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Heat Transfer Performance Properties of a Hybrid Nanofluid (Cu-Al_2O_3/Water) Employed as a Coolant in a Car Radiator

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Abstract

The heat transfer performance of a hybrid nanofluid (Al_2O_3-Cu particles in water) as a coolant for automobile radiators will be investigated in this study. The primary objective is to examine its potential to improve cooling efficiency. Through experimental tests using a custom setup, the study analyzes heat transfer coefficient, thermal conductivity, and convective heat transfer to gain valuable insights into the nanofluid's thermal behavior. Positive findings could lead to an innovative and efficient cooling solution for car radiators, driving advancements in automotive engineering and sustainability. Ball milling approach was used to synthesize nanoparticles and then hybrid nanofluids at varied volumetric concentrations (0.02%, 0.04%, and 0.06%), and their heat transfer performance characteristics were then experimentally examined in an automobile radiator. A fan that creates a cross-air flow within the tube bank at a steady pace was used to facilitate forced convection heat transfer as the test liquid passed through the radiator's 37 vertical tubes. The experiment was conducted using a range of flow rates, from 6 to 14 liters per minute, and a constant 60°C radiator inlet temperature. The findings suggest that, in comparison to the pure base fluid, heat transmission was improved at all hybrid nanofluid concentrations. The convective heat transfer coefficient has increased by 24.6%, 43.16%, and 66.75% when a Cu-Al_2O_3/Water hybrid nanofluid at volume concentrations of 0.02%, 0.04%, and 0.06% was used.

Keywords
Hybrid nanofluid, Automobile radiator, Heat transfer coefficient, Thermal conductivity, Convective heat transfer

1. Introduction
The primary function of a car radiator is to regulate and dissipate the excess heat produced by the engine, maintaining its temperature within the optimal range. It circulates coolant through a system of tubes, where heat is transferred to the surrounding air via fins, aided by vehicle motion or cooling fans. After cooling, the fluid returns to the engine to continue the cycle. Without a radiator, overheating can cause severe engine damage, leading to degradation of seals,

gaskets, lubricants, and other components. Early automobiles used simple cooling mechanisms such as air cooling or thermosiphon systems, but as engines became more powerful, these methods proved insufficient. Modern radiators, introduced in the early 20th century, featured honeycomb cores and liquid coolants, with brass or copper tubes and fins. The use of antifreeze and additives in the 1920s improved efficiency and durability, while aluminum radiators, popularized in the 1970s, offered lighter weight, better heat conductivity, and corrosion resistance. Subsequent advances include multi-core radiators, electric fans, and improved coolant flow technologies, all designed to enhance compactness and efficiency. Recent research has focused on nanofluids and hybrid nanofluids, which enhance heat transfer compared to conventional coolants. Nanofluids, which contain suspended nanoparticles such as Al_2O_3, Cu, or CNTs, improve thermal conductivity and convective heat transfer. Hybrid nanofluids combine different nanoparticles, like Al_2O_3 and Cu, to leverage the benefits of both metallic and non-metallic particles. While Al_2O_3 provides stability and chemical inertness, metals such as Cu or Ag offer superior conductivity but limited stability. Combining them enhances both thermal and physical properties, enabling more effective cooling and compact heat exchangers. Studies confirm that hybrid nanofluids significantly enhance heat transfer, although research in this area remains limited in its application-based context.

1.1 Objectives

The overall aim of this study is to evaluate the heat transfer performance characteristics of Cu-Al_2O_3/water hybrid nanofluid when used as a coolant in automobile radiators. To achieve this aim, the study focuses on three specific objectives. Firstly, it investigates the heat transfer characteristics of the hybrid nanofluid within a car radiator system. Secondly, it examines the impact of varying concentrations of Cu-Al_2O_3 nanoparticles on thermal performance. Finally, the study compares the heat transfer characteristics of the Cu-Al_2O_3/water hybrid nanofluid with those of conventional water-based cooling to assess its potential as a more efficient and sustainable alternative.

2. Literature Review

The automotive sector depends heavily on cooling systems. The engine must be refilled to improve performance and long-term compactness and to avoid overheating. Previously, scientists have focused on a range of qualities and strategies for mitigating excessive heat. The heat exchanger, heat pipe, fin, and other components were their main design priorities. Numerous tube types with different fin configurations and other features were examined. In many experiments, inserts were also employed. Along with rough surfaces or vibration processes, several investigations also looked into magnetic or electric field performance approaches. Despite this, researchers have always placed a significant premium on improving heat transport. With the advancement of technology and research, heat transfer fluids have a greater impact on increasing flow techniques and thermal characteristics. (Jibhakate et al., 2023) performed an analytical study on a radiator using a water-based Al_2O_3 + CuO hybrid nanofluid with 30% ethylene glycol (EG) as the base fluid. The nanoparticle concentrations of Al_2O_3 and CuO were maintained at 0.1% each. A cooling circuit was modelled in ANSYS (v17) under transient conditions. The results demonstrated that the inclusion of hybrid nanoparticles significantly enhanced the heat transfer rate compared to the base fluid, highlighting their potential for improving radiator performance.(Hassaan, 2024)investigated the thermal performance of a 2005 Honda radiator using MWCNT–Al_2O_3/water hybrid nanofluid at different volumetric concentrations with a 50:50 mixing ratio. Compared to distilled water, the hybrid nanofluid enhanced the convective heat transfer coefficient by up to 28.5%, while the effectiveness and Nusselt number improved by 22.54% and 23.74%, respectively.

A pressure drop increase of approximately 24% was also observed at higher concentrations, consistent with the results of previous studies. (Suresh et al., 2012) utilized a hybrid Cu- Al_2O_3/water nanofluid to examine pressure drop characteristics and fully developed laminar convective heat transfer in a uniformly heated circular tube. The experimental findings have shown a maximum 13.56% increase in Nusselt number compared to water at a Reynolds number of 1730. Additionally, 0.1% Al_2O_3-Cu/water hybrid nanofluids have exhibited slightly higher friction factors than 0.1% Al_2O_3/water nanofluids, corroborating well with predicted empirical correlations.(X. Li et al., 2021) employed SiC-MWCNTs/EG hybrid nanofluid, observing a 32.01% maximum enhancement at 0.4 vol%. With increased particle loading, viscosity rises, but decreases with higher temperatures. Additionally, SiC-MWCNTs nanofluids exhibit a 26% higher maximum convective heat transfer coefficient than pure EG under similar conditions. (Ramadhan et al., 2020) investigated experimentally the heat transfer properties of Al_2O_3-TiO_2- SiO_2 based water/ethylene glycol and compared to a water/ethylene glycol mixture. Tri-hybrid nanofluid nanoparticles were dispersed in a water/ethylene glycol mixture at 0.05 to 0.3 vol.% to produce four different nanofluid concentrations. The most considerable improvement in the heat transfer coefficient for the coolant side is 39.7% at 0.3% volume concentration.(Sidik et al., 2016) We have compiled and analyzed extensive research on hybrid nanoparticles and nanofluids, with a focus on their production methods and thermophysical properties. Their findings have revealed that hybrid nanofluids exhibit superior thermal properties compared to base fluids and those containing single nanoparticles, with enhancements observed in both temperature and volume fraction. (Moghadassi et al., 2015) modeled a CFD analysis of a horizontal circular tube to assess nanofluids' impact on laminar forced convective heat transfer, considering 0.1% volume concentration Al_2O_3 and Al_2O_3-Cu hybrid nanofluids with an average particle size of 15 nm. Results indicate the hybrid nanofluid enhances convective heat transfer, with average Nusselt numbers increasing by 4.73% and 13.46% compared to Al_2O_3/water and pure water, respectively. (Sarkar et al., 2015) We have summarized recent studies on the synthesis, thermophysical properties, heat transport, pressure drop, applications, and challenges of hybrid nanofluids, suggesting their potential for enhancing heat transfer. Research indicates that the proper hybridization of nanofluids leads to improved performance, driven by increased thermal conductivity and a higher heat transfer coefficient, particularly with composite nanoparticles. (Yıldız et al. 2019) Compared theoretical and experimental correlations to assess hybrid nanofluids' heat transfer performance, analyzing Al_2O_3/water, SiO_2/water, and their hybrid combinations' natural convection at varying particle volume fractions. Findings suggest poor heat transmission in theoretical models for thermal conductivity, an unexpected decline in efficiency with SiO_2/water nanofluid, and potential heat transmission enhancement at lower particle volume percentages through nanoparticle hybridization. (Ahmed et al., 2018) used TiO_2 nanofluid with concentrations of 0.1, 0.2, and 0.3% volume concentrations in their studies, which used flow rates between 0.097 and 0.68 m3/h and Reynolds numbers ranging from 560 to 163. They found that using a TiO2-water nanofluid at a 0.2 concentration as a coolant, compared to 0.1% and 0.3% concentrations of TiO2-water nanofluid and pure water, might increase a car radiator's efficiency by 47%. (Naiman et al., 2019) analyzed radiator performance at high coolant temperatures below 80°C, as well as comparative data from experimental and one-dimensional analytic data. The found thermal conductivity values are maximal at 0.9% concentrations. (Sahoo et al., 2017) investigated the thermal performance of a louvered fin car radiator using water-based (50/50 volume ratio) hybrid nanofluids of Fe_2O_3, CuO, TiO_2, Ag, and Cu as coolants.

They found that (50/50) volume fraction of Cu, CuO, Fe_2O_3, and TiO_2 hybrid nanofluids is the next best radiator coolant, followed by Al_2O_3-Ag/water hybrid nanofluid, which has higher efficiency, heat transfer rate, pumping power, and pressure drop than water by 0.8%, 3%, 6%, and 5.6%, respectively. (Hussein, 2017) Conducted experiments in a twin pipe heat exchanger to assess thermal behavior and characteristics of a hybrid nanofluid, with volume fractions ranging from 1% to 4% and a 30 nm diameter. Findings reveal that while the friction factor decreases with flow rate, it increases with nanofluid concentration. The Nusselt number increases with both flow rate and concentration, demonstrating up to a 35% improvement in thermal performance compared to the base fluid at higher volume fractions. (Rashad et al., 2018)investigated the convective heat transfer of a hybrid nanofluid in a triangle-shaped cavity that was heated from below by a continuous heat flow source and exposed to a constant magnetic field. A hybrid nanofluid composed of an equal mixture of Cu and Al_2O_3 nanoparticles dispersed in a water-based fluid was used to compare its outcome with that of a standard nanofluid. (Mollamahdi et al. 2018)Investigated forced convection heat transfer in a porous channel filled with Al_2O_3-Cu/water micropolar hybrid nanofluid under a magnetic field, revealing that as the Reynolds number increases, temperature and microrotation decrease, with significantly higher heat transfer coefficient compared to regular nanofluid, and the Nusselt number increases with the Hartmann number. (Phanindra et al., 2018)They investigated the forced convection heat transfer and flow properties of a 0.1% volume concentration Al_2O_3/Cu hybrid nanofluid in Transformer oil, finding a 10.34% average increase in the Nusselt number compared to pure oil and a maximum improvement of 12.06% at a Reynolds number of 1820 in concentric tube heat exchangers.(Hussien et al., 2019)They conducted a rapid assessment of hybrid nanofluid synthesis, observing a heat transfer coefficient increase of up to 148% compared to the base fluid, which they attributed to enhanced thermal conductivity and nanoparticle kinetic motion. (Selvam et al., 2017)Conducted experimental investigations on automobile radiators using graphene nanofluid to improve heat transfer characteristics, varying volume concentrations from 0.1% to 0.5%. Results revealed a 29% improvement in thermal conductivity and convective heat transfer coefficient at 0.5 vol%, along with an analysis of graphene nanofluid stability and performance metrics, such as the Nusselt number and friction factor. (Hussien et al., 2017) They experimentally investigated heat transfer enhancement using a hybrid nanofluid composed of MWCNTs and GNPs, finding the highest heat transfer increase (43.4%) at Reynolds number 200 with the hybrid nanofluid (0.035 GNPs + 0.25 MWCNTs), attributing improvements to the hybrid nanoparticles' Brownian motion and noting an 11% greater pressure drop with nanofluid use. (L.S. Sundar et al., 2013) Tested the thermal conductivity of ethylene glycol and water mixtures with low volume concentrations of Al_2O_3 and CuO nanofluids, finding that as the particle volume concentration increases, so does the thermal conductivity. Compared to the base fluid, both nanofluids exhibit higher thermal conductivities with temperature increases, ranging from 9.8% to 17.89% for Al_2O_3 nanofluid and 15.6% to 24.56% for CuO nanofluid.

The reviewed studies indicate that hybrid nanofluids, such as Al_2O_3–Cu/water mixtures, offer significant potential for enhancing heat transfer performance in automobile radiators. Experimental results demonstrate improvements in thermal conductivity, convective heat transfer, and overall cooling efficiency compared to conventional coolants. Although an increase in pressure drop is often observed, the overall thermal benefits highlight hybrid nanofluids as a promising and sustainable solution for advanced automotive cooling systems.

3. Methods

The combustion process in automobile engines generates a considerable amount of heat, which must be removed effectively to maintain the engine's optimal temperature and protect its internal components. This cooling is achieved through a circulating fluid that absorbs heat from the engine and carries it to the radiator. Acting as a heat exchanger, the radiator uses a network of tubes and fins to release the absorbed heat into the surrounding air. Convection plays the dominant role in this process, as the airflow over the radiator facilitates the cooling of the heated fluid. Once cooled, the fluid circulates back to the engine, ensuring a continuous cycle of heat absorption and dissipation as long as the engine remains in operation.

3.1 Outline of Methodology

The steps of this experiment are shown in the following flowchart:

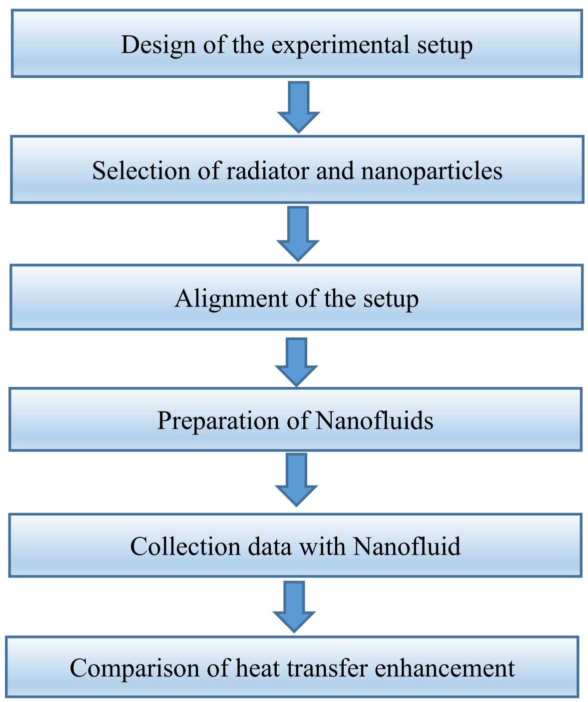

Figure 1. Flowchart of research outline

3.2 Schematic Diagram

The picture depicts a schematic representation of the experimental setup used in the investigation. In this experiment, a flat tube radiator was utilized as the primary component. Within the tank, a heater will be used to aid the flow of heat to the water. In addition, a fan will be used to create forced convection and remove the generated heat. The experimental setup contains three thermometers strategically placed to monitor the temperature at the nanofluid intake, nanofluid outflow, and radiator wall. The fluid will be circulated using a water pump, with the flow rate controlled by a gate valve. A pressure gauge will be included to measure the pressure drop between the fluid's entrance and outflow. We would like to emphasize that the experimental system will be operated as a closed system. When the input and output thermometer readings achieve a steady state, data collection will start. The working fluid will be sent from the tank to the radiator, with the flow rate carefully controlled by a valve. The fluid will be pressured to aid in its passage to the radiator. A rotameter will be used to measure flow rate precisely. Furthermore, two additional thermometers will be installed at the intake and exit points to ensure accurate temperature readings, and two pressure gauges will be installed to monitor pressure fluctuations. Finally, a thermometer will be placed in direct contact with the radiator wall to measure its temperature properly during the experiment.

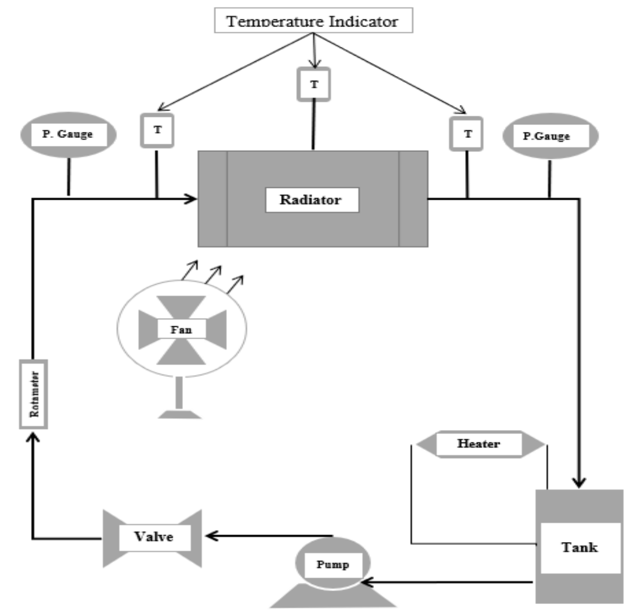

Figure 2. Schematic diagram of the experimental setup.

3.3 Properties of Base Fluid

In this investigation, water will serve as the primary fluid. The attributes of basic fluid are as follows:

Table 1. Base fluid characteristics

Base Fluid	Water
Density	1000 Kg/m^3
Molar Mass	18 g/mol
Freezing Point	0ºC
Boiling Point	100ºC
Specific Heat	4200 J/Kg. K
Viscosity	1.002×10^{-3} Ns/m^2
Thermal Conductivity	0.61Wm/K

3.4 Preparation of Hybrid Nanofluid

This process involves ball milling to produce nanoparticles, which are then uniformly dispersed throughout a base fluid in the next phase. In this work, planetary ball milling was conducted at ambient temperature and pressure. For proper balance during high-speed rotation, two containers were used, each loaded with 10 g of the powder sample, positioned in opposite directions. The milling parameters applied to both powder samples are listed in Table 2. Similar parameters have also been adopted by (Ghadami et al., 2021; L. Li et al., 2018; Mazaheri et al., 2010; Rajeshkanna & Nirmalkumar, 2014) and other researchers to successfully reduce Cu and Al_2O_3 particles from the microscale to below 100 nm.

Table 2. Parameters of Ball Milling

Parameter	**Value**	**Remarks**
Container material	-	Stainless steel
Ball material	-	Stainless steel
Ball size (mm)	4, 6, 8, 12, 16	-
Ball to powder weight ratio	15:1	-
Rotational speed (rpm)	400	-
Milling time (hours)	2	-

In this experiment, the nanofluid was prepared in predetermined proportions using a two-step procedure. Using a magnetic stirrer, the nanoparticles were first mixed with water and stirred for five hours. After preparing separately the nanofluids, they were combined to make the desired hybrid nanofluid.
(Abbas et al., 2021) used the following equation of volume concentration for nanofluid.

$$\varphi_{p1} = \left[\frac{\frac{m_{p1}}{\rho_{p1}}}{\frac{m_{p1}}{\rho_{p1}}+\frac{m_{bf}}{\rho_{bf}}}\right]$$

$$\varphi_{p2} = \left[\frac{\frac{m_{p2}}{\rho_{p2}}}{\frac{m_{p2}}{\rho_{p2}}+\frac{m_{bf}}{\rho_{bf}}}\right]$$

φ_{p1} = Volume concentration of Al_2O_3 nanoparticle.
φ_{p2} = Volume concentration of Cu nanoparticle.
m_{p1} = Mass of Al_2O_3 nanoparticle
m_{p2} = Mass of Cu nanoparticle
m_{bf} = Mass of base fluid
ρ_{p1} = Density of Al_2O_3 nanoparticle
ρ_{p2} = Density of Cu nanoparticle
ρ_{bf} = Density of base fluid
(Sahoo et al., 2017) used the following equation to determine the hybrid nanofluid's total volume concentration.

$$\varphi_p = \varphi_{p1}+\varphi_{p2}$$

Here,
φ_p=Overall volume concentration of hybrid nanofluid
To prepare the Cu–Al_2O_3/water hybrid nanofluid, individual nanofluids of Cu and Al_2O_3 were first synthesized in equal volumes. Three different concentration levels were considered. For the first case, nanofluids of Cu and Al_2O_3, each at 0.01 vol%, were prepared and subsequently mixed in a 1:1 ratio to obtain a Cu−Al_2O_3 (50:50)/water hybrid nanofluid at 0.02 vol%. Similarly, nanofluids of 0.02 vol% each were combined to get a hybrid concentration of 0.04 vol%, and nanofluids of 0.03 vol% each were combined to achieve a hybrid concentration of 0.06 vol%.

Figure 3 illustrates every step involved in preparing the respective 0.02, 0.04, and 0.06 vol% concentrations of Cu-Al_2O_3 (50:50)/water hybrid nanofluids.

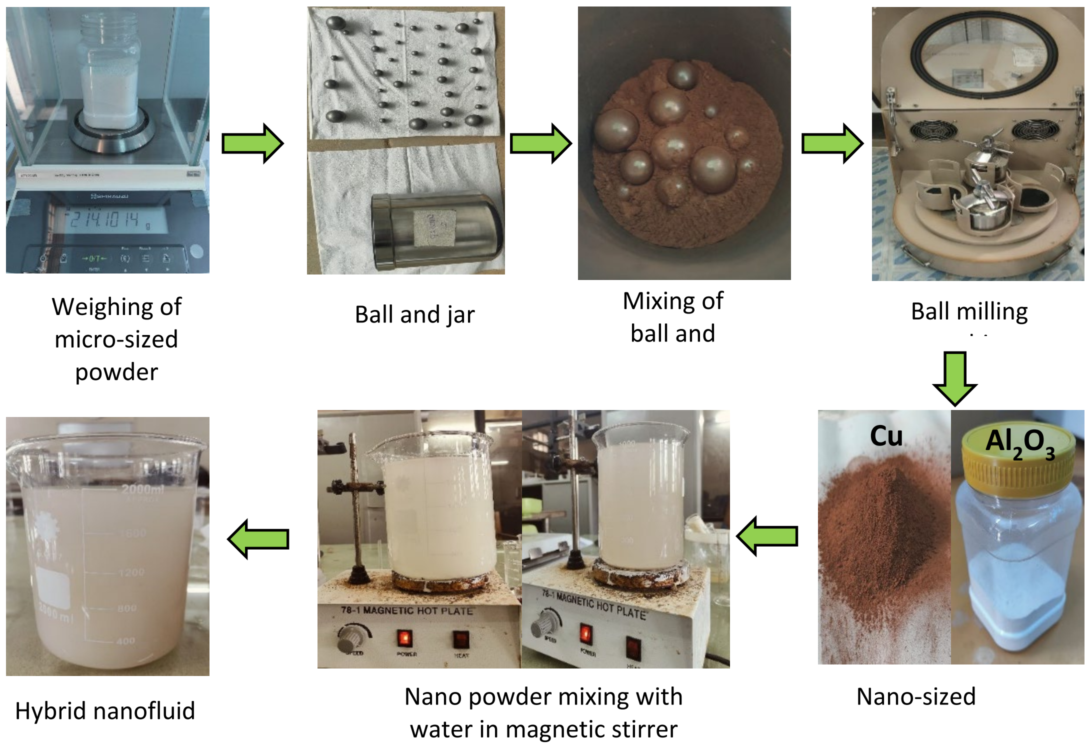

Figure 3. Flowchart of hybrid nanofluid preparation

3.5 Experimental Set Up and Equipment

The experimental arrangement was developed based on the schematic diagram. A storage tank/bucket was used to contain the prepared hybrid nanofluid, and a pump was employed to circulate the fluid throughout the setup. A pressure gauge and thermometers were installed to record the inlet and outlet pressure and temperature data. The primary equipment used in this study was a flat tube vertical radiator, serving as the heat exchanger for evaluating cooling performance. The detailed dimensions of the radiator are presented in Table 3.

Table 3. Radiator Dimension

SL. NO.	Dimensions	Value (m)
1	Radiator Length	0.7
2	Radiator Height	0.42
3	Radiator Width	0.015
4	Tube Length	0.65
5	Tube Height	0.004
6	Tube Width	0.018
7	Tube Thickness	0.0001
8	Number of Tube	70

The photographs of the experimental setup are shown in Figure 4.

(c)

Figure 4. Photograph of Experimental Setup (a, b, c)

4. Data Collection and Analysis

Overall, the calculated values are presented in Tables 4 and 5.

Table 4. Thermo-physical properties of Hybrid Nanofluid

Properties / Fluid	Density(kg/m^3)	Specific heat (J/kg. k)	Thermal conductivity (W/m. k)	Dynamic viscosity (Pa. s)
Base fluid	983.20	4200	0.61	0.4658×10^{-3}
0.02 vol% Cu-Al_2O_3/Water	1092.59	3767.34	1.061	4.67×10^{-4}
0.04 vol% Cu-Al_2O_3/Water	1201.972	3413.46	1.124	4.68×10^{-4}
0.06 vol% Cu-Al_2O_3/Water	1311.358	3118.6	1.190	4.69×10^{-4}

Table 5. Experimental results of heat transfer performance and pumping power for water and Cu–Al_2O_3/water hybrid nanofluids at different volumetric concentrations and flow rates.

Coolant	Flowrate (LPM)	Heat Transfer Rate, Q (Watt)	Heat Transfer Co-Efficient, h (W/m^2°C)	Pumping Power, P (Watt)
water	**2**	1101.182	56	0.58
	4	2064.720	113.6	1.38
	6	2890.608	169.03	3.09
	8	3303.543	190.99	5.33
0.02 vol% Cu-Al_2O_3/Water	**2**	1303.447	83.41	0.8
	4	2469.693	165.8	2.07
	6	3498.734	250.0	3.58
	8	4390.566	344.63	6.00
0.04 vol% Cu-Al_2O_3/Water	**2**	1504.390	118.08	0.92
	4	2872.018	250.48	2.53
	6	4100.579	373.6	4.13
	8	4923.459	465.18	6.42
0.06 vol% Cu-Al_2O_3/Water	**2**	1772.160	231.84	1.22
	4	3408.000	489.8	2.74
	6	4703.041	675.92	5.23
	8	5725.441	846.71	7.49

4.1 Governing Formula

4.1.1 Hybrid Nanofluid Density

The density formula is taken from (Takabi & Salehi, 2014)

$$\rho_{hnf} = (1 - \varphi_p)\rho_{bf} + \varphi_{p1}\rho_{p1} + \varphi_{p2}\rho_{p2}$$

Here, ρ_{hnf}= Density of hybrid nanofluid.

4.1.2 *Heat capacity of the hybrid nanofluid*

The following formula was used by [26] to determine the specific heat capacity of the hybrid nano fluid.

$$c_{P(hnf)} = \left(1 - \varphi_p\right)\left(\frac{\rho_{bf}}{\rho_{hnf}}\right)c_{p(bf)} + \left(\frac{\varphi_{p1}c_{p1}\rho_{p1}+\varphi_{p2}c_{p2}\rho_{p2}}{\rho_{hnf}}\right)$$

Here,
$c_{P(hnf)}$= Specific Heat Capacity of Hybrid Nanofluid
$c_{p(bf)}$= Specific Heat Capacity of Base Fluid
c_{p1}= Specific Heat Capacity of Cu Nanoparticle
c_{p2}= Specific Heat Capacity of Al2O3 Nano-particle

4.1.3 Thermal Conductivity
The formula provided by (Hamilton & Crosser, 1962) will be used to calculate the thermal conductivity of the hybrid nanofluid.

$$k_{hnf} = [\frac{\left(\frac{\varphi_{p1}k_{p1}+\varphi_{p2}k_{p2}}{\varphi_p}\right)-(\mathrm{n}-1)\varphi_p k_{bf}+(\mathrm{n}-1)(\varphi_{p1}k_{p1}+\varphi_{p2}k_{p2})}{\left(\frac{\varphi_{p1}k_{p1}+\varphi_{p2}k_{p2}}{\varphi_p}\right)+(\mathrm{n}-1)\varphi_p k_{bf}-(\varphi_{p1}k_{p1}+\varphi_{p2}k_{p2})+\varphi_p k_{bf}}] \times k_{bf}$$

Here,
k_{hnf}= Thermal Conductivity of Hybrid Nanofluid.
k_{bf}= Thermal Conductivity of base fluid.
k_{p1}= Thermal Conductivity of Cu nanoparticle.
k_{p1}= Thermal Conductivity of Al_2O_3 nanoparticle.
n= Empirical shape factor = 3

4.1.4 Dynamic Viscosity of Hybrid Nanofluid
In order to determine the dynamic viscosity of the hybrid nanofluid, (Akilu et al., 2018) provided the correlation that follows

$$\frac{\mu_{hn_f}}{\mu_{bf}} = 0.9894\ [1 + \frac{\varphi_p}{100}]^{6.6301} \times [\frac{T_{hnf}}{T_o}]^{0.064}$$

here,
μ_{hn_f}= Dynamic Viscosity of Hybrid Nanofluid
μ_{bf}= Dynamic Viscosity of base fluid
T_o= 273k
T_{hnf}= Temperature of Hybrid Nanofluid

4.2 Mathematical Formulation

From Newton's Law of Cooling,
$Q_{nf} = h_{in}A_{in}\,\Delta T = h_{in}A_{in}\,[(T_b)_{hnf} - (T_w)_{hnf}]$
Where,
$(T_b)_{hnf}$= Bulk temperature of Fluid = $\frac{(T_{in})_{hnf}+(T_{out})_{hnf}}{2}$
$(T_w)_{hnf}$= Avg. Radiator wall temperature (surface) = $\frac{T_1+T_2+......+T_6}{6}$
The heat transfer efficiency of the hybrid nanofluid will be estimated from,
$Q_{hnf} = \dot{m}_{hnf}\,(C_p)_{hnf}\,\Delta T = \dot{m}_{hnf}(C_p)_{hnf}\left((T_{in})_{hnf} - (T_{out})_{hnf}\right)$
The heat transfer coefficient of air will be computed using
$Q_a = \dot{m}_{air}\ (C_p)_{air}\,\Delta T = \dot{m}_{air}(C_p)_{air}((T_{in})_{air} - (T_{out})_{air})$

5. Results and Discussion

5.1 Numerical Results

The experimental findings demonstrate a progressive enhancement in thermal performance with increasing Cu-Al2O3 hybrid nanofluid concentration, where the base water fluid achieved heat transfer rates of 1101.18-3303.54 W with heat transfer coefficients of 56-190.99 W/m²°C at pumping powers of 0.58-5.33 W. The introduction of a 0.02% concentration resulted in significant improvements, with heat transfer rates reaching 1303.45-4390.57 W and coefficients of 83.41-344.63 W/m²℃, although requiring slightly higher pumping power (0.8-6 W). Further concentration increases to 0.04% yielded heat transfer rates of 1504.39-4923.46 W with coefficients of 118.08-465.18 W/m²°C at 0.92-6.42 W pumping power, while the optimal 0.06% concentration achieved the highest thermal performance with heat transfer rates of 1772.16-5725.44 W and remarkable heat transfer coefficients of 231.84-846.71 W/m²°C, despite requiring the highest pumping power of 1.22-7.49 W. These results clearly indicate that the 0.06% Cu- Al_2O_3 hybrid nanofluid provides the most substantial thermal enhancement, with heat transfer coefficients improving by up to 343% compared to base water, validating the synergistic effects of the copper-alumina nanoparticle combination in enhancing convective heat transfer performance, albeit with proportional increases in pumping power requirements that remain acceptable for practical applications.

5.2 Graphical Representation

In comparison to pure water, we have investigated the effects of different hybrid nanofluid concentrations (0.02%, 0.04%, and 0.06%) on heat transfer rate, pressure drop, heat transfer coefficient, and pumping power. Our research has clarified how effectively these concentrations improve cooling efficiency, providing important insights for maximizing the energy and performance of automobile radiators. Figure 5 demonstrates that with increasing concentration, the heat transfer rate increases significantly, showing 33% improvement at 0.02% concentration (from 3300 Q to 4400 Q at 8 LPM), 52% improvement at 0.04% concentration (reaching 5000 Q), and an impressive 76% improvement at 0.06% concentration (reaching 5800 Q) compared to pure water. This nearly doubling of heat transfer efficiency with the highest concentration nanofluid makes it highly valuable for enhanced thermal performance in industrial heat exchangers, cooling systems, and automotive radiator applications where maximum heat dissipation is critical.

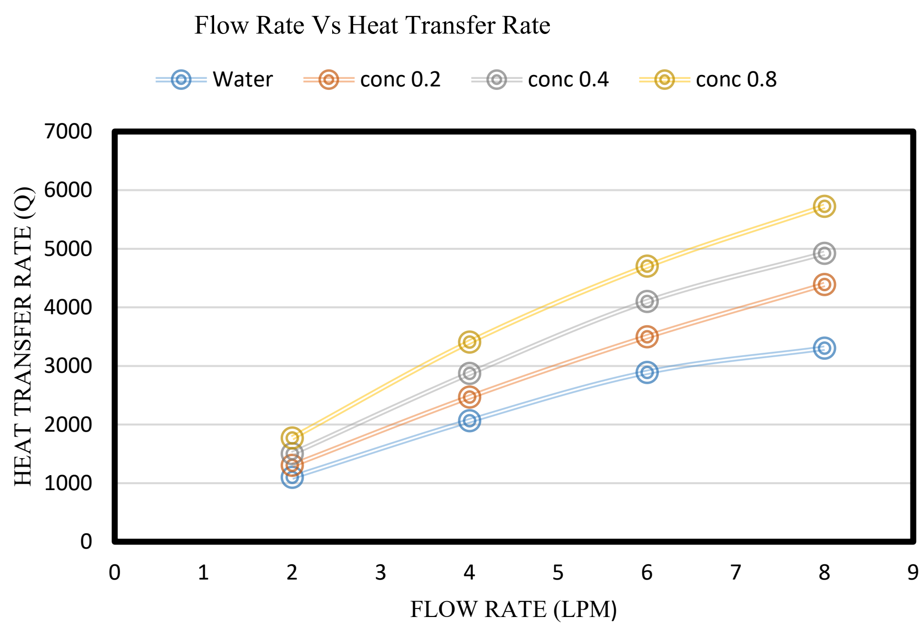

Figure 5. Variation of Heat Transfer Rate with Flow Rate

As we can see, three different concentrations of Cu-Al2O3/Water hybrid nanofluid were used in this study. It is found that the heat transfer rate increases by 24.6% at a 0.02% concentration, 43.16% at a 0.04% concentration, and 66.75% at a 0.06% concentration compared to pure water. Figure 6 clearly illustrates this progressive enhancement through a bar chart showing the percentage increase of heat transfer rate with respect to water for different concentrations. The data reveals that doubling the concentration from 0.02% to 0.04% results in a 75% relative improvement in heat transfer enhancement (from 24.6% to 43.16%), while increasing from 0.04% to 0.06% provides an additional 55% relative improvement (from 43.16% to 66.75%). This demonstrates that the Cu-Al2O3 hybrid nanoparticles exhibit excellent thermal conductivity enhancement properties, with the highest concentration achieving nearly a 67% improvement over pure water, making them highly effective for automotive radiator cooling applications where maximum heat dissipation is crucial for engine performance and efficiency.

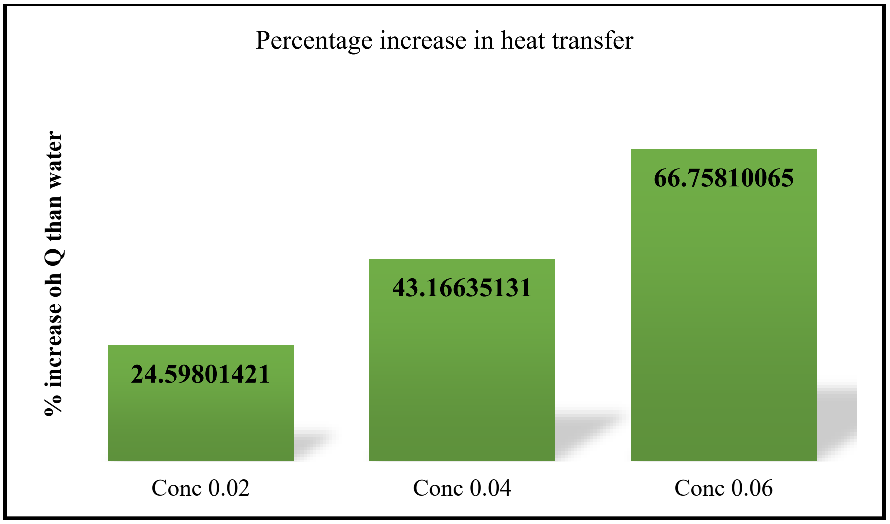

Figure 6. Increased Heat Transfer with respect to Water in Percent

Figure 7 demonstrates that nanofluid concentration significantly enhances heat transfer performance, with the highest concentration (0.06) achieving approximately 4.5 times better heat transfer coefficients than water at an 8 LPM flow rate (~850 vs ~190 W/m²K). The graph reveals a clear hierarchy, where higher concentrations consistently outperform lower ones across all flow rates. Notably, nanofluids exhibit greater sensitivity to flow rate changes compared to water, which responds relatively flatly. However, this enhanced thermal performance comes with significant trade-offs: higher concentrations increase fluid viscosity, resulting in greater pumping power requirements, higher material costs, and potential long-term stability concerns due to nanoparticle agglomeration. The optimal selection depends on balancing the substantial heat transfer gains against increased operational costs. Concentration 0.04 potentially offers the best performance-to-cost ratio for most applications, while concentration 0.06 should be reserved for high heat flux applications where maximum thermal performance justifies the additional expenses.

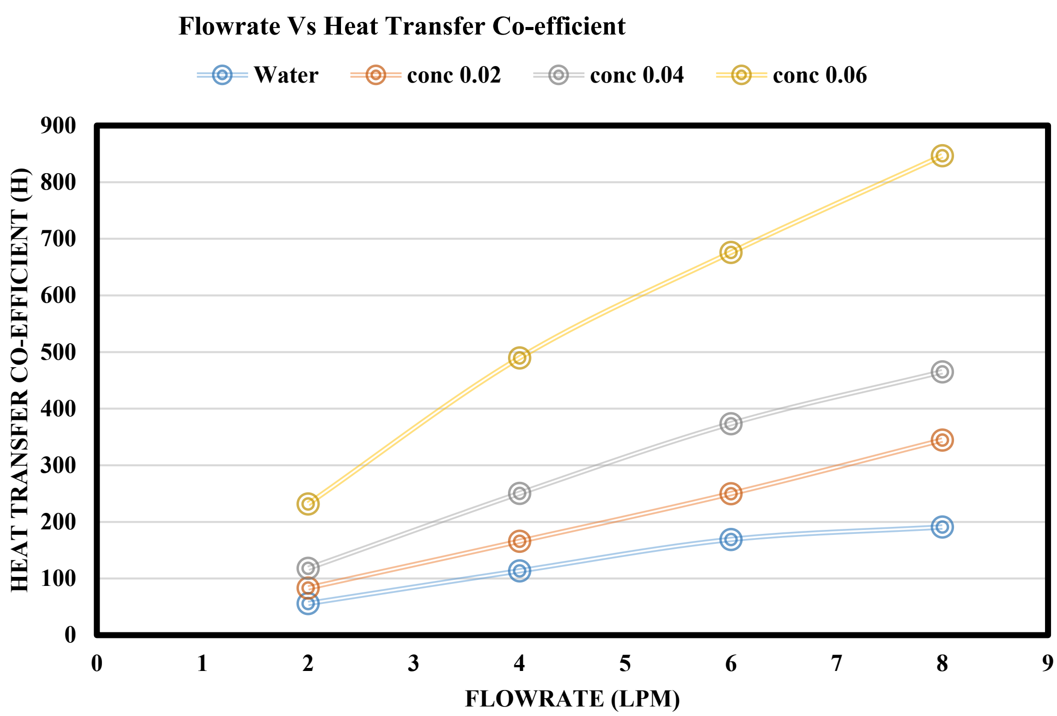

Figure 7. Variation of Heat Transfer Rate with Flow Rate

Figure 8 clearly demonstrates the substantial enhancement in heat transfer performance achieved by hybrid nanofluids compared to pure water, with the improvement being directly proportional to nanoparticle concentration. The lowest concentration (0.02%) yields a significant 37.24% increase in the heat transfer coefficient over water, indicating that even minimal nanoparticle addition can substantially enhance thermal performance. As the concentration doubles to 0.04%, the enhancement jumps to 56.1%, representing a 50% improvement over the 0.02% concentration and demonstrating the non-linear relationship between particle loading and thermal performance. The highest concentration (0.06%) yields the most impressive result, with a 76.4% increase over water, which is more than double the enhancement achieved by the lowest concentration. This progressive improvement pattern (37.24% → 56.1% → 76.4%) reveals that higher nanoparticle concentrations provide increasingly better heat transfer enhancement, likely due to improved thermal conductivity, enhanced particle-fluid interactions, increased Brownian motion effects, and better disruption of thermal boundary layers, making hybrid nanofluids highly effective heat transfer fluids with performance gains that justify their use in applications requiring superior thermal management.

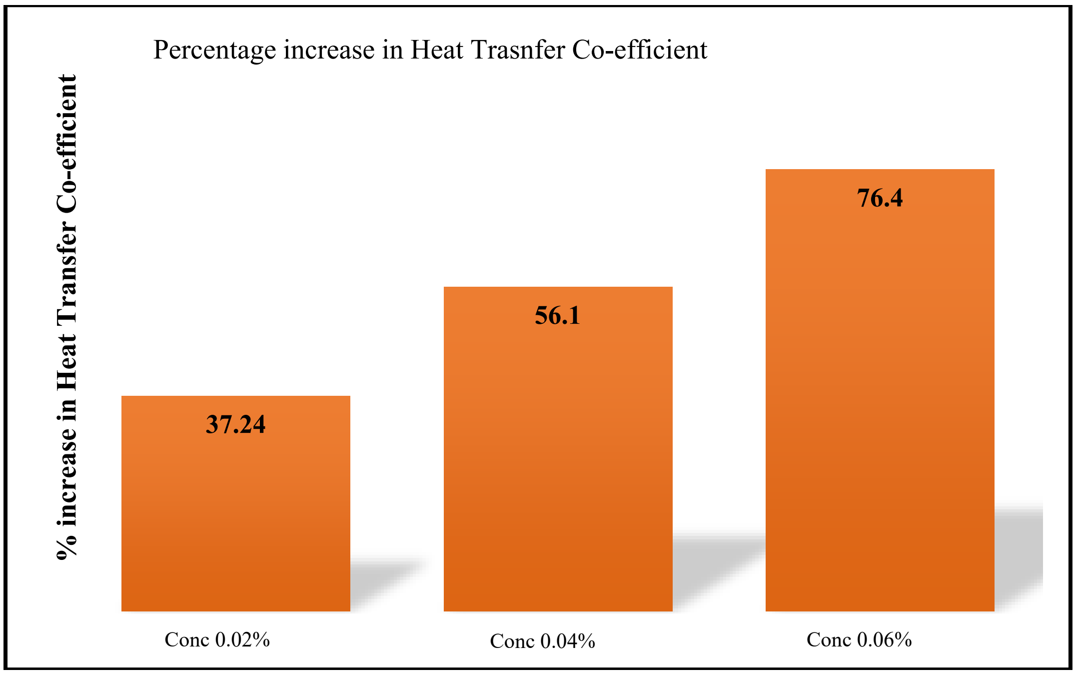

Figure 8. Increased Heat Transfer with respect to Water in Percent

Based on the graphical representation in Figure 9, the superior performance of 0.06% volume concentration Cu-Al_2O_3/Water hybrid nanofluid can be explained through a comprehensive trade-off analysis. The figure demonstrates that while all nanofluid concentrations exhibit higher heat transfer rates compared to pure water, the 0.06% concentration achieves the optimal balance between thermal enhancement and pumping power requirements. At identical pumping power levels, the 0.06% concentration consistently delivers the highest heat transfer rates across the entire operational range, indicating enhanced thermal conductivity and convective heat transfer coefficients due to the synergistic effects of copper and aluminum oxide nanoparticles. However, this performance advantage comes with trade-offs: higher concentrations typically increase fluid viscosity and density, resulting in greater pressure drops and increased pumping power requirements. In comparison, lower concentrations (0.02% and 0.04%) show diminishing thermal enhancement benefits. The 0.06% concentration represents the sweet spot where the thermal performance gains from increased particle loading outweigh the viscosity penalties, maximizing the heat transfer rate per unit of pumping power invested. This optimization is crucial for practical applications where energy efficiency and thermal performance must be balanced, as excessive nanoparticle concentrations beyond this optimal point would likely result in diminishing returns due to particle agglomeration, increased pressure losses, and higher pumping costs that offset the thermal benefits.

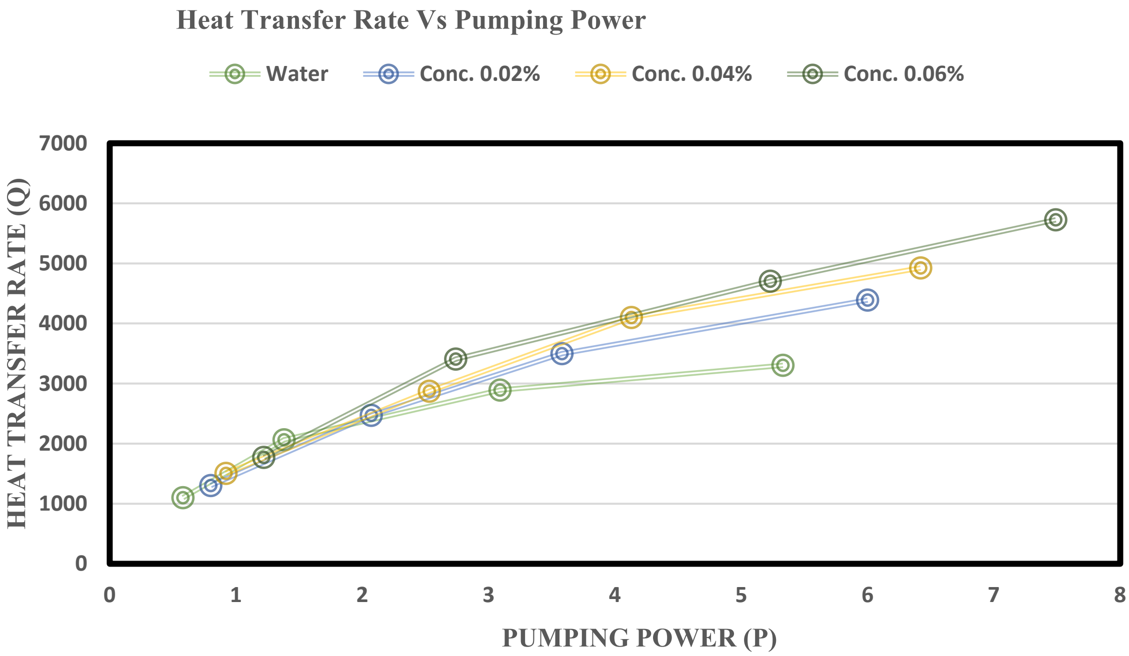

Figure 9. Variation of Heat Transfer Rate with Pumping Power

6. Conclusion

In this work, we examined the convective heat transfer rate, heat transfer coefficient, and pumping power for Cu-Al_2O_3/Water hybrid nanofluid at 0.02%, 0.04%, and 0.06%. The primary goal of this research was to compare the hybrid nanofluid in concern and increase heat transfer as much as possible. Several notable observations and results have arisen from careful testing and analysis, indicating the efficacy of our suggested hybrid nanofluid. Cu-Al_2O_3/water hybrid nanofluids at concentrations of 0.02%, 0.04%, and 0.06% have exhibited higher heat rates and heat transfer coefficients, demonstrating greater effectiveness in providing pumping power compared to water. Among these, the convective heat transfer coefficient and heat transfer rate were greater at a 0.06% volume concentration. Additionally, 0.06% has been more efficient at pumping power because a higher heat transfer rate has been demonstrated for the same pumping power. The maximum heat transfer rate of 66.75% was achieved when 0.06% of the Al_2O_3-Cu/Water hybrid nanofluid was used. In other words, the heat transfer rate has increased when a hybrid nanofluid with a higher volumetric concentration is used instead of water. This has improved radiator cooling efficiency while also increasing engine work rate. At an 8 LPM flow rate, the maximum increase in convective heat transfer coefficient was observed at 76.4% for a 0.06% Cu-Al_2O_3/Water hybrid nanofluid. This observable enhancement highlights the importance of cutting-edge cooling methods, such as the use of hybrid nanofluids as a coolant, in enhancing the radiator's overall performance and viability, as well as that of the engine. A higher volumetric concentration of the hybrid nanofluid has resulted in a notable increase in heat transfer rate at the same pumping power. Overall, our work confirms that using the aforementioned Cu-Al2O3/Water hybrid nanofluid plays a crucial role in enhancing the efficiency and effectiveness of the car radiator, as well as increasing the engine's power output. The improvements demonstrated in the necessary production indicate that the suggested hybrid nanofluid has the potential to enhance the sustainability and viability of most heat exchangers significantly. Our findings suggest that adopting a hybrid nanofluid for advanced cooling can substantially improve the performance of a car radiator.

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Biographies

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Sadia Nourin Mim is a Mechanical Engineer currently working as an Engineer at Abul Khair Group, Bangladesh, and pursuing her M.Sc. in Mechanical Engineering at Chittagong University of Engineering & Technology (CUET). She earned her B.Sc. in Mechanical Engineering from CUET, where her undergraduate thesis focused on the "Experimental Study for Thermal Performance and Pressure Loss Characteristics on a Car Radiator Using Nature (Rice Husk) Based SiO_2 Nanofluid." Her research interests include heat transfer, renewable energy, automotive engineering, and manufacturing optimization. Professionally, she has gained valuable industrial experience through her role at Abul Khair Match Factory Ltd. (Gas Lighter Unit), as well as through internships and site visits at RPCL (Raozan Power Plant) and Four H Group (Dyeing & Printing Ltd.). These experiences strengthened her expertise in production processes, supply chain management, Quality Control and industrial operations. She aims to extend her research toward advanced nanofluid applications and sustainable engineering solutions with a focus on process optimization for broader applications in automotive and industrial systems.

Rupak Saha is a mechanical engineer and M.Sc. candidate at the Chittagong University of Engineering & Technology (CUET), currently serving as an Assistant Engineer (Mechanical Maintenance) at KSRM Steel Plant Limited in Chattogram, Bangladesh. His graduate research focuses on optimizing third-generation microalgae biodiesel production via a two-stage (acid–base) process and evaluating engine performance and emissions for diesel–biodiesel blends enhanced with nano-additives, using statistical optimization (RSM/ANOVA) and rigorous property characterization against standards. Earlier, during his B.Sc. at CUET, he investigated heat transfer enhancement in automotive radiators using MgO–ZnO/water hybrid nanofluids across varying concentrations and reported comparative Nusselt number performance. Rupak's research interests span renewable energy, alternative fuels and biofuels, thermo-fluids, nanomaterials, and composite materials. Beyond research, Rupak brings hands-on industrial experience from KSRM and BSRM, complemented by prior training at Zodiac Power Chittagong. Collectively, his academic, industrial, and leadership experiences position him to bridge laboratory innovation with practical, sustainable engineering solutions.

Itquan Hossen is a graduate mechanical engineer known for being organized, efficient, and passionate about research, with strong analytical skills and a proven ability to adapt to varied engineering challenges. He earned a Bachelor of Science in Mechanical Engineering from the Chittagong University of Engineering and Technology (CUET) in July 2025. His undergraduate thesis, supervised by Professor Dr. Muhammad Mostafa Kamal Bhuiya, focused on optimizing biodiesel production from microalgae (Chlorella vulgaris oil) using response surface methodology (RSM), an area in which he continues to conduct research. Itquan is currently working as a research assistant in the Energy Lab at CUET, specializing in the optimization of biodiesel production from microalgae using advanced modeling techniques like RSM. He has also supported projects on engine performance and emission testing with biodiesel-diesel blends enhanced by nano additives such as TiO_2 and ZnO, demonstrating his hands-on expertise in experimental research and data analysis. He has several publications, including papers and proceedings focused on third-generation biodiesel, engine oil nanofluids, and CFD heat exchanger analysis, with work accepted in international conferences and peer-reviewed journals such as Future Energy. Itquan's professional experience includes an internship at FOUR H Dyeing and Printing Ltd., where he worked with industrial boilers, compressors, and water treatment plants, gaining insight into large-scale process management and environmental compliance.

Ahmad Abdullah Mujahid is a lecturer in Mechanical Engineering at the World University of Bangladesh, with a strong academic and research background in thermal sciences and energy systems. He earned his M.Sc. in Mechanical Engineering through a joint program between the University of Agder (UiA), Norway, and Chittagong University of Engineering & Technology (CUET), Bangladesh, graduating with distinction under the prestigious NORPART-CARE scholarship. His master's thesis focused on assessing the impact of electrode structures on the thermal behavior of 18650 lithium-ion batteries using physics-based modeling, while his bachelor's thesis explored heat transfer enhancement techniques with innovative tube inserts. Ahmad has authored two journal papers and three conference papers, covering areas such as computational fluid dynamics, heat transfer, and numerical methods. Professionally, he has served as Production Engineer at BSRM Wires Ltd. and R&D Engineer at Electro Mart Ltd., gaining hands-on expertise in manufacturing processes, product development, and quality control. His research interests span heat transfer, CFD, additive manufacturing, composite materials, thermal energy storage, and renewable energy.