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CFD Analysis of Automobile Radiator Performance: Investigation of Heat Input, Mass Flow Rate, and Coating Thickness Effects

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Abstract
This research paper delves into the realm of Computational Fluid Dynamics (CFD) analysis to optimize the thermal performance of automobile radiators through the application of coatings. The study focuses on the impact of three different coating sizes, namely 50 micrometres, 80 micrometres, and 100 micrometres, aiming to enhance heat transfer efficiency and overall radiator performance. To systematically investigate the influence of these coatings on thermal behaviour, the L9 Orthogonal array is employed as a robust experimental design. The experimental methodology involves simulating the radiator's heat dissipation capabilities using CFD techniques, considering the interaction of fluid dynamics and heat transfer within the coated radiator. The L9 Orthogonal array provides a systematic and efficient approach to conducting experiments, allowing for the exploration of various coating combinations and their effects on thermal performance. The research not only analyses the impact of different coating sizes on the overall heat transfer efficiency but also seeks to identify optimal combinations that yield superior results. Insights gained from this study contribute to the development of advanced thermal management strategies in automotive engineering, aiming to enhance the cooling efficiency of radiators while maintaining operational and material constraints. Key findings highlight the significant role that coating thickness plays in augmenting the heat dissipation capabilities of automobile radiators. The outcomes of this research bear implications for the automotive industry, guiding future design considerations for improved radiator performance in terms of heat transfer efficiency, energy consumption, and overall system sustainability.

Keywords: Automobile, Radiator, CFD, Orthogonal Array, Coating

1. INTRODUCTION

Automobile radiators play a pivotal role in maintaining the optimal operating temperature of internal combustion engines, ensuring efficient performance and longevity. As the demand for increased engine power and fuel efficiency continues to rise, the need for advanced thermal management strategies becomes paramount. This research focuses on leveraging Computational Fluid Dynamics (CFD) analysis to enhance the thermal performance of automobile radiators through the strategic application of coatings. The application of coatings to radiator surfaces has emerged as a promising avenue for improving heat transfer efficiency, with varying thicknesses presenting an intriguing parameter for exploration. In this study, we delve into the influence of coating thickness on the thermal behavior of automobile radiators, considering three distinct sizes: 50 micrometers, 80 micrometers, and 100 micrometers. The selection of these coating sizes is motivated by the desire to comprehensively assess the impact of thickness variation on heat dissipation capabilities. To systematically investigate the intricate interplay between coating thickness and thermal performance, we employ the L9 Orthogonal array, a robust experimental design that facilitates a structured exploration of the parameter space. Through CFD simulations, we analyze the fluid dynamics and heat transfer characteristics within the coated radiators, aiming to identify optimal combinations that enhance overall efficiency. This research seeks to contribute valuable insights to the field of automotive engineering, offering a nuanced understanding of how coating thickness affects the heat dissipation capabilities of radiators. The outcomes of this study not only have implications for the advancement of thermal management strategies in automobiles but also provide a foundation for future design considerations that prioritize efficiency, energy conservation, and sustainability. As we embark on this exploration, the quest is to uncover innovative solutions that will propel automotive thermal systems into a new era of enhanced performance and reliability.

2. LITERATURE SURVEY

The authors of the paper are S.A. Angayarkanni et al [1]. Nanofluids, which are mixtures of nanomaterials in base fluids, have generated significant attention due to their remarkable improvements in thermal conductivity. Amidst the dispute surrounding their behaviour, investigations concentrate on factors such as Brownian motion and interfacial resistance to clarify these improvements. Current research focuses on customising nanofluids to enhance thermal conductivity, particularly for use in heat transfer applications and thermal energy storage, such as phase change materials (PCMs) and hybrid nanofluids. This study provides a thorough analysis of nanofluid creation, stabilisation, assessment of thermal properties, theoretical models, and their incorporation into phase change materials (PCMs). It is suitable for senior researchers as well as newbies who are looking for a full understanding of the subject. The authors of the paper are Nor Azwadi Che Sidik et al [2]. Nanofluids provide a groundbreaking method for cooling engines by utilising their high thermal diffusivity, which allows them to quickly respond to changes in temperature in vehicle engines. Nanofluids, which are improved by the addition of nanoparticles, have better mixing capabilities and higher thermal conductivity compared to regular fluids. This leads to enhanced efficiency in removing heat in radiator systems and improved lubrication in engines. The authors of the paper are Hussein S. Moghaie and his colleagues [3]. An experiment was conducted to study the effect of γ-Al_2O_3/water nanofluid on engine cooling. The results showed that the convective heat transfer was improved when using the nanofluid. This improvement was directly related to the increase in flow velocity and decrease in bulk temperature. The heat transfer coefficient increased by 78.67% when the nanofluid had a nanoparticle volume concentration of 1% compared to using pure water. However, restrictions exist in its utilisation for cooling cast iron engine components notwithstanding its efficiency. Ahmad Moradi et al [4] This work studies the heat transfer characteristics of multi-walled carbon nanotube aqueous nanofluids within a countercurrent double-pipe heat exchanger utilizing aluminum porous media ($\varepsilon = 67\%$). Implementing plate porous media considerably boosts heat transfer coefficients by up to 35%, particularly visible at lower mass fractions (0.04 mass%) with three-plate porous media designs, whereas higher mass fractions show reduced enhancement. Furthermore, lower volume flow rates exhibit considerable gains in enhancement coefficients compared to larger flow rates within the investigated range. Mohammad Fares et al [5] This experimental study studies graphene nanofluids' impact on convective heat transfer within a vertical shell and tube heat exchanger, generated from sugar-based graphite foam. Varying nanofluid concentration, flow rate, and inlet temperature demonstrated a 29% improvement in heat transfer coefficient utilising 0.2% graphene/water nanofluids, boosting the heat exchanger's thermal performance by 13.7% on average, validating graphene's usefulness in enhancing thermal efficiency. Ferhat Kılın et al [6] This study evaluates the cooling performance of a vehicle radiator utilising pure water, graphene oxide (GO), and graphene nano ribon (GNR) nanofluids, altering inlet temperatures and flow rates. At 0.01% and 0.02% vol. concentrations, GO/water nanofluids revealed overall heat transfer coefficient enhancements of 5.41% and 26.08%, while GNR/water nanofluids showed enhancements of 15.62% and 20.64%, verifying their usefulness in enhancing heat transfer in the radiator. Mohammad Hatami et al [7] et al This comprehensive analysis analyses nanofluid applications in internal combustion engines (ICEs), stressing nano-coolants' impact on radiator, exhaust EGR, and cylinder cooling. Evaluating varied base fluids and nanoparticles, it amalgamates experimental and numerical data to identify appropriate nano-coolants, giving the most efficient solutions for certain engine applications within ICEs. R. Prasanna Shankara et al [8] The study explores graphene oxide (GO) nanofluids mixing ethylene glycol (EG) and deionized water (DW) in varied ratios for automobile radiator cooling, exhibiting enhanced heat transfer capabilities. The optimized 60% EG, 40% DW, and 0.1 wt% GO combination exhibit remarkable heat transfer increases of 42.77% at 300 LPH, 18.14% at 360 LPH, and 71.1% at 240 LPH. This nanofluid application possibly reduces radiator frontal area, allowing design flexibility, encouraging eco-friendly automobiles with less drag, and ultimately cutting fuel costs. Farrukh Abbas et al [9] The study explores graphene oxide (GO) nanofluids mixing ethylene glycol (EG) and deionized water (DW) in varied ratios for automobile radiator cooling, exhibiting enhanced heat transfer capabilities. The optimized 60% EG, 40% DW, and 0.1 wt% GO combination exhibit remarkable heat transfer increases of 42.77% at 300 LPH, 18.14% at 360 LPH, and 71.1% at 240 LPH. This nanofluid application possibly reduces radiator frontal area, allowing design flexibility, encouraging eco-friendly automobiles with less drag, and ultimately cutting fuel costs. Gurpreet Singh Sokhal et al [10] The study explores graphene oxide (GO) nanofluids mixing ethylene glycol (EG) and deionized water (DW) in varied ratios for automobile radiator cooling, exhibiting enhanced heat transfer capabilities. 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Jodh Singh et al [12] This experimental work explores the thermal conductivity of hybrid nanofluids (GO-CuO/DW), along with mono nanofluids (GO/DW, CuO/DW) at particle concentrations of 0.03, 0.1, and 0.3 wt%. Notably, at 60 °C and 0.3 wt% concentration, improvements of 12.4%, 51.6%, and 30% in thermal conductivity were reported for CuO/DW, GO/DW, and GO-CuO/DW nanofluids, respectively. Additionally, the thermal conductivity of CuO/DW was compared with theoretical model values, supporting the experimental findings. Xiaoke Li et al [13] This study studies ethylene glycol-based silicon carbide-multiwalled carbon nanotubes (SiC-MWCNTs) hybrid nanofluids as automotive engine coolants, finding a remarkable 32.01% thermal conductivity boost at 0.4 vol.%. These nanofluids exhibited Newtonian behavior and displayed increased viscosity with particle loading but reduced with warming. Notably, the nanofluid displayed a 26% better convective heat transfer coefficient than pure EG, indicating its probable applicability in vehicle radiator systems. Iman Fazeli et al [14] This study applies a novel surfactant mixture to stabilize a 0.1 wt% hybrid nanofluid (MWCNT-CuO) in a brazed plate heat exchanger, displaying adequate stability without sedimentation. Hybrid nanofluid exhibits large gains in convective heat transfer coefficients compared to water, culminating at 139.19% at a volume flow rate of 24.4 L/min with a continuous hot fluid temperature of 35°C. Analysis of variance (ANOVA) and response surface techniques were utilised to validate components and interactions, creating an empirical link and optimization for convective heat transfer coefficients.

3.1. COMPUTATIONAL SETUP AND ANALYSIS

The present work deals with widely used aluminum alloy material in an automobile radiator. Aluminum 6063 alloy is the base material. It has medium strength and high corrosion resistance. Table 3.2 shows the chemical, physical, mechanical and thermal characteristics of 6063 alloy.

Table 3.1: Various Properties of Aluminum 6063 alloy

Properties	Metric
Chemical Composition	
Silicon (Si)	0.365 %
Iron (Fe)	0.103 %
Copper (Cu)	< 0.010 %
Manganese (Mn)	0.012 %
Magnesium (Mg)	0.570 %
Chromium (Cr)	< 0.001 %
Zinc (Zn)	0.053 %
Titanium (Ti)	0.003 %
Aluminum (Al)	98.847 %
Physical Properties	
Density	2.70 g/cm^3
Melting Point	655 °C
Mechanical Properties	
Tensile Strength	195 Mpa
Shear Strength	83 Mpa
Yield Strength	125 Mpa
Fatiguq Strength	55 Mpa
Poisson's Ratio	0.33
Elastic Modulus	69.5 Gpa
Hardness	25
Elongation	7 %
Thermal Properties	
Thermal Conductivity	201 WmK

Thermal Expansion Coefficient	23.5 (10-6 /K)

Table 3.2: Parameters for Control (Design Factors) and their Levels

Control Parameters	Level_One	Level_Two	Level_Three
Heat Input	323	343	363
Mass Flow Rate (Kg/Sec)	0.15	0.3	0.45
Coating Thickness (m)	50	80	100

A cuboid, supplied with porous media, was the heart of the radiator. The center of the calculation has dimensions of 500 × 500 × 30 mm3. There is an entrance pipe in the header over the radiator, and there was an outlet pipe below the header that guided the water flow. The two cuboids represented the air regions in front of and behind the radiator. The inlet and outlet for both fluids and interfaces between the various bodies were created before the physical model's meshing and selection. A new area was established to define different borders.

3.2. Reasons for the Selection of Boundary Condition Input

3.2.1: Heat Input Levels (323K, 343K, 363K):

These temperatures likely represent a range of operating conditions for the radiator.

323K represent a lower temperature, perhaps typical of cooler weather or when the vehicle is idling.

363K represent a higher temperature, such as during hot weather or when the vehicle is under heavy load or high-speed operation.

343K represent a moderate or typical operating temperature.

3.2.2: Mass Flow Rate Levels (0.15 kg/s, 0.30 kg/s, 0.45 kg/s):

These flow rates could correspond to various vehicle speeds or engine loads.

Lower flow rates correspond to lower vehicle speeds or idling conditions.

Higher flow rates correspond to higher speeds or heavier engine loads, where more coolant is needed to dissipate heat effectively.

3.2.3. Coating Thickness Levels (50 µm, 80 µm, 100 µm):

Coating thickness can affect heat transfer and surface properties.

Different thicknesses represent variations in manufacturing processes or material choices.

Thicker coatings may provide better protection against corrosion or wear, but they could also affect heat transfer efficiency by increasing thermal resistance.

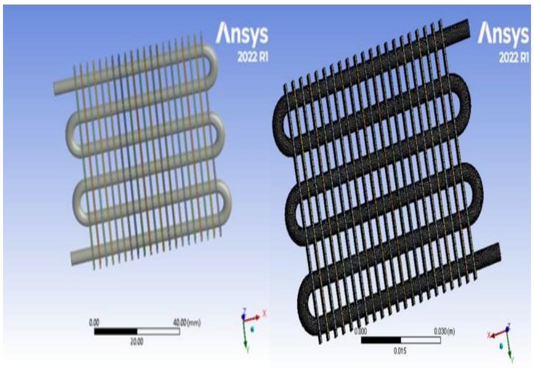

Figure 3.1: Geometry of the Radiator

Table 3.3: Boundary Conditions

Inlet/Outlet	Type
Coolant Inlet	Mass Flow Rate
Coolant Outlet	Pressure Outlet
Air Inlet	Velocity Inlet
Air Outlet	Velocity Outlet

4. RESULTS AND DISCUSSION

4.1. Analysis of Heat Transfer at Different Mass Flow Rate and Different Coatings Thickness with or Without Coating

4.1.1: Control parameters: Level One for Het Input 323 K

Based on the nine orthogonal cases of table 4.5, simulation in CFD for the provided heat input 323 K and three different thicknesses for the coating and three various flow rates of fluid were performed in CFD. CFD analysis result of radiator 323 K is shown in table 5.1.

Table 4.1: CFD Analysis Reading for 323 K

Coating Thickness	Mass Flow Rate	Heat Input (K)	Heat Output (Without Coating) (K)	Heat Output (With Coating) (K)
50	0.15	323	315	311.67
80		323		311.22
100		323		310.49
50	0.3	323	316	312.13
80		323		311.83
100		323		311.27
50	0.45	323	317	312.23
80		323		311.98
100		323		311.42

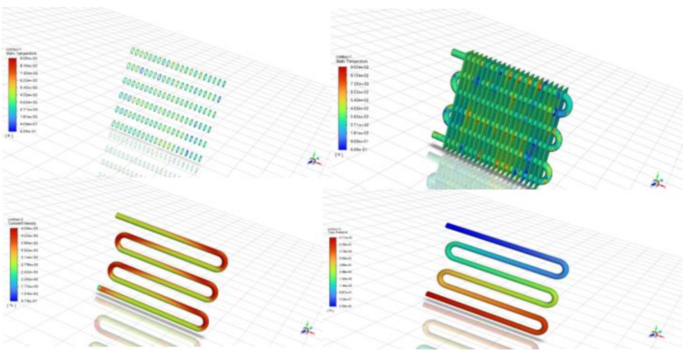

Figure 4.1: Heat input at 323 K vs. mass flow rate (a) 0.15, (b) 0.30, (c) 0.45 kg/sec (Before Coating).

4.1.2 Control parameters: Level One for Het Input 343 K

Table 4.2: CFD Analysis Reading for 343 K

Coating Thickness	Mass Flow Rate	Heat Input (K)	Heat Output (Without Coating) (K)	Heat Output (With Coating) (K)
50	0.15	343	328	324.15
80		343		323.62
100		343		321.79
50	0.3	343	331	325.18
80		343		324.69
100		343		323.96
50	0.45	343	332	325.87
80		343		324.76
100		343		323.13

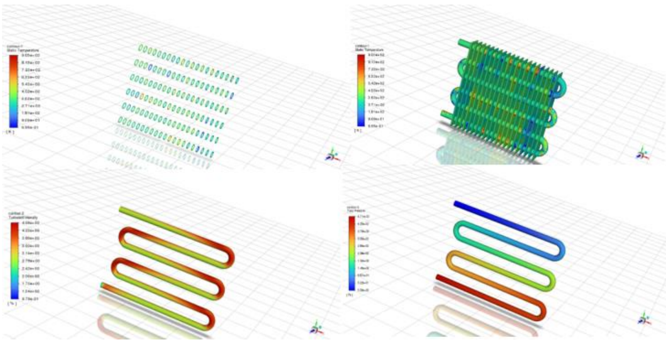

Figure 4.2: Heat input at 343 K vs. mass flow rate (a) 0.15, (b) 0.30, (c) 0.45 kg/sec (Before Coating).

4.1.3. Control parameters: Level One for Het Input 363 K

Table 4.3: CFD Analysis Reading for 363 K

Coating Thickness	Mass Flow Rate	Heat Input (K)	Heat Output (Without Coating) (K)	Heat Output (With Coating) (K)
50	0.15	363	341	339.13
80		363		336.9
100		363		333.98
50	0.3	363	345	340.13
80		363		337.13
100		363		334.95
50	0.45	363	348	341.48
80		363		338.48
100		363		336.64

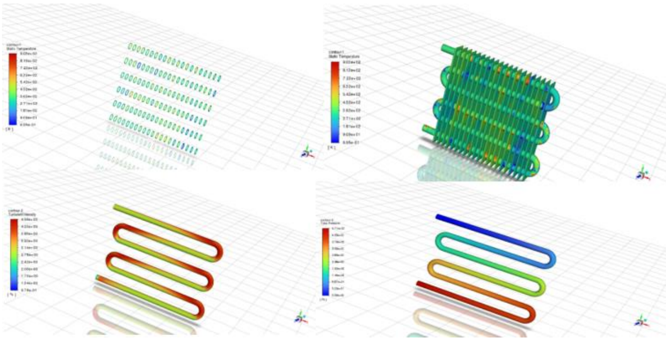

Figure 4.3: Heat input at 363 K vs. mass flow rate (a) 0.15, (b) 0.30, (c) 0.45 kg/sec (Before Coating).

6. CONCLUSION AND FUTURE SCOPE

CFD simulations were conducted, varying heat inputs of 50°C, 70°C, and 90°C, along with different coating thicknesses and fluid flow rates. The study aimed to analyze the impact of coating under varied conditions. Results indicated that across all parameters, nano-coated tubes notably enhanced heat transfer efficiency. Notably, a 100 µm coating thickness exhibited superior yield, paired with a satisfactory minimum mass flow rate of 15 kg/s, leading to a 7.1651 K difference in heat output compared to uncoated scenarios.

Post-test evaluation of nano-coated pipe efficiency revealed several key observations:

- The Taguchi analysis highlighted the A1 B3 C2 parameter configuration as optimal for temperature control.
- Pipes with a 100µm nano-coating displayed higher heat transfer coefficients across all flow rates.
- Specifically, at maximum heat inputs, a 0.15 kg/s mass flow rate of the coolant fluid demonstrated superior heat conduction.
- Taguchi's optimal solutions significantly improved the efficiency metrics for nano-coated pipe operations, reducing the number of experiments needed.
- Experimental findings underscored the pivotal roles of heat input (A), mass flow rate (B), and coating thickness (C) in nano-coated pipe operations.

Further research could focus on using advanced optimization algorithms to find the most efficient combination of heat input, mass flow rate, and coating thickness for the radiator design. This could lead to improved thermal performance and overall efficiency.

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