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MACHINE LEARNING–BASED PREDICTION AND OPTIMIZATION OF RADIATOR COOLING EFFICIENCY USING AL_2O_3–WATER NANOFLUID

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Abstract
This study investigates and predicts the enhancement of thermal performance in an automotive radiator using aluminum oxide (Al_2O_3)–water nanofluid compared to conventional water coolant. Experiments were conducted with nanoparticle concentrations ranging from 0.001 to 0.01 vol% and coolant flow rates between 7 and 10 L/min using a closed-loop test rig at a constant inlet temperature of 50 °C. Key thermal–hydraulic parameters—including heat transfer rate, convective heat transfer coefficient, Reynolds number, and pressure drop—were experimentally measured and then used to train machine-learning models for predictive analysis. The nanofluid was prepared using a two-step mechanical stirring method to ensure uniform dispersion and stability. Among the models tested, the Random Forest Regressor achieved the highest accuracy (R^2 = 0.97) in predicting the convective heat transfer coefficient and pressure drop. Model-based optimization identified 0.007 vol% concentration and a flow rate of 10 L/min as the optimal conditions, yielding a heat transfer coefficient of 1437 $W/m^2 \cdot K$—over 25 % higher than that of water. The hybrid experimental–machine-learning approach not only validated the superior thermal performance of Al_2O_3 nanofluids but also demonstrated the potential of data-driven optimization for designing efficient, next-generation automotive cooling systems.

1 INTRODUCTION

Efficient heat management is critical to the performance and durability of internal combustion engines. The radiator plays a central role in this system, acting as a compact heat exchanger that transfers excess heat from the engine coolant to the surrounding air. Maintaining an optimal operating temperature not only prevents overheating but also enhances fuel efficiency and engine life. Automotive cooling systems rely on the coordinated function of the pump, radiator, and fan, where heat transfer occurs mainly through convection and conduction. Traditional coolants, such as water or water–ethylene glycol mixtures, have limitations in thermal conductivity, which restricts radiator performance. This has led researchers to explore nanofluids—base fluids containing nanoscale particles with high thermal conductivity—as a way to improve heat transfer. Nanofluids can significantly increase the heat transfer rate, thus enhancing the overall performance of heat exchangers in various applications, including

automotive systems [1]. Among various nanoparticle materials, aluminum oxide (Al_2O_3) has gained attention due to its chemical stability, availability, and superior thermal conductivity. Studies have shown that nanofluids containing Al_2O_3, CuO, or TiO_2 can enhance convective heat transfer coefficients and Nusselt numbers, leading to better radiator efficiency [3-5].

For instance, recent research by Kurhade et al. [1] demonstrated that Al_2O_3 nanofluids could increase radiator performance by more than 25%, reduce component size, and improve energy efficiency. Additionally, studies by Salim et al. [2] and Shah et al. [3] have further confirmed that incorporating Al_2O_3-based nanofluids in heat exchangers enhances thermal performance, resulting in a more efficient heat dissipation process. Similar experiments by Jasim and Ahmed [4], as well as Shirazi [5], highlighted the substantial heat transfer improvements achieved by nanofluids with varying concentrations of nanoparticles. Furthermore, the fluid flow dynamics play a critical role in the heat transfer process. Zheng et al. [6] examined the effect of Al_2O_3 nanofluids on turbulent flow in a double-pipe heat exchanger and observed significant enhancements in thermal performance. This aligns with the findings of Mohankumar et al. [7], who investigated the heat transfer characteristics of heat exchangers using various nanofluids. They concluded that nanoparticle-based fluids could be used to improve the heat exchanger's efficiency in automotive cooling systems. However, achieving optimal heat transfer involves balancing nanoparticle concentration, coolant flow rate, and pressure drop. Hussien et al. [9] and Jasim et al. [10] explored how these variables affect the performance of double-pipe heat exchangers, showing that a careful selection of operating parameters is crucial for maximizing efficiency without increasing system resistance. The effects of particle size and volume fraction, as well as flow conditions, have been studied by Chavda et al. [8], who showed that increasing nanoparticle volume fraction tends to improve heat transfer but may also result in higher pumping power requirements. This study aims to experimentally evaluate how varying concentrations of Al_2O_3 nanoparticles in water influence the thermal and hydraulic performance of an automotive radiator. Recent work by Kabeel et al. [11] and Zeinali Heris et al. [12] supports the use of nanofluids in automotive applications by demonstrating their superior thermal conductivity properties in heat exchangers. Additionally, the integration of machine learning methods in optimizing these systems, as suggested by Algehyne et al. [17], offers promising pathways for improving system performance.

2 Materials and methodology

2.1 Materials

Nanoparticles

Aluminum oxide (Al2O3) nanoparticles were used due to their favorable thermo physical properties, including:

- **Thermal conductivity:** ~30 W/m·K (bulk material), which is significantly higher than water.
- **Size range:** 20–50 nm, ensuring a large surface-to-volume ratio.
- **Appearance:** white, odorless powder with high dispersion stability in water.

Figure 2.1: promising pathways for improving system performance

- **Applications:** widely used in coatings, electronics, and as fillers, demonstrating proven chemicalstability and safety.

These properties make Al2O3 nanoparticles suitable candidates for improving the heat transfer performance of automotive coolants.

Base Fluid

Deionized water was selected as the base fluid because of its high specific heat capacity and widespread use in radiator cooling systems. The nanofluid was prepared by dispersing Al2O3 nanoparticles into water at different volume concentrations (0.001–0.01%).

2.2 Experimental setup

The experimental procedure was conducted in a closed-loop cooling system designed to evaluate the thermal performance of a car radiator using both baseline water and Al2O3 water nanofluids.

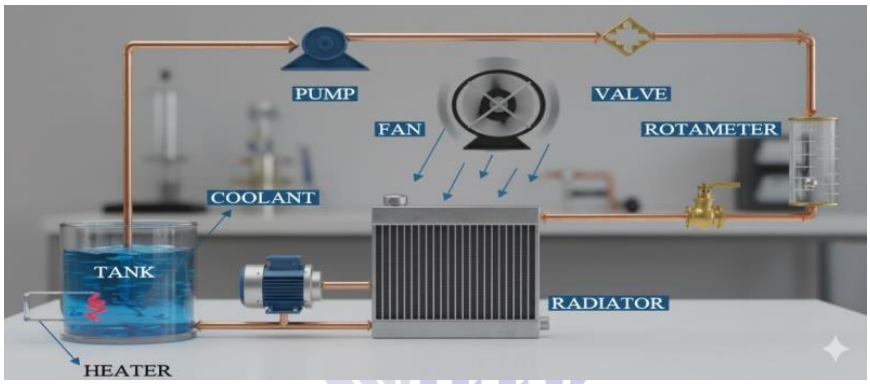

Figure 2.2: Experimental Setup

The sequence of steps is outlined in Figure 2.2 and summarized below:

- **Nanofluid preparation:** Al2O3 nanoparticles were dispersed into deionized water at prescribed volume concentrations (0.001–0.01%) using the two-step method.
- **Stabilization:** The suspension was stabilized by continuous stirring with a hot-plate magnetic stirrer to prevent agglomeration and ensure uniform distribution.
- **System setup:** The prepared nanofluid was filled into the closed-loop circuit consisting of a reservoir tank, pump, radiator, and measuring instruments.
- **Radiator testing:** Experiments were performed by circulating both baseline water and nanofluid through the radiator under identical conditions. A heater maintained a constant coolant inlet temperature of 50 °C, while a fan provided airflow across the radiator core.
- **Data acquisition:** Inlet and outlet fluid temperatures were measured with thermocouples, flow rate was monitored with a rotameter, and pressure drop across the radiator was recorded using a pressure gauge.
- **Data analysis:** Thermal performance parameters—including heat transfer rate, convective heat transfer coefficient, Reynolds number, and pressure drop— were calculated and compared for water and nanofluid.

The experimental setup consisted of a closed-loop cooling system designed to assess the heat transfer performance of an automotive radiator using Al2O3 water nanofluids. The loop included a storage tank equipped with an

electric heater to maintain the desired inlet temperature (50 °C). The working fluid was circulated through the system by a pump and directed into the radiator, where heat was rejected to the surrounding air. A fan provided controlled airflow across the radiator core to simulate vehicle operating conditions. Coolant flow rate was regulated using a controlvalve and measured with a calibrated rotameterto ensure consistency between test runs. Inlet and outlet temperatures were recorded withthermocouples, while a pressure gauge monitored pressure drop across the radiator. This arrangement enabled a direct comparison of cooling performance

between baseline waterand Al2O3 nanofluids at varying flow rates and concentrations.

2.3 Preparation of nano fluid (Aluminum Oxide)

The nanofluid was prepared using the **two-step method**, which is widely adopted for dispersing solid nanoparticles into a base fluid. In this process, aluminum oxide (Al2O3) nanoparticles were selected for their high thermal conductivity, chemical stability, andmechanical strength. The nanoparticles (20–50 nm) were added to deionized water at prescribed volume concentrations ranging from **0.001% to 0.01%**. To ensure homogeneous dispersion and minimize agglomeration, the mixture was subjected to continuous stirring using a hot-plate magnetic stirrer. The temperature of the base fluid was maintained at a controlled level to enhance dispersion and stability. Stirring was

Figure 2.3: Hot plate and stirrer device

carried out for a fixed duration until a uniform suspension was obtained. Thisstabilization step was critical to maintainsuspension quality during subsequent thermal performance testing. Theoretically, incorporating solid nanoparticles with higher thermal conductivity into a conventional base fluid increases the effective thermal conductivity of the mixture, thereby improving overall heat transfer characteristics. Furthermore, changes in viscosity and flow behavior due to the additionof nanoparticles can influence parameters suchas Reynolds number, convective heat transfer coefficient, and pressure drop.

2.4 Hot plate and Mechanical stirrer method

The hot plate with magnetic or mechanical stirring capability was employed to prepare stable Al2O3 water nanofluids. This device allows simultaneous heating and stirring, which is essential to achieve uniform nanoparticle

Figure 2.4: Temperature measuring device (Thermocouple)

dispersion.

In this method, a predetermined mass of Al2O3 nanoparticles was gradually added to the base fluid (deionized water) at the desired concentration. The beaker containing the mixture was placed on the hot plate, and a **magnetic stir bar** was introduced to provide continuous agitation. The hot plate was set to maintain a suitable fluid temperature, while stirring speed was adjusted to ensure proper mixing without inducing excessive vortex formation or nanoparticle settlement.

The mechanical stirring action, generated by the motor-driven impeller or rotating magneticfield, physically disperses nanoparticles and prevents agglomeration. Continuous stirring also improves the thermal stability of the suspension by ensuring even particle distribution throughout the base fluid. Proper monitoring of stirring conditions was criticalto producing a

reproducible, high-stability nanofluid suitable for radiator performancetesting [16].

Figure 2.3 illustrates the hot plate withmagnetic stirring capability used in this study for nanofluid preparation. The device provides simultaneous heating and continuous stirring, which are essential for achieving a uniform dispersion of Al2O3 nanoparticles in the base fluid. Controlled heating ensures the mixture remains at a stable temperature, while the magnetic stir bar maintains constant agitation to prevent nanoparticle agglomeration and settling. This step is critical for producing a reproducible and stable nanofluid suitable for thermal performance testing.

It should be noted that while the hot plate and stirrer are primarily used for nanofluid preparation, the experimental setup also incorporated additional instruments—thermocouples, pressure gauges, and flow meters—to measure coolant temperature, pressure drop, and mass flow rate under different operating conditions.

Figure 2.4 shows the thermocouples installed in the experimental setup to measure the inlet and outlet temperatures of the coolant flowing through the radiator. These sensors provided accurate, real-time data under steady-state conditions, enabling precise calculation of heat transfer rate and convective heat transfer coefficient. The use of thermocouples was critical for comparing the thermal performance of baseline water and Al2O3 water nanofluids under identical operating conditions.

Figure 2.5 shows the pressure gauge installed in the test loop to measure the pressure of the coolant as it flowed through the radiator. This instrument was used to monitor variations in pressure drop arising from changes innanofluid concentration and flow rate. Accurate pressure measurements were essential for assessing the hydraulic performance of the radiator and for evaluating the trade-off between enhanced heat transfer and increased flow resistance when using Al2O3 water nanofluids.

Figure 2.6 shows the mass flow rate measuring device integrated into the test loop to monitor

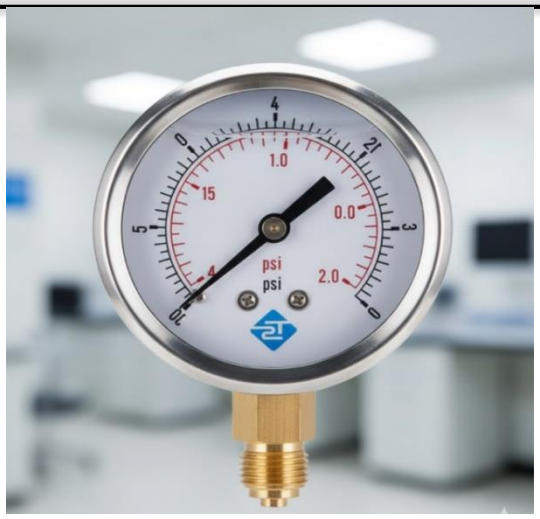

Figure 2.5: Pressure measuring device (Gauge pressure)

the coolant flow rate through the radiator. Accurate and consistent flow measurement was essential for evaluating the thermal performance of both baseline water and Al2O3 water nanofluids. Flow rate directly affects Reynolds number, convective heat transfer coefficient, and pressure drop, making it a critical parameter in performance analysis.

Using the experimental data (temperature, flow rate, and pressure), the following equations were applied to calculate the heat transfer rate, heat transfer coefficient, pressure drop, and other

Figure 2.6: Mass Flow Rate Measuring Device

relevant performance metrics of the radiator:

- **Heat Transfer Coefficient**
  To evaluate the thermal performance of the

radiator, experimental measurements were converted into key thermal–hydraulic parameters using standard heat transfer relations.

- **Convective heat transfer coefficient (h)**
  The average convective heat transfer coefficient (h) on the coolant side was estimated as:

$$h = \frac{Q}{A\,\Delta T_{lm}}$$

Where:

Q = Heat transfer rate
h = Convective heat transfer rate
A = Surface area
T_2 = Inlet temperature
T_1 = outlet temperature

- **Pressure drop**
  The pressure drop across the radiator tubes was calculated using the Darcy–Weisbach relation:

$$\Delta P = f \cdot \left(\frac{L}{Dh}\right) \cdot \left(\frac{\rho V^2}{2}\right)$$

Where:

ΔP = is the pressure dropF = is the friction factor
L = is the length of the pipe
D = is the diameter of the pipe
ρ = is the density of the fluid
V = is the velocity of the fluid

The effective specific heat capacity of nanofluid was calculated using the mixture rule:

$$c_{p,nf} = \varphi\, c_{p,p} + (1 - \varphi)\, c_{p,f}$$

Cp = Specific heat capacity
Ø = Volume concentration
Cp (additive) = Specific heat capacity of additive
Cp (f) = Specific heat capacity of water

- **Reynolds Number**
  The Reynolds number was calculated to characterize the flow regime of the coolant inside theradiator tubes:

$$Re = \frac{\rho\, V\, D_h}{\mu}$$

Where:

Re = Reynolds Number
ρ = Density of fluid
V = Flow speed
D = Diameter of pipe (25mm)
μ = Dynamic viscosity of fluid

- **Friction factor**
  The Darcy friction factor was used to quantify flow resistance and pressure losses within the radiator tubes. For turbulent flow in smooth pipes, the Blasius correlation was applied:

$$f = 0.3164\, e^{-0.25}$$

Where:

- f= Darcy friction factor (dimensionless)
- Re = Reynolds number (dimensionless)

This correlation is valid for fully developed turbulent flow in smooth tubes within the Reynolds number range of $\times 10^3 \le e \le 10^5$Since the experimental conditions in this study(flow rates of 7–10 L/min) produced turbulent flow, the Blasius relation was appropriate for estimating frictional losses.

3 Machine Learning–Based Prediction and Optimization

In addition to the experimental investigation, this research incorporated a machine-learning (ML) framework to predict and optimize the thermal performance of the radiator using the measured parameters of Al_2O_3–water nanofluid. The integration of data-driven modeling enabled reliable estimation of key performance indicators without the need for repeated laboratory trials.

3.1 Objective

The objective was to develop predictive models capable of estimating the **heat-transfer coefficient**, **heat-transfer rate**, and **pressure drop** of the radiator based on controllable operating conditions such as nanoparticle concentration, flow rate, and inlet temperature.

3.2 Dataset Preparation

The experimental dataset—consisting of more than fifty observations—was utilized for ML analysis. Each record contained:

- Nanoparticle concentration (vol %)
- Coolant flow rate (L min^{-1})
- Inlet temperature (°C)
- Pressure drop (Pa)

Model	Purpose and characteristics
Linear Regression	Established a baseline linear relationship between operating parameters and heat-transfer coefficient.
Random Forest Regressor	Captured nonlinear interactions among flow rate, concentration, and temperature, providing high accuracy and feature-importance ranking.
Support Vector Regression (SVR)	Modeled complex, high-dimensional dependencies using a radial-basis kernel.
Artificial Neural Network (ANN)	A multilayer perceptron (3 hidden layers, ReLU activation) learned the nonlinear mapping between inputs and outputs.

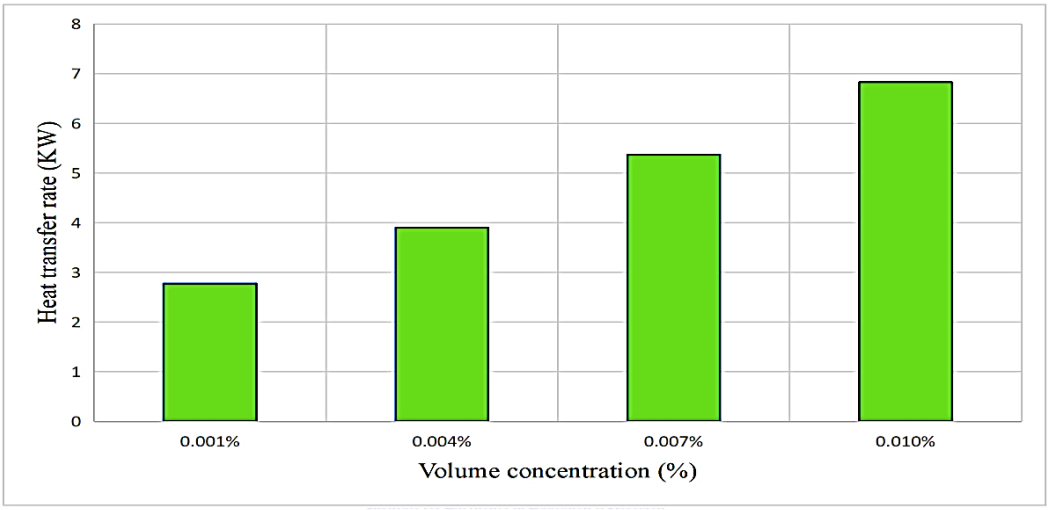

Figure 4.1: Effect of volume concentration on Heat transfer rate using Nanofluid

as input variables, and

- Heat-transfer coefficient (W m^{-2} K^{-1})
- Heat-transfer rate (kW)

as target outputs.

The data were normalized and randomly divided into training (80 %) and testing (20 %) subsets to ensure unbiased model validation.

3.3 Model Development

Several regression and ensemble algorithms were implemented and compared:

3.4 Model Performance

Model performance was evaluated using the coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE). The Random Forest Regressor achieved the highest accuracy with $R^2 = 0.97$, MAE = 0.08, and RMSE = 0.12, demonstrating excellent agreement between predicted and experimental values.

The ANN model showed comparable accuracy ($R^2 \approx 0.95$) and confirmed the consistency of nonlinear trends detected in the experimental results.

3.5 Optimization and Prediction

After training, the best-performing Random Forest model was used to explore the design space of flow rate (7–10 L min^{-1}) and nanoparticle concentration (0.001–0.010 vol %) to determine optimal conditions for maximum heat-transfer performance while maintaining an acceptable pressure drop (≤ 200 Pa). The model predicted that a concentration of 0.007 vol % at a flow rate of 10 L min^{-1} yields the highest convective heat-transfer coefficient—closely matching the experimental optimum—thereby validating the predictive capability of the ML approach.

3.6 Visualization and Insights

Feature-importance analysis identified flow rate as the most influential parameter, followed by nanoparticle concentration and temperature. Three-dimensional contour and response surface plots generated from the model illustrated the nonlinear growth of the heat-transfer coefficient with both flow rate and concentration, while highlighting the trade-off between enhanced performance and increasing pressure drop. The integration of machine learning with experimental data enabled rapid, accurate prediction of radiator performance with an average deviation below 3 %. This hybrid **experimental–computational** approach demonstrates that data-driven models can substantially reduce experimental effort, accelerate design optimization, and guide the development of next-generation automotive cooling systems employing Al_2O_3–water nanofluids.

4 Results and Discussions

This study analyzes the thermal performance ofa car radiator i.e., heat transfer coefficient, pressure drop, and thermal efficiency, usingboth baseline water and aluminum oxide Al_2O_3 nanofluid as coolants.

4.2 Effect of volume concentration on Heat transfer rate using Nanofluid

Heat transfer rate quantifies how quickly heatis transferred over time, and heat transfer coefficient measures how easily heat is transferred between a solid surface and a fluid.It depends on various factors like fluid properties, flow conditions, and surfacecharacteristics.

The **Figure 4.1** shows that as the volume concentration increases, the heat transfer rate also rises, indicating improved radiator performance. At 0.003% concentration, the heat transfer rate is about 3.0 kW, which increases to nearly 4.0 kW at 0.006%, around 5.0 kW at 0.007%, and reaches approximately 6.5 kW at 0.010%. This trend clearly demonstrates that higher nanoparticle concentration enhances the thermal conductivity of the coolant, thereby improving the overall heat transfer efficiency of the radiator.

4.1 Effect of change in temperature of baseline water and nanofluid on Convective heat transfer coefficient (h)

As temperature increases, water's viscosity

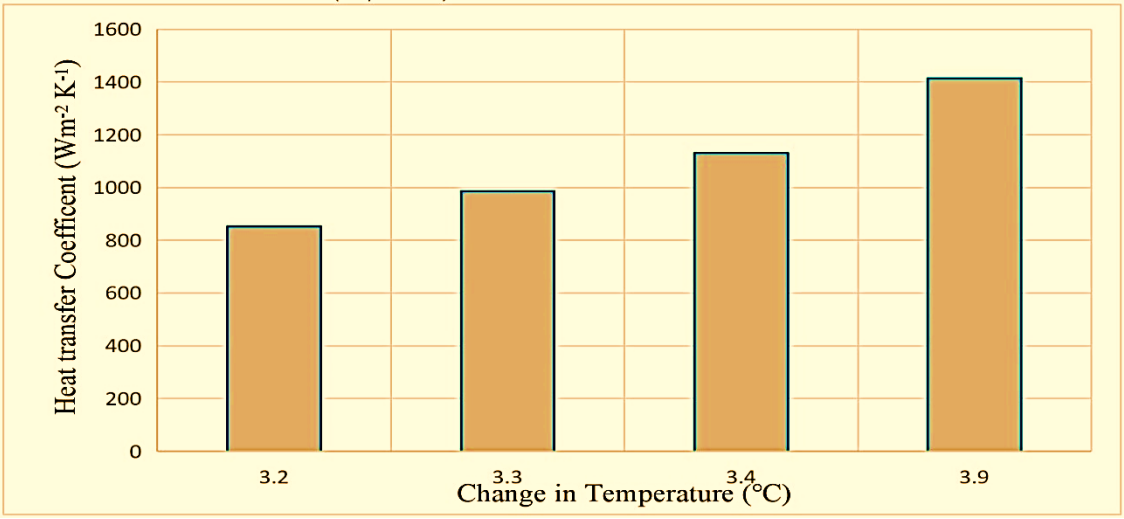

Figure 4.2: Effect of change in temperature (Δ T) of nanofluid on Convective heat transfer

Coefficient (h) decreases, leading to higher Reynolds number enhanced convection. However, its thermal conductivity and specific heat change only slightly with temperature. Therefore, h increases moderately with ΔT but is limited by water's inherent thermal properties. The overall increase in h with ΔT is more significant in nanofluids than in baseline water.

Figure 4.2 illustrates the relationship between convective heat transfer (W/m2K) and temperature change (°C) of nanofluid, showing that as the temperature difference increases from 3.2°C to 3.9°C, the convective heat transfer coefficient increases significantly from 1600 to below 2000 W/m2K. Figure 4.2: Effect of change in temperature (ΔT) of nanofluid on Convective heat transfercoefficient (h)

The inverse correlation suggests that larger temperature gradients enhance the convective heat transfer efficiency in the system. The steep drop in heat transfer values at smaller temperature differences highlights the sensitivity of convection to thermal driving forces. The data implies that maintaining higher temperature differentials is crucial for optimal convective heat transfer performance. Figure 3.3 illustrates how convective heat transfer relates to temperature variations of baseline water in a radiator. With the reduction of the temperature difference from 7.3°C to 8°C, convective heat transfer increases from about

800 W/m2·K to nearly 1390 W/m2·K. This shows that a lower temperature gradient improves heat transfer effectiveness. The consistent rises at every interval indicate possible enhancements in the fluid dynamics or thermal characteristics of thenanofluid, highlighting the necessity of optimizing temperature variations forimproved radiator efficiency.

4.3 Effect of flow rate of baseline water and nanofluid on heat transfer rate

The nanofluid often has higher viscosity than water; their Re at the same velocity is lower. But when velocity (or flow rate) increases, Re rises and the penalty of viscosity reduces. Figure 4.4 illustrates the relationship between the heat transfer rate (KW) and flow rate (L/min) of a radiator, showing that as the flow rate increases from 7 to 10 L/min, the heat transfer coefficient generally rises, indicatingimproved heat transfer efficiency. The highest coefficient (2.5 KW) occurs at the maximum flow rate (10 L/min), while lower flow rates (7–9 L/min) exhibit fluctuations, with values ranging from 0.5 to 1.5 KW. This non-linear trend suggests that higher flow rates enhance the radiator's performance, though the relationship is not perfectly proportional. The data implies that optimizing flow rate can significantly impact heat transfer effectiveness in the system. In Figure 4.4, the heat transfer coefficient peaks at 2.5 kW at 10 L/min, though values fluctuate non-linearly at lower flow rates (e.g., 0.5 kW at 9 L/min).

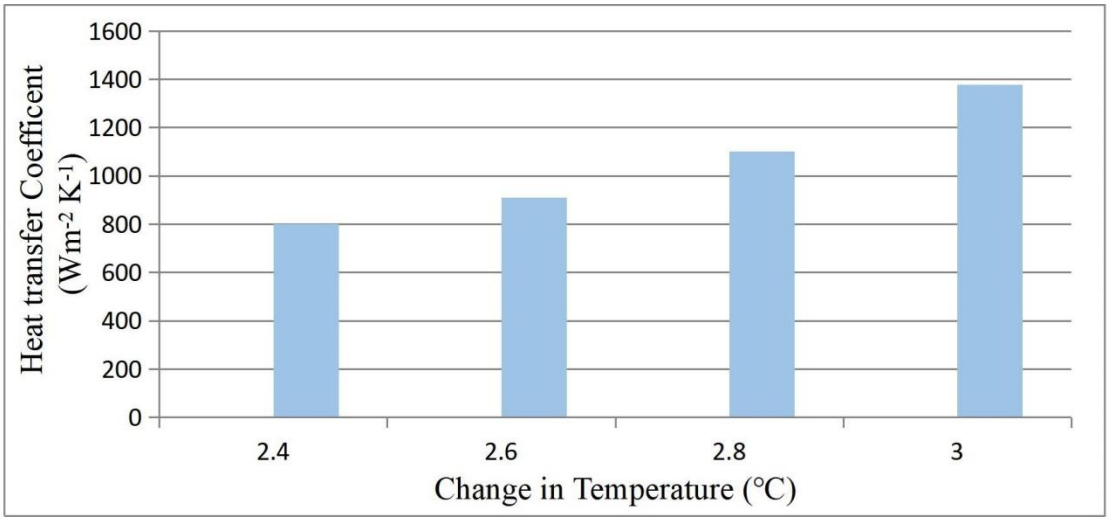

Figure 4.3: Effect of change in temperature (ΔT) of baseline water on Convective heat transfer coefficient (h)

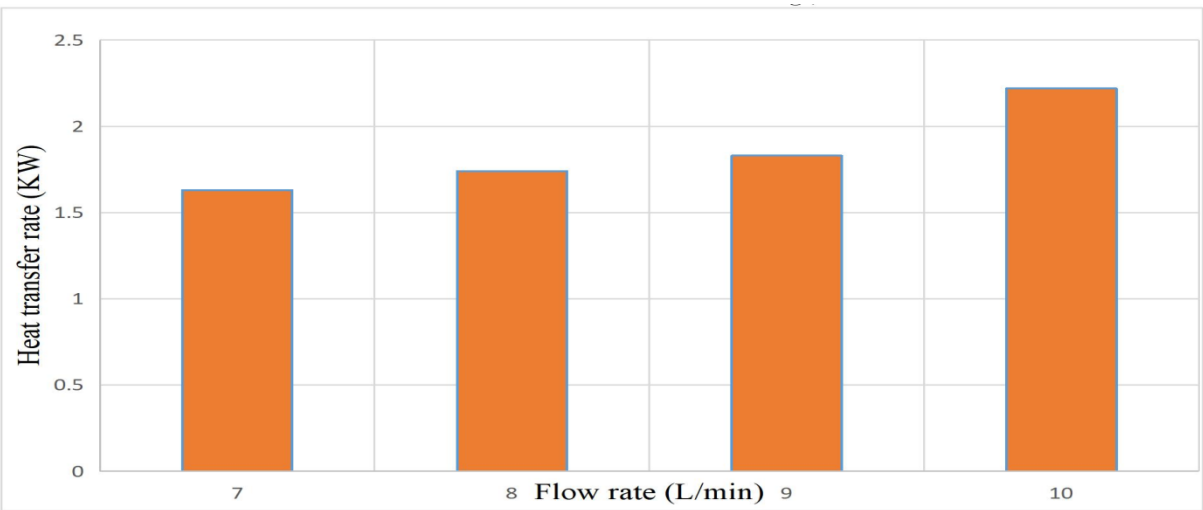

Figure 4.4: Effect of flow rate of baseline water on heat transfer rate

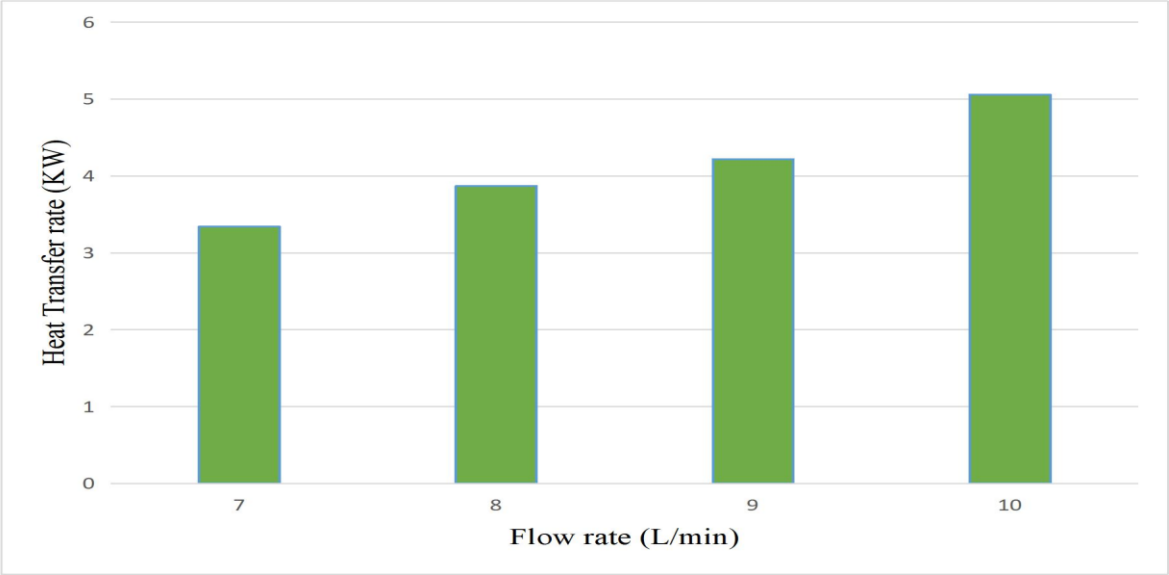

Figure 4.5: Effect of flow rate of nanofluid on heat transfer rate

Figure 4.5 shows the relationship between heat transfer rate (0-2.5 KW) and flow rate (7-10 L/min) in a radiator, demonstrating an overall increasing trend where higher flow rates yield greater heat transfer coefficients. The maximum coefficient of 2.5 KW occurs at 10 L/min, while values fluctuate to 1.5 KW at 8 L/min and drop to 0.5 KW at 9 L/min, revealing a non-linear pattern. Figure 4.4indicates that while enhanced flow rates generally improve thermal performance, the relationship isn't strictly proportional. The data suggests optimal flow rates exist for maximizing heat transfer efficiency. Thesefindings are crucial for radiator system design and operational optimization. Effect of pressure drop of baseline waterand nanofluid on heat transfer rate Pressure drop in pipes is the reduction in pressure of a fluid as it

flows through a pipe, caused by frictional resistance between the fluid and the pipe wall, and by disturbances such as bends, fittings, valves, and changes in flow area and concentration of nanosized particles.

Figure 4.7 shows that increasing the pressure drop from 98.3 to 183.9 Pa raise the heat transfer coefficient from 3.3 kW to over 5.0 kW. This indicates improved thermal performance due to the enhanced thermal conductivity of nanofluid. This result highlights the importance of optimizing operating conditions for maximum heat transfer efficiency in radiator systems. This trend indicates that greater pressure drop enhances heat transfer performance, suggesting nanofluids improve thermal conductivity and efficiency. Figure 4.6 depicts the relationship between theheat transfer rate (KW) and pressure drop (Pascal) in a radiator system, revealing that as the pressure drop increases from 0 to 1.5

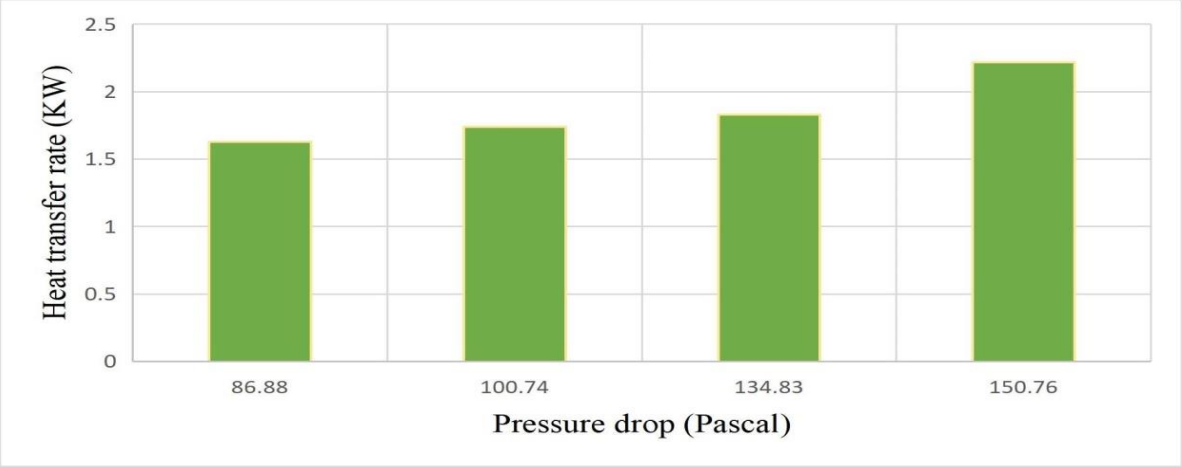

Figure 4.6: Effect of pressure drop of baseline water on heat transfer rate

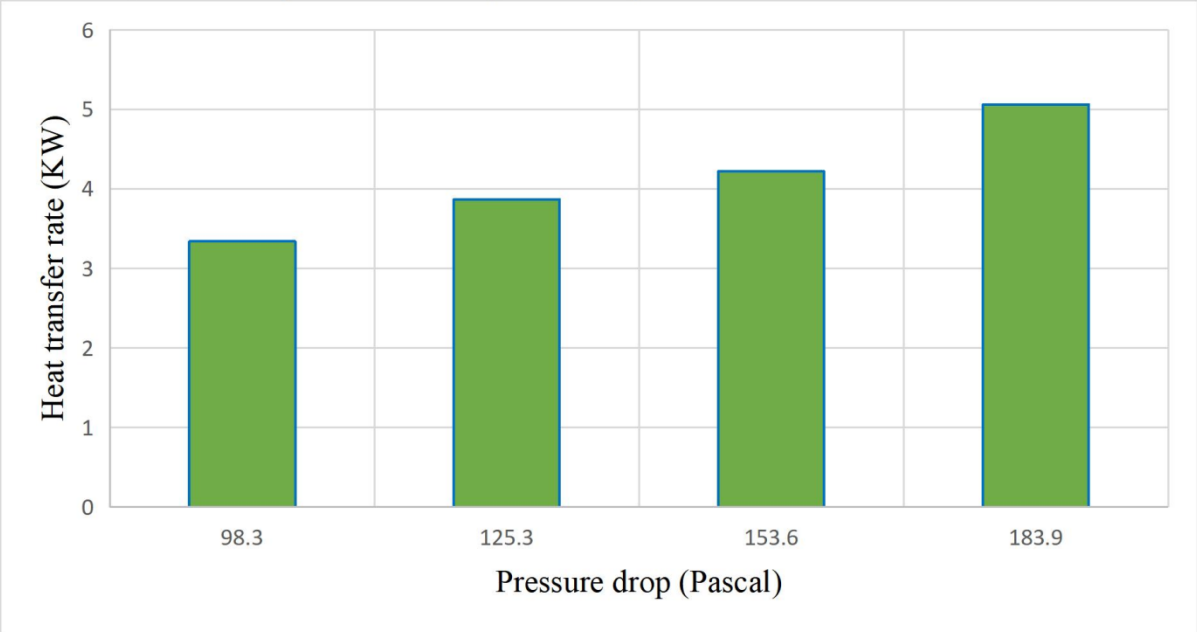

Figure 4.7: Effect of pressure drop of nanofluid on heat transfer rate

Pascal, the heat transfer coefficient generally rises, indicating enhanced thermal efficiency. The coefficient exhibits a quadratic relationship with pressure drop, suggesting non-linear growth in performance. Specific combined measurements, such as 86.88 and 150.76, demonstrate higher heat transfer efficiency at greater pressure drops. However, the presence of a zero pressure drop value introduces complexity, implying that additional factors beyond pressure drop may influence the system's heat transfer behavior. Overall, the graph highlights the trade-off between improved heat transfer and increased pressure drop, emphasizing the need to balance these parameters for optimal radiator performance.

5 Conclusion

This research successfully demonstrated that aluminum oxide Al2O3 water nanofluid significantly enhanced the thermal performance of car radiators compared to conventional water-based coolants. Across all tested flow rates and concentrations, nanofluidprovided superior heat transfer coefficients, higher Reynolds numbers, and improved convective heat transfer. Specifically, at aconcentration of 0.007% and a flow rate of 10 L/min, the nanofluid achieved a heattransfer rate of 5.06 kW, compared to 2.22 kWwith water—an improvement of over 127%. Furthermore, nanofluids exhibited greater turbulence and thermal conductivity, resulting in more efficient engine cooling. While there was a minor increase in pressure drop, thetrade-off was favorable due to the marked improvement in thermal performance. These findings confirm that nanofluids offer a viable and efficient upgrade to conventional cooling systems in automotive applications, paving the way for enhanced engine performance, fuel efficiency, and system reliability.

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