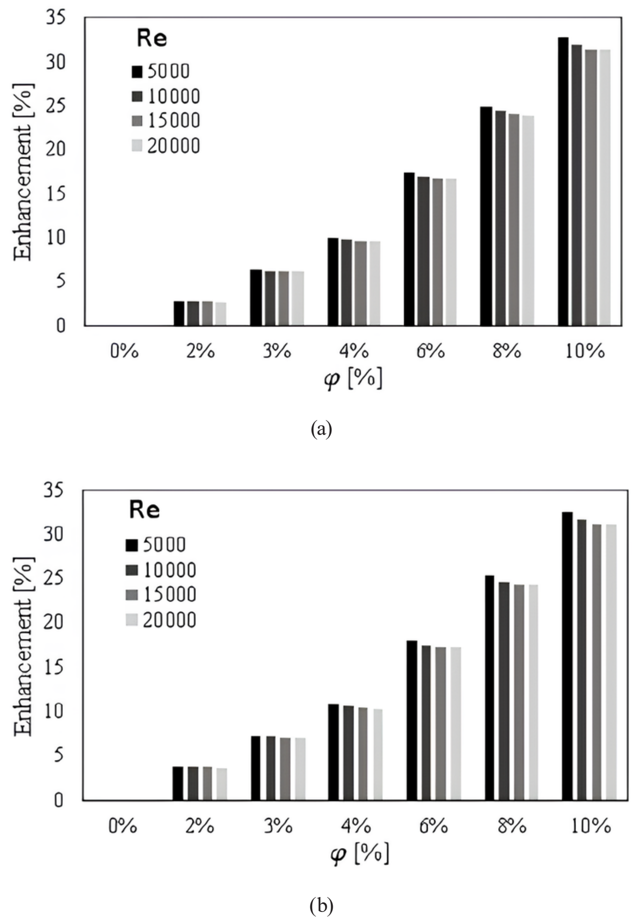

Fig. 10 Heat transfer enhancement of (a) Al_2O_3 nanoparticles, and (b) TiO_2 nanoparticles at varying volume concentrations (Neves et al., 2022)

radiators known for their light weight and superior heat conductivity. The study extends to the industrial realm with a detailed look at Air Cooled Heat Exchangers (ACHE), utilizing axial flow fans, multi-fan air coolers, and fin-fan air coolers, each catering to specific needs and providing alternatives to water-based cooling systems. Additionally, the paper introduces the innovative use of nanofluids, engineered fluids with suspended nanoparticles, demonstrating their potential to enhance heat transfer efficiency and thermal conductivity in engine radiators. The selection of nanofluids considers factors such as compatibility, temperature stability, and the promise of improved cooling performance. Emphasis is placed on the importance of regular maintenance and monitoring to ensure the sustained enhancement of heat transfer efficiency in radiator systems. This comprehensive exploration spans traditional and contemporary technologies, offering insights into diverse applications across automotive, industrial, and nanofluid domains.

The research emphasizes the importance of understanding the flow characteristics of nanofluids and their impact on heat transfer performance for practical applications. Notably, the study reveals that nanofluids generally require more pumping power compared to their base fluids, and an increase in nanoparticle concentration results in higher energy consumption. The addition of aluminum nanoparticles has been found to reduce coolant pressure due to increased fluid density. The investigation further explores the influence of fin geometries on heat transfer rates, indicating that the straight fin configuration produces the greatest heat transfer rate in radiation effects. The study also examines the cooling efficiency of new and old radiators, revealing that limescale and corrosion affect cooling effectiveness over time. Additionally, the viscosity of nanofluids decreases with rising inlet temperatures, determining a direct correlation between temperature and viscosity.

Based on previous results, nanofluids show improved radiator performance by enhancing thermal conductivity and heat transfer, especially at lower Reynolds numbers and higher nanoparticle concentrations. Their effectiveness also depends on factors like fin geometry, flow rate, and operating temperature, emphasizing the importance of thoughtful system design in real world applications.

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