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Experimental Study and CFD Analysis of Thermal Performance Improvement of Car Radiator by Mgo/Water Nanofluid

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Abstract:

This study aims to enhance the thermal efficiency of a cross-flow car radiator by utilizing an innovative coolant—MgO/water nanofluid. Conventional engine cooling systems primarily rely on water or ethylene glycol-based fluids; however, nanofluids have emerged as a promising alternative due to their superior heat transfer properties. This research experimentally investigates the thermophysical characteristics of MgO/water nanofluid, including density, thermal conductivity, dynamic viscosity, and specific heat capacity. The study was conducted under controlled conditions, maintaining a flow rate between 5 and 9 LPM. The results demonstrated a significant improvement in heat transfer performance, with an enhancement ranging from 40% to 70% depending on the nanofluid concentration. To further validate these findings, computational fluid dynamics (CFD) simulations were employed to analyse temperature distribution across the radiator. The experimental and numerical results confirm the potential of MgO/water nanofluid as an efficient coolant for automotive thermal management systems.

Keywords: Radiator, nanofluid, MgO particles, thermal conductivity, heat transfer rate

1. INTRODUCTION

In this research, our primary objective is to improve the thermal efficiency of automobile cooling systems, ensuring faster and more effective heat dissipation into the surroundings. In recent decades, nanofluids have emerged as highly efficient heat transfer agents due to their superior thermal conductivity and enhanced cooling properties. Unlike conventional fluids such as water or ethylene glycol, nanofluids exhibit improved heat transfer characteristics, making them ideal for various heat exchanger applications. A car radiator, which functions as a cross-flow heat exchanger, is a crucial component of an automobile's engine cooling system. Its primary role is to regulate engine temperature by dissipating excess heat. In this study, we utilize magnesium oxide (MgO) nanoparticles, with an average size of 40 nm, dispersed in water to form a nanofluid coolant. This MgO/water nanofluid is tested as a replacement for traditional coolants to evaluate its thermal performance. Experimental analysis is conducted, followed by computational modeling and validation using CFD simulations in STAR-CCM+ to assess the outlet temperature and heat dissipation efficiency.

Overview of the Engine Cooling System

A standard four-cylinder vehicle traveling at approximately 50 miles per hour generates around 4,000 controlled explosions per minute within the engine as the spark plugs ignite the fuel in each cylinder. These continuous explosions generate substantial heat, which, if not properly managed, can severely damage the engine within minutes. The cooling system plays a critical role in maintaining optimal engine temperature, preventing overheating while also ensuring that the engine does not run too cold, which could negatively impact fuel efficiency and increase emissions. Automobiles primarily utilize two types of cooling systems: **liquid-cooled** and **air-cooled**. Air-cooled engines were historically used in vehicles like the Volkswagen Beetle and Chevrolet Corvair, and they are still found in some motorcycles. However, the majority of modern vehicles rely on liquid-cooled systems, which this study focuses on.

The cooling system comprises several key components, including coolant passages within the engine block and cylinder heads, a water pump to circulate the coolant, a thermostat to regulate coolant temperature, a radiator for heat dissipation, a radiator cap to maintain system pressure, and hoses to transport coolant between the engine, radiator, and heater core. The coolant absorbs heat from the engine as it flows through internal passages, then travels via hoses to the radiator. Here, it moves through thin tubes, where incoming air from the vehicle's front grille facilitates heat exchange, cooling the fluid before it recirculates back to the engine. The water pump ensures continuous coolant circulation, maintaining the system's efficiency and preventing thermal damage.

By integrating MgO/water nanofluid into this system, our research explores its potential to enhance heat dissipation rates, reduce thermal resistance, and improve overall cooling efficiency in automobile engines. The results of this study could contribute to the development of more advanced and efficient cooling technologies in modern vehicles.

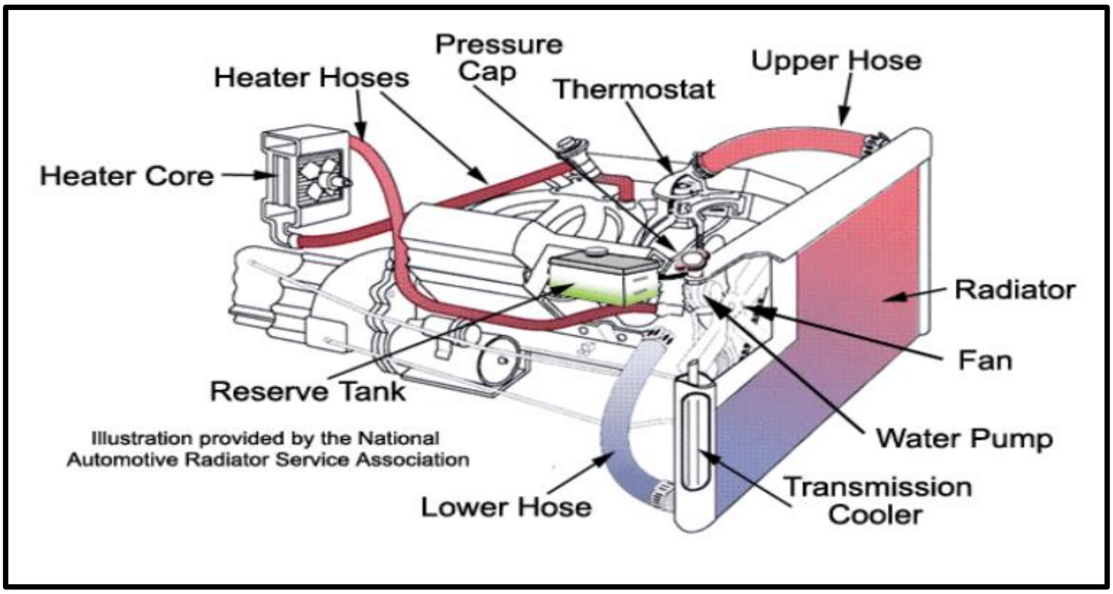

Fig 1.1: Engine cooling system component

Thermostat and Radiator: Key Components of the Cooling System

The thermostat plays a crucial role in maintaining the engine's optimal operating temperature by regulating coolant flow between the engine and the radiator. It ensures that the coolant remains above a predetermined temperature by restricting its flow to the radiator when the temperature is too low. Instead, the coolant is redirected through a bypass, allowing it to recirculate within the engine until it reaches the desired temperature. Once this threshold is met, the thermostat opens a valve, allowing the coolant to flow through the radiator for cooling.

To prevent the coolant from boiling, the entire cooling system is designed to operate under pressure, significantly increasing the boiling point of the fluid. However, excessive pressure can lead to system damage, including hose ruptures and leaks. To prevent this, a radiator cap is employed to regulate pressure levels. This cap is designed to release excess pressure once it reaches a predefined limit. Before the 1970s, excess coolant was simply expelled onto the road. Modern vehicles, however, feature a closed-loop system where the excess fluid is temporarily stored in a reserve tank and later returned to the cooling system after the engine cools down.

Coolant Circulation Process

The cooling system follows a specific pathway to regulate engine temperature efficiently. The water pump initiates the coolant flow through internal channels within the engine block, where it absorbs heat generated by the combustion process. From there, the coolant moves to the cylinder head, collecting additional heat from the combustion chambers. If the thermostat is open, the heated coolant flows through the upper radiator hose and into the radiator, where it is cooled as it passes through a network of thin tubes exposed to airflow. The cooled fluid then travels through the lower radiator hose and back to the water pump, completing the cycle.

Cooling system capacity is carefully designed based on the engine type, size, and expected workload. Larger and more powerful engines, such as V8 engines in heavy-duty vehicles, require a more robust cooling system with a larger radiator and additional coolant pathways. In contrast, compact cars with smaller four-cylinder engines require less cooling capacity. To enhance cooling efficiency, larger vehicles feature wider and taller radiators with an increased number of tubes, maximizing airflow from the front grille.

Radiator Design and Function

The radiator, a key component of the cooling system, is responsible for dissipating heat from the coolant before it recirculates through the engine. Most modern radiators feature a core made of flattened aluminum tubes, with aluminum fins arranged in a zigzag pattern between them. These fins enhance heat transfer by increasing the surface area exposed to airflow, allowing efficient heat dissipation.

The radiator core is enclosed by tanks that help direct coolant flow. In contemporary radiators, these tanks are typically made of durable plastic, while older models used brass tanks with copper cores. Modern aluminum-plastic radiators offer improved efficiency and cost-effectiveness compared to their traditional counterparts. In designs where plastic end tanks are used, gaskets are installed between the aluminum core and the plastic components to prevent coolant leakage, ensuring a sealed and efficient cooling system.

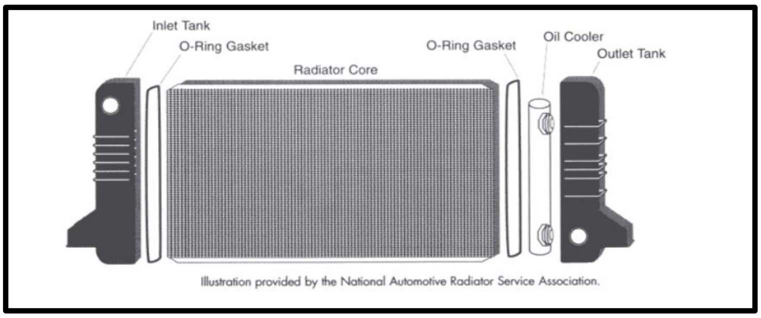

Illustration provided by the National Automotive Radiator Service Association.

Fig 1.2: The Radiator

Radiator Tanks and Cooling System Components

The radiator tanks, whether constructed from plastic or brass, play a crucial role in directing coolant flow through the system. Each tank features a large hose connection—one positioned near the top of the radiator to allow heated coolant to enter and another at the bottom to return the cooled fluid back to the engine. Additionally, the top of the radiator includes an opening sealed by the radiator cap, which helps regulate system pressure and prevent overheating.

For vehicles equipped with an automatic transmission, an additional internal cooling mechanism is incorporated within one of the radiator tanks. This consists of a secondary chamber, commonly referred to as a transmission cooler, which is connected to the transmission system via steel tubes. Transmission fluid flows through this internal chamber, where it is cooled by the surrounding engine coolant before circulating back to the transmission. This design helps maintain optimal transmission temperature, preventing overheating and ensuring efficient performance.

Radiator Fans: Function and Importance

To facilitate proper cooling, most vehicles feature one or more electric fans mounted behind the radiator, positioned close to the engine. These fans are enclosed within protective housing, which not only prevents accidental contact but also enhances airflow efficiency. Their primary function is to maintain airflow through the radiator when the vehicle is stationary or moving at low speeds. Without these fans, the engine temperature could rise rapidly during idle conditions or stop-and-go traffic.

Older cooling systems relied on a mechanically driven fan attached to the front of the water pump, which operated continuously as long as the engine was running. Since this type of fan was belt-driven, its speed increased with engine RPM. In cases where the engine temperature rose in heavy traffic, drivers of older vehicles sometimes revved the engine in neutral to accelerate the fan, enhancing cooling. However, in modern vehicles equipped with electric fans, revving the engine would not have the same effect and could even generate additional heat without adequate cooling.

Electric radiator fans are controlled by the vehicle’s onboard computer system. A temperature sensor continuously monitors engine heat levels and relays this data to the computer. When the temperature exceeds a set threshold, the computer activates a relay to switch on the fan, increasing airflow through the radiator to prevent overheating. This automated system ensures efficient cooling, optimizing both engine performance and fuel efficiency.

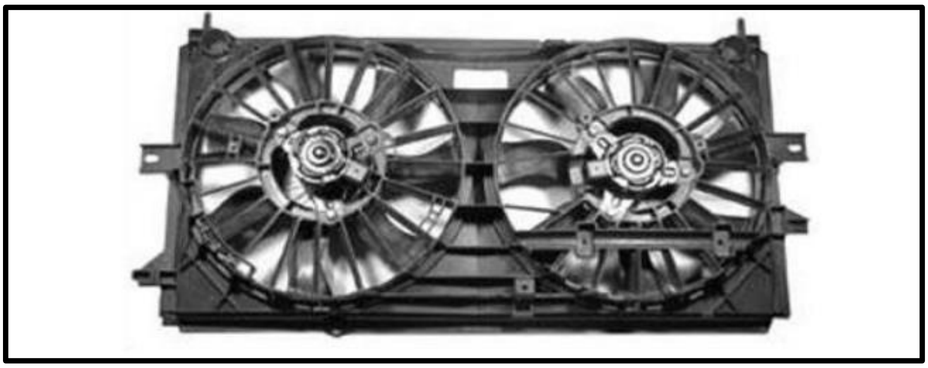

Fig 1.3: Radiator Fans

Air Conditioning Condenser and Its Role in Cooling

Vehicles equipped with air conditioning have an additional cooling component known as the **air conditioning condenser**, which is mounted in front of the main radiator. This component functions as a heat exchanger, dissipating heat from the refrigerant before it cycles back into the air conditioning system. Since the condenser also relies on airflow for cooling, it must receive sufficient ventilation to operate efficiently.

When the air conditioning system is activated, the vehicle's cooling fan remains operational regardless of engine temperature. This continuous airflow is essential because, without it, the condenser would not be able to cool the refrigerant effectively. As a result, the air conditioning system would struggle to provide cold air to the vehicle's interior.

Pressure Cap and Reserve Tank: Managing Coolant Expansion

As the engine runs, coolant absorbs heat and expands. Since the cooling system is sealed, this expansion naturally increases the internal pressure. This is an intentional design feature, as raising the pressure within the system also increases the boiling point of the coolant, allowing it to function at higher temperatures without vaporizing.

The use of ethylene glycol-based coolant further enhances this effect, enabling the cooling fluid to safely withstand temperatures exceeding **250°F (121°C)**. The pressure cap plays a crucial role in regulating this pressure. It is designed to release excess coolant into the **reserve tank** when pressure surpasses a certain limit, preventing potential damage to hoses and other components. Once the engine cools down, the coolant in the reserve tank is drawn back into the system, ensuring a consistent coolant level and maintaining optimal engine performance.

Fig 1.4: Pressure Cap

Radiator Pressure Cap: Function and Importance

The **radiator pressure cap** is a crucial component that helps regulate pressure within the cooling system. Designed as a safety mechanism, it maintains the system's pressure up to a specific limit. If the internal pressure exceeds this threshold, the cap features a **spring-loaded valve** that is precisely calibrated to release excess pressure at a predetermined **Pounds per Square Inch (PSI)** level. Under extreme conditions, such as stop-and-go traffic on particularly hot days or when the cooling system is malfunctioning, pressure may build up beyond the cap's set limit. When this happens, a small amount of coolant is expelled to prevent potential damage to the system. Instead of being lost, this excess coolant is collected in a separate **expansion tank**, which is typically unpressurized.

Coolant Recovery and Reserve Tank System

In a **closed cooling system**, the radiator cap also includes a **secondary valve** that allows coolant to be drawn back into the radiator once the engine cools down. As the temperature decreases, the coolant contracts, creating a partial vacuum. This vacuum effect pulls the coolant from the reserve tank back into the radiator, ensuring that the system maintains the correct coolant level without air pockets forming. This process works similarly to pulling back the plunger of a syringe, allowing fluid to return smoothly. The **reserve tank** is typically a translucent plastic container with clearly marked indicators for coolant levels: **Full-Hot** and **Full-Cold**. When the engine reaches its normal operating temperature, the coolant level should align with the **Full-Hot** mark. After the vehicle has been turned off and the engine has cooled completely, the fluid should settle at the **Full-Cold** mark. Monitoring these levels regularly helps ensure the cooling system functions efficiently and prevents overheating or coolant loss.

Fig 1.5: Coolant Tank

Water Pump: Circulating Coolant for Efficient Engine Cooling

The **water pump** is a vital component in the cooling system, ensuring continuous coolant circulation while the engine is running. It is typically positioned at the front of the engine and operates in sync with engine movement. The pump is driven by one of the following mechanisms:

- A **fan belt**, which may also power other components such as the alternator or power steering pump.
- A **serpentine belt**, which is responsible for driving multiple accessories, including the alternator, power steering pump, and air conditioning compressor.

- A **timing belt**, which not only drives the water pump but also controls the movement of one or more camshafts. The **construction of a water pump** includes a **housing**, generally made of **cast iron or aluminum**, which encloses an **impeller**. The impeller is mounted on a **spinning shaft**, with a pulley connected externally to allow rotation. A **seal** prevents coolant leakage from the pump housing, ensuring efficient operation.

As the impeller spins, it utilizes **centrifugal force** to draw coolant in from the **lower radiator hose** and propel it under pressure into the **engine block**. This process ensures that coolant is efficiently circulated, maintaining the engine at an optimal temperature. A **gasket** is placed between the water pump and engine block to prevent leaks where the pump is mounted.

Thermostat Valve: Regulating Coolant Flow and Temperature

The **thermostat** is a **temperature-sensitive valve** responsible for regulating coolant flow based on the engine's temperature. If the coolant is sufficiently heated, the valve opens to allow coolant to pass through the **radiator** for cooling. However, if the coolant is still cold, the thermostat remains closed, directing the coolant back through a **bypass system** that returns it to the engine. This bypass ensures continuous circulation, preventing localized overheating while allowing the engine to reach optimal temperature more quickly.

By preventing premature cooling, the thermostat helps the engine **warm up faster**, which is especially beneficial in cold weather, as it enables the vehicle’s **heater** to produce warm air more quickly. Since the **1970s**, thermostats have been designed to maintain **coolant temperatures between 192°F and 195°F**, whereas earlier models typically operated around **180°F**. Research has shown that higher engine temperatures improve **fuel combustion efficiency**, reduce **emissions**, and minimize **moisture buildup** inside the engine, contributing to improved longevity and performance.

At the core of the thermostat is a **sealed copper chamber** containing **wax and a metal pellet**. When the coolant reaches the designated temperature, the wax expands, forcing a **piston** to move against a **spring**, which in turn opens the valve and allows coolant circulation.

The thermostat is generally housed within a **water outlet** at the **top front of the engine**, which also serves as the attachment point for the **upper radiator hose**. It is typically secured to the engine using **two bolts** and a **gasket**, which may be made of **heavy-duty paper, rubber O-ring, or a specialized silicone sealant** to ensure a leak-proof connection.

Fig 1.6: Thermostat Valve

There is a mistaken belief by some people that if they remove the thermostat, they will be able to solve hard to find overheating problems. This couldn't be further from the truth. Removing the thermostat will allow uncontrolled circulation of the coolant throughout the system. It is possible for the coolant to move so fast, that it will not be properly cooled as it races through the radiator, so the engine can run even hotter than before under certain conditions. Other times, the engine will never reach its operating temperature.

2. LITERATURE REVIEWS

Xie et al[1] reported heat transfer enhancement using nanofluids of Al2O3, ZnO, TiO2 and MgO with a mixture of water and ethylene glycol of 55% and 45% respectively. Al2O3, MgO and ZnO nanofluids showed superior increment in heat transfer compared to TiO2 nanofluids.

Peyghambarzadeh et al.[2] tested a car radiator using Al2O3/water based nanofluids. The volumetric concentrations were varied in a range of 0.1-1%. A maximum heat transfer enhancement up to 45% at 1% volumetric concentration was recorded.

Naraki, et al.[3] reported experimental results for CuO/water nanofluids tested under laminar flow regime in a car radiator. Volumetric concentration was varied from 0 to 0.4% and inlet temperature was changed from 50 to 80 C. An 8% increase in overall heat transfer coefficient compared with water was reported for 0.4% vol. nanofluids.

Hussein et al.[4] tested TiO2 and SiO2 water based nanofluids in a car radiator under laminar flow regime. Volumetric concentration and fluid inlet temperature was changed in a range of 1-2% and 60-80 C.

Lee et al.[5] experimentally studied the mixture of ethylene glycol and CuO nanoparticles of 35 nm size at the concentration of 4.0 vol.% and found a 20% increase in thermal conductivity.

Yu et al.[6] experimentally investigated that, the thermal conductivity of nanofluid strongly depends on nanoparticle volume concentrations and it increases nonlinearly with the increase of volume concentration and the enhanced thermal conductivity was found to be 26.5% at 5.0vol.% concentration.

Nguyen et al [7] experimentally investigated the effect of volume concentrationand temperature on the dynamic viscosity of Al2O3–water nanofluid and found that viscosity of the nanofluid considerably increases with the increase of particle volume concentrations, but it decreases with the increase of temperature.

Wang et al.[8] investigated the viscosity of Al2O3–water nanofluid prepared by mechanical blending with particle size of 28nm at 5 vol.% concentration and viscosity increased by 86% compared to the base fluid. They also investigated Al2O3/ethylene glycol nanofluid and found a 40% increase in viscosity.

Das et al.[9] also observed that with the increase of particle volume concentration, viscosity of the nanofluid increases.

Elias et al.[10] reported findings about thermal conductivity, viscosity,specific heat and density of Al2O3 nanofluids in water and ethylene glycol used as coolant in car radiator. Volume concentration and coolant temperature were kept up to 1% and 50C respectively. Viscosity, thermal conductivity and density of the nanofluids were found to increase whereas specific heat of nanofluid was found to decrease with increasing volumetric concentrations.

Masuda et al.[11] studied the thermophysical properties of Al2O3–water, SiO2– water and TiO2–water nanofluids. The transient hot-wire method was used to measure the thermal conductivity of nanofluids. They establish that the thermal conductivity of nanofluids increasing by 32 % at the concentration of 4.3 vol. %. They concluded that temperature did not have any effect on the increase of relative thermal conductivity.

Lee et al.[12] conducted an experiment to measure the thermal conductivity of Al2O3 and CuO suspended in water and ethylene glycol. Particle sizes of Al2O3 and CuO were 23.6 nm and 38.4 nm, respectively. Their results indicated that nanofluids had higher thermal conductivity than the base fluid, and it increased with the increasing level of concentration.

Wang et al.[13] studied thermal conductivity of Al2O3 and CuO nanofluids with a particle size of 20 nm. Each was suspended in water, vacuum pump oil, engine oil, and ethylene glycol. The steady state method was used to measure thermal conductivity. Their results showed that the thermal conductivity of both nanofluids were higher than that of the base fluids and varying with concentration level.

Sundar and Sharma [14] obtained thermal conductivity enhancement of 6.52% with Al2O3 nanofluid, 24.6% with CuO nanofluid at 0.8% volume concentration compared to water.

Vahid Delavari et al [15] CFD simulation of heat transfer enhancement of Al2O3/water and Al2O3/ethylene glycol nanofluids in a car radiator.

Thirumala Reddy[16] Performance Improvement of an Automobile Radiator using CFD Analysis.

3. EXPERIMENTAL SET UP AND PROCEDURE

The experimental set up consists of following specifications: Reservoir tank (40-50 Lit), electrical heater (2000 W), pump (0.5 hp), flow meter (0- 25lpm),tubes, valves, forced fan (1500 rpm), digital thermocouples type K type for temperature measurement, heat exchanger (Car radiator) made of aluminium alloy having 22 tubes equally spaced along entire rectangular area, MgO/water nanofluid prepared with mechanical stirrer by heating and sedimentation for 48 hours**.**

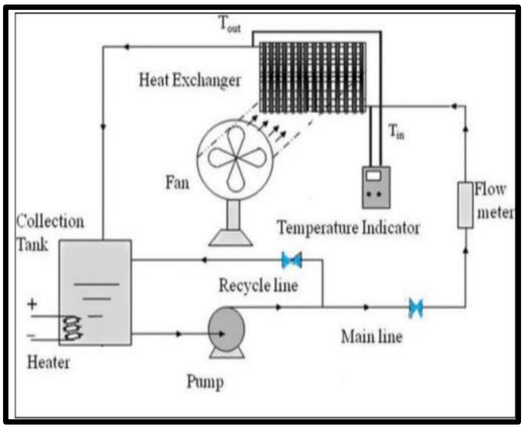

Fig -2.1: Schematic of Experimental Set up.

Fig -2.2: Actual Picture of Experimental Set up

Experimental Setup Details

The collection tank (reservoir), with a capacity of 40-50 liters, serves as a storage unit for the coolant fluid. This coolant is heated using a 2 kW electric heater until it reaches the desired operating temperature. Once heated, the coolant is pumped through the system by a 0.5 hp pump, which provides a head pressure of 10-12 meters, ensuring smooth circulation.

To regulate the fluid movement, a flow control valve is installed, allowing precise adjustments. A flow meter (0-25 lpm) is used to maintain a constant flow rate within the 5-9 lpm range. The inlet and outlet temperatures of the coolant are continuously monitored to assess the system’s thermal efficiency.

A forced convection fan (1500 rpm), also referred to as an exhaust air fan, is positioned to cool the heated coolant as it passes through the radiator tubes. This forced airflow accelerates the cooling process, allowing the coolant to return to the reservoir at a reduced temperature, thus completing the cycle.

The experiment is conducted using water as the initial coolant. Subsequently, different nanofluid concentrations are introduced, with volume fractions of 0.25, 0.50, 0.75, and 0.90, to analyze their impact on the radiator’s cooling performance. Observations from these tests are systematically recorded for further calculations and thermal performance analysis.

Properties of MgO Nanoparticles and Nanofluid Preparation

The preparation of MgO/water nanofluid begins with obtaining high-purity (99%) MgO nanoparticles with a particle size of 40 nm. These nanoparticles are white in color and have a density of 3.58 g/cm³.

To ensure proper dispersion of MgO particles in water, the pH level of the water is slightly adjusted, enabling complete dissolution of nanoparticles and preventing agglomeration. The nanofluid is prepared at a 2% mass concentration (m/v), meaning 2 grams of MgO is dissolved in 100 ml of water.

The preparation process involves heating and continuous stirring to achieve a uniform mixture. After stirring, the solution is left for sedimentation over 48 hours to enhance stability. Different volume fractions of the prepared MgO nanofluid are then used as coolant, and their thermal and physical properties are analyzed to assess performance improvements in the automobile radiator cooling system.

Fig -2.4: Preparation of MgO/water nanofluid.

Modelling of Radiator:

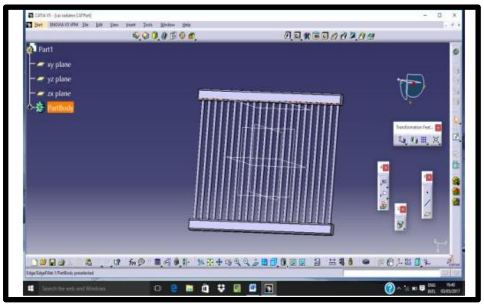

Fig.2.5 Modelling of radiator on CATIA V5

CFD Simulations:

Fig.2.6 Polygon meshed model of radiator

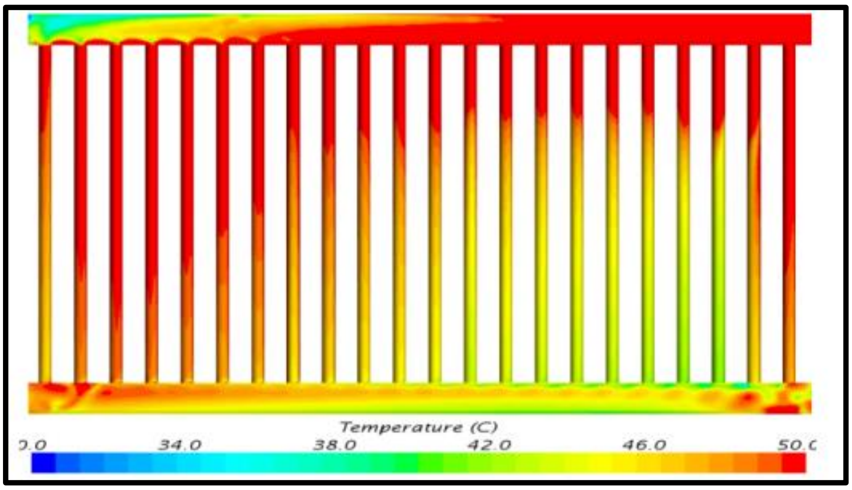

Fig.2.7 Water at 5 lpm