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EXPERIMENTAL STUDIES ON THE EFFECT OF AL_2O_3+WATER NANOFLUID CONCENTRATIONS ON HEAT TRANSFER COEFFICIENT IN A CLEANROOM AIR HANDLING UNIT

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Abstract— **Nanofluid, a suspension of nanoparticles in a base fluid, is widely employed to enhance heat transfer properties across various industrial sectors. Meanwhile, cleanrooms play a pivotal role in numerous industries, ensuring control over air-borne pollutants and environmental conditions. This study delves into the heat transfer characteristics of a nanofluid consisting of Al_2O_3 nanoparticles suspended in water, investigating various nanoparticle concentrations (ranging from 1% to 4%) within a prototype cleanroom air handling chiller unit under laminar flow conditions. Through experimental analysis, the research demonstrates improvements in heat transfer properties within the chiller unit when employing nanoparticle-infused base fluid. Notably, the study reveals a substantial increase in the heat transfer coefficient, alongside a noteworthy enhancement (ranging from 6.78% to 12.70%) in the ratio of heat transfer coefficient between the Al_2O_3+Water nanofluid and pure water. 10% pressure rise at 4% volume with higher power & 11.61% higher thermal conductivity at 50°C. These enhancements are observed across different nanoparticle concentrations and Peclet numbers, indicating the efficacy of nanoparticle manipulation in augmenting heat transfer efficiency. Importantly, the research's novelty lies in its exploration of the impact of varying nanofluid concentrations on heat transfer parameters within a cleanroom air handling unit, offering valuable insights for optimizing heat transfer efficiency in controlled and critical environments and addressing a significant research gap in the field.**

Keywords— **Cleanroom, Nanoparticle, Nanofluid, Al_2O_3+Water, Heat transfer coefficient**

I. INTRODUCTION

Fluid-based heat transfer is essential in various industrial cooling and heating applications within production and space industries. Unlike solid materials such as metals and metal oxides, traditional heat transfer fluids like water, ethylene glycol, and oil exhibit relatively lower thermal conductivity. However, nanofluids, which involve suspending solid nanoparticles in a base fluid, offer a notable enhancement in heat transfer performance compared to conventional fluids.

Cleanrooms serve as controlled environments for managing airborne, surface, molecular, and microbial contaminants, alongside regulating environmental factors like temperature and relative humidity. Adhering to standards such as ISO 14644-1 and FED-STD-209E [1, 2] cleanrooms find extensive use across various sectors including electronics, semiconductors, micromechanics, optics, biotechnology, food processing, pharmaceuticals, hospitals, scientific research laboratories, and space industries.

Enhancing heat transfer properties in cleanroom air handling chiller units through the use of nanofluids, specifically Al_2O_3+Water nanofluids, presents a promising avenue for improving overall cleanroom performance. By investigating the effects of different concentrations of these nanofluids on heat transfer parameters within the heat exchanger, we can address a significant gap in knowledge. This research has the potential to pave the way for substantial advancements in cleanroom environments, ensuring consistent operational efficiency across diverse sectors.

A cleanroom air handling chiller unit functions as a heat exchanger where water circulates inside tubes while cleanroom air circulates outside. Heat transfer occurs within the heat exchanger, facilitating the exchange of heat between cleanroom air and water, thereby regulating temperatures within the cleanroom.

Nanofluids, a term coined by Choi [3], were initially demonstrated to exhibit a substantial increase in thermal properties upon the addition of suspended nanoparticles to base fluids.

According to Lee et al. [4], the suspension of CuO nanoparticles at a volume concentration of 4.0% in ethylene glycol led to a 20% increase in thermal conductivity.

Theoretical models such as Maxwell [5] are unable to precisely determine the enhancement of heat transfer properties in nanofluids. Therefore, it is crucial to conduct studies on the mechanisms of heat transfer enhancement.

Das et al. (2003) [6] investigated the impact of temperature variation on the enhancement of thermal conductivity in nanofluids. The findings demonstrated a substantial improvement in thermal conductivity, ranging from 2 to 4 times, with temperature variations ranging from 21 to 51 °C.

Wen and Ding (2004) [7] conducted an investigation on heat transfer under constant heat flux conditions along the wall in the laminar zone using Al_2O_3/water nanofluid. The study illustrated that an increase in both the concentration of nanoparticles and Reynolds number led to improvements in the heat transfer coefficient.

Roy et al. (2004) [8] conducted a numerical investigation on the heat transfer characteristics of Al_2O_3/water and Al_2O_3/ethylene glycol nanofluids in the laminar flow zone. The study highlighted a significant enhancement in heat transfer for both types of nanofluids.

Nguyen et al. [8] explored the use of nanofluid (Al_2O_3+water) within a radiator-type heat exchanger, employing a nanoparticle concentration of 6.8%. The results demonstrated a significant 40% enhancement in the heat transfer coefficient compared to conventional fluids.

Teng et al. [9] examined the influence of particle size, temperature, and weight fraction on the thermal conductivity ratio of Al_2O_3+water nanofluids. Various nanoparticles sizes and concentrations were employed, revealing a correlation between smaller nanoparticle size, higher temperature, and increased thermal conductivity ratios. An empirical equation was developed based on experimental data, which accounted for these factors and exhibited good agreement with the results. The margin of error ranged from -3.5% to +2.7%.

Hassaan AM (2022) [10] examined the performance of a shell and tube heat exchanger using multi-wall carbon nanotubes (MWCNTs) and distilled water nanofluid. The study unveiled a notable enhancement in heat transfer across different nanoparticle concentrations.

S. I. Abdelsalam et al. (2023) [11] investigated the performance of zirconium nanoparticles in a slime-like fluid, focusing on understanding bacterial gliding motion. They developed a model using the Rabinowitsch fluid model to represent bacterial motion on surfaces. The study analyzed the impact of factors such as pseudoplasticity and dilatation on zirconium concentration, bacterial velocity, and pressure increase for both Newtonian and non-Newtonian fluids. The findings suggest that increasing zirconium nanoparticle concentration accelerates bacterial flow near the substrate surface but behaves differently elsewhere. This study offers insights into the dynamics of bacterial locomotion in complex fluid environments, with implications for microbiology and nanotechnology.

Muhammad Mubashir Bhatti et al. (2023) [12] underscored the importance of nanofluids in improving heat transfer rates, particularly in renewable energy technologies. They stressed the need for further research to understand the interactions between nanoparticles and base fluids and their impact on heat convection. The text also addressed challenges in developing cost-effective computational tools for predicting nanofluid heat transfer characteristics and called for more experimental investigations, especially in large-scale renewable energy applications like solar thermal collectors and geothermal systems. Additionally, it discussed the broader goal of decarbonizing the energy sector and the role of thermal energy in this transition, emphasizing the significance of carbon-free thermal technologies. Lastly, it introduced a Special Issue aimed at consolidating recent research on nanofluid-enabled heat transfer and its relevance to renewable energy challenges, featuring contributions from numerous scientists across various institutions.

Hamza Babar et al. (2023) [13] investigated thermal management challenges in advanced systems such as electric vehicles, electronic devices components, and photoelectric application modules, particularly focusing on coolants and heat exchangers. They reviewed recent literature on nanofluids and heat exchanger tubes, exploring methods to improve heat transfer. The study emphasized nanofluid performance in various tube geometries and innovative augmentation mechanisms like turbulators and fins. Additionally, it discussed the potential of introducing flow pulsations and magnetic effects to enhance heat exchange, foreseeing promising prospects for highly efficient cooling systems. A bibliometric analysis was conducted to identify emerging trends in integrating nanofluids into heat transfer systems.

Habib Ben Bacha et al. (2023) [14] summarized recent progress in nanofluid research, highlighting their significant property enhancements and diverse applications across industries. Nanofluids, suspensions containing nanoparticles, exhibit remarkable heat transfer capabilities and find use in various sectors. The paper discusses preparation techniques, existing applications, and the need for future research to develop a comprehensive framework for understanding nanofluid characteristics. Overall, it underscores the importance of nanofluids in advancing heat transfer technologies and calls for continued exploration and innovation in the field.

Sara I. Abdelsalam et al. (2023) [15] investigated non-Newtonian nanofluid behavior under peristaltic waves in an asymmetric channel, considering thermal radiation and activation energy. Equations for momentum, mass, and temperature are derived for Sutterby nanofluids. The study analyzes the effects of physical variables on flow features, showing that increasing the temperature ratio parameter enhances temperature and concentration. It also finds that the dimensionless reaction rate increases kinetic energy, leading to higher temperatures. Activation energy and thermal radiation are crucial for cancer treatment, especially in hyperthermia therapy.

Improving the thermal properties of heat-transfer fluids is critical for advancing energy-efficient compact heat transfer equipment. Various techniques have been introduced to enhance heat transfer efficiency. This experiment aims to investigate the effect of different concentrations of Al_2O_3+Water nanofluid on the heat transfer coefficient in a cleanroom air handling unit. The nanofluid utilized comprises Al_2O_3 nanoparticles dispersed in water. The study seeks to examine the impact of nanoparticle size and volume concentrations within the laminar zone to gain a comprehensive understanding of the nanofluid's heat transfer capabilities in cleanroom air handling units.

Research on nanofluid utilization in cleanroom air handling units is crucial due to the increasing demand for energy-efficient heat transfer solutions in diverse industrial applications. Despite advancements in heat transfer techniques, there is still limited understanding regarding the influence of variable nanoparticle concentrations on heat transfer parameters in cleanroom air handling units. While existing literature extensively explores the thermal properties of nanofluids and their potential to improve heat transfer, studies focusing specifically on cleanroom air handling units are lacking. Although some research investigates nanofluid applications in conventional heat exchangers, the unique requirements and strict cleanliness standards of cleanroom facilities necessitate dedicated exploration to assess the feasibility and effectiveness of nanofluid usage.

Research gaps exist in understanding how varying nanoparticle concentrations affect the heat transfer coefficient within the laminar zone of cleanroom air handling units. Additionally, investigating the compatibility and performance of nanofluids in controlled environments is essential, considering factors such as particle sedimentation and fouling risks. To address these gaps, future research should conduct experimental investigations to quantify the heat transfer enhancements achieved by altering nanofluid concentrations within cleanroom air handling units. Computational modeling and simulation studies can complement experimental findings by providing insights into fluid dynamics and heat transfer mechanisms at the microscale level.

The novelty of this research lies in its focus on cleanroom air handling units, where stringent cleanliness requirements and energy efficiency are crucial. By systematically examining the impact of variable nanoparticle concentrations and sizes, this study aims to offer valuable insights into optimizing heat transfer performance in cleanroom environments, ultimately contributing to the advancement of energy-efficient heat transfer technologies.

II. MATERIALS & METHODOLOGY

A. Nanofluids formulation and characterization -

Al_2O_3 nanofluids are chosen for their favorable thermal properties, stability in water-based systems, chemical inertness, non-toxicity, widespread availability, and cost-effectiveness compared to alternative nanomaterials. These attributes make them highly suitable for enhancing heat transfer efficiency in cleanroom air handling units.

Commercially available Al_2O_3 was employed to prepare the nanofluids. Nanoparticles were uniformly dispersed in water using an ultrasonic vibrator, without the use of dispersants or stabilizers. Nanofluids were created using 20nm-sized Al_2O_3 nanoparticles at concentrations of 1%, 2%, 3%, and 4% by volume. The dispersion remained stable without coagulation or deposition for a period of 48 hours.

Table-1 presents essential information regarding the thermophysical properties of both the nanoparticles and the base fluid. These properties are crucial for understanding and analyzing the heat transfer characteristics and performance of the nanofluid in cleanroom air handling units. Thermophysical properties encompass parameters such as density, dynamic viscosity, thermal conductivity, and specific heat capacity, all of which influence the behavior of materials with respect to heat transfer.

Table 1. Thermophysical properties of nanoparticles and base fluid

Thermophysical behaviours	Base Fluid Water	Nanoparticles Al_2O_3 Purity: 99.9%, Size: 40 nm
Density	998.203 Kg/m^3	3970 Kg/m3
Dynamic viscosity	2.01 x10-3 $N.s/m^2$	-
Thermal conductivity	0.613 W/mk	40 W/mk
Specific heat (C_P)	4.1822 KJ / kg.K	0.765 KJ/kg.K

B. Experiment setup–

To investigate the heat transfer process, a scaled (1:50) simulated cleanroom air handling chiller unit test setup was constructed. This setup featured a 1-meter-long annular copper tube with an outer diameter of 9.5 mm and a thickness of 0.8 mm. Within the tube, Al_2O_3 + Water nanofluids were circulated, while air circulated outside the tube. The experimental apparatus included temperature sensors, pressure gauges, a blower, and a pump. Temperature sensors and pressure gauges were positioned at the entry and exit points of the test specimen to measure temperature variations and pressure drop, respectively. Air was circulated outside the test specimen tube in heat exchanger-1 using a blower air handling unit, while nanofluids circulated inside the test specimen in heat exchanger-1.

During the experiment, Peclet numbers were determined and compared using a second set of nanofluids containing 20 nm-sized Al_2O_3 nanoparticles with volume concentrations of 1%, 2%, 3%, and 4%. The experiment was conducted under laminar flow conditions. To prevent heat loss, the external portion of the heat exchanger and environmentally exposed pipelines were insulated with polyurethane foam and glass wool. Thermal conductivity computation was performed using the transient hot wire technique.

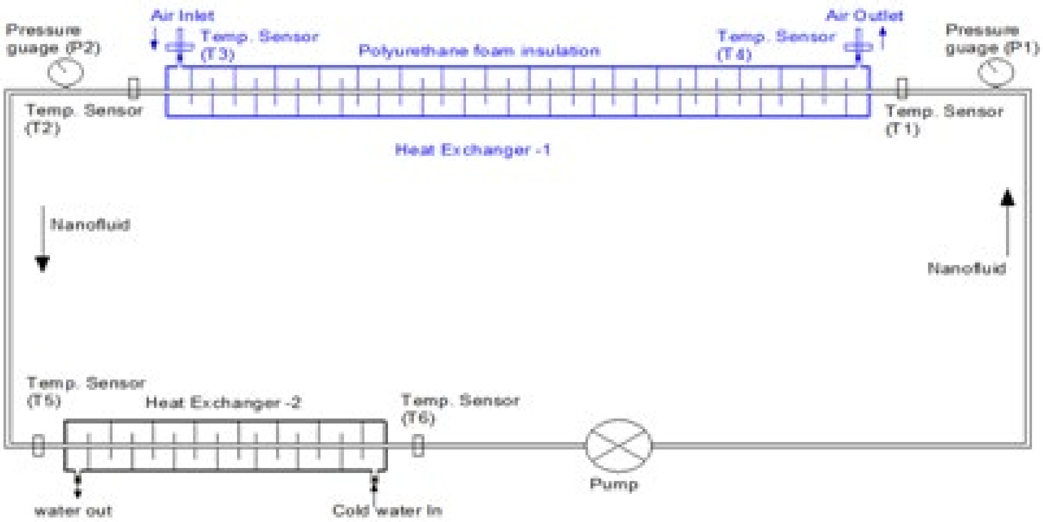

Fig.1. Schematic diagram depicting the experimental apparatus

C. Data Analysis-

The outcomes of the experiments were employed for the computation of the following analyses:

Maxwell's [5] effective thermal conductivity (K_{eff}) is defined as:

$$K_{nf\ Maxwell} = \left[\frac{2K_S+K_W+\phi(K_S-K_W)}{2K_S+K_W-2\phi\,(K_S-K_W)}\right]K_W \tag{1}$$

Where K_s : Nanoparticle's thermal conductivity;
K_w : Water's thermal conductivity.
Φ : Volume fraction of nanoparticle.

The heat transfer coefficient of a nanofluid can be expressed as:

$$\overline{h_{nf}}(exp) = \frac{(C_{Pnf} \cdot \rho_{nf} \cdot \bar{U}.A.(T_2 - T_1)}{\pi.D.L.(T_w - T_b)_{I.M}} \quad (2)$$

Where C_{Pnf} : specific heat of nanofluid;

ρ_{nf} : Density of nanofluid

$\bar{U}$: Average velocity of nanofluid;

L : Length of annular tube (m)

D : Annular tube's diameter (m);

A : Annular tube's cross section area (m^2)

T_{B2} : Outlet's bulk temperature (K);

T_{B1} : Inlet's bulk temperature (K)

T_w : Annular tube's wall temperature

$(T_w - T_b)_{lm}$ denotes difference of logarithmic mean temperature.

The average Nusselt number of a nanofluid can be expressed as: [17]

$$\overline{Nu}_{nf}\ (\mathrm{Exp}) = \frac{h_{nf}\,(exp).D}{k_{nf}} \quad (3)$$

$h_{nf}\ (exp)$: Nanofluid's average heat transfer coefficient.

k_{nf} : Nanofluid's effective thermal conductivity.

Nanofluid Reynolds number (Re_{nf}) can be defined as:

$$Re_{nf} = \frac{\rho_{nf}.\bar{U}.D}{\mu_{nf}} \quad (4)$$

Nanofluid Prandtl number (Pr_{nf}) can be stated as:

$$Pr_{nf} = \frac{C_{Pnf} \cdot \mu_{nf}}{K_{nf}}$$

Peclet Number is defined as (Pe_{nf}) = $Re_{nf} . Pr_{nf}$ (5)

Where, Re_{nf} Is Reynolds number of nanofluid;

μ_{nf} Is viscosity of nanofluid.

The physical properties of the nanofluid were determined as follows: (Drew & Passman, 1999; Yu & Choi, 2003). [16, 17]

Nanofluid density can be derived as:

$$\rho_{nf} = \phi\,.\,\rho_s + (1-\phi).\,\rho_w \quad (6)$$

Where, ϕ is nanoparticle volume fraction.

ρ_s is nanoparticle density; ρ_w is water density.

Nanofluid viscosity can be derived as:

$$\mu_{nf} = \mu_w(1 + 2.5\phi) \quad (7)$$

Where, μ_w Is water viscosity.

The validity of the nanofluid's specific heat is confirmed for particles with a spherical shape and volume fractions below 5.0%. (Drew & Passman,1999). [16]

$$C_{P\,nf} = \frac{\phi.(\rho_s.C_{P_s}) + (1-\phi).(\rho_w.C_{P_w})}{\rho_{nf}} \quad (8)$$

Where,

C_{P_s} : Nanoparticle's specific heat; C_{P_w} : water's specific heat

III. RESULTS & DISCUSSION

The experimental investigation aimed to measure the heat transfer coefficient, as depicted in Figure 2 and calculated using Equation (2). The experiments utilized a series of nanofluids comprising 20 nm-sized Al_2O_3 nanoparticles at volume concentrations of 1%, 2%, 3%, and 4%. Additionally, the Peclet number, calculated using Equation (5), was varied within the range of 2650 to 6100.

Figure 2 illustrates the variation of the heat transfer coefficient of the Al_2O_3+Water nanofluid concerning changes in nanoparticle volume concentration and Peclet number. Notably, an increase in the heat transfer coefficient of the Al_2O_3+Water nanofluid compared to pure water was observed across the different Peclet numbers and nanoparticle volume concentrations. Specifically, the increase ranged from 16.95% to 26.65%, 22.88% to 33.24%, 27.11% to 35.88%, and 34.74% to 50.39% as the Peclet number varied from 2750 to 6100 for nanoparticle volume concentrations of 1%, 2%, 3%, and 4%, respectively.

These findings are of significant importance for optimizing both the design and operational efficiency of heat transfer systems utilizing nanofluids. The observed enhancements in the heat transfer coefficient can be attributed to several underlying reasons.

Firstly, the incorporation of Al_2O_3 nanoparticles into the fluid matrix results in an increase in thermal conductivity. This enhancement facilitates more efficient heat transfer by enabling better conduction of heat within the nanofluid.

Secondly, the presence of nanoparticles increases the surface area available for heat transfer within the fluid. This phenomenon enhances the interaction between the fluid and the heat source, thereby promoting more effective heat transfer.

Moreover, the disruption of thermal boundary layers by the nanoparticles reduces the resistance to heat transfer. Consequently, heat transfer is facilitated across the fluid boundary, leading to higher heat transfer coefficients.

Furthermore, variations in the Peclet number influence the convective heat transfer mechanisms within the fluid. Higher Peclet numbers correspond to greater dominance of convective heat transfer, resulting in more pronounced enhancements in heat transfer coefficient.

Overall, the observed improvements underscore the potential of Al_2O_3+Water nanofluids in enhancing heat transfer efficiency. These results provide valuable insights for further advancements in nanofluid-based heat transfer systems, ultimately contributing to improved energy efficiency and performance optimization in various industrial applications.

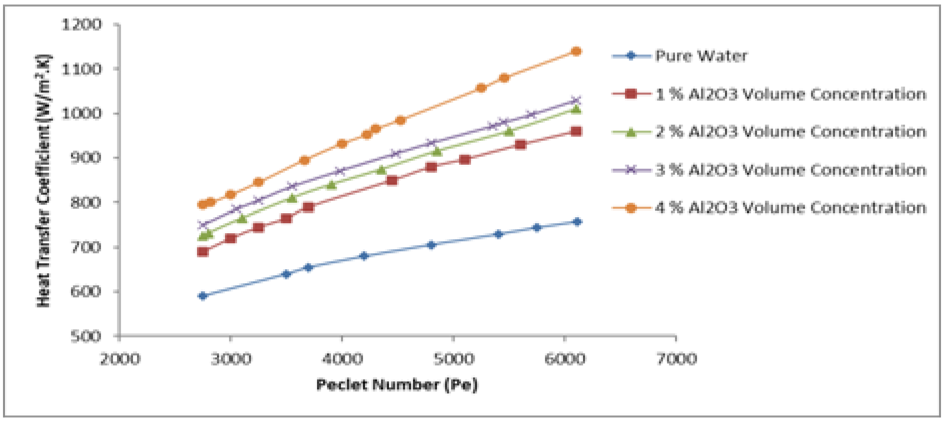

Fig.2. Variation of heat transfer coefficient with varying Peclet number & nanoparticles volume concentration.

Figure 3 illustrates the variation of the heat transfer coefficient ratio of Al_2O_3+Water nanofluid to water concerning changes in nanoparticle volume concentration and Peclet number. The ratio of the heat transfer coefficient of Al_2O_3+Water nanofluid to water was observed to increase with increasing Peclet number and nanoparticle volume concentration.

Specifically, the ratio of the heat transfer coefficient of Al_2O_3+Water nanofluid to water was found to be 6.78%, 9.09%, 12.09%, and 12.70% as the Peclet number varied from 2650 to 6100 for nanoparticle volume concentrations of 1%, 2%, 3%, and 4%, respectively.

These observed trends can be attributed to several underlying factors. Firstly, the inclusion of Al_2O_3 nanoparticles in the water medium leads to enhancements in thermal conductivity, which in turn facilitates more efficient heat transfer within the nanofluid. This improvement in thermal conductivity results in an increased heat transfer coefficient for the nanofluid compared to pure water.

Moreover, the presence of nanoparticles increases the effective surface area available for heat transfer within the fluid. This increased surface area promotes better interaction between the fluid and the surrounding environment, leading to enhanced heat transfer efficiency.

Additionally, the disruption of thermal boundary layers by the nanoparticles reduces the resistance to heat transfer, further contributing to the increased heat transfer coefficient observed in the nanofluid.

Furthermore, variations in the Peclet number influence the convective heat transfer mechanisms within the fluid, with higher Peclet numbers leading to greater enhancements in heat transfer coefficient ratio due to increased dominance of convective heat transfer.

Overall, the observed increase in the heat transfer coefficient ratio of Al_2O_3+Water nanofluid to water highlights the efficacy of utilizing nanofluids for enhancing heat transfer efficiency. These results provide valuable insights for the optimization of heat transfer systems employing nanofluids, ultimately contributing to improved energy efficiency and performance in various industrial applications.

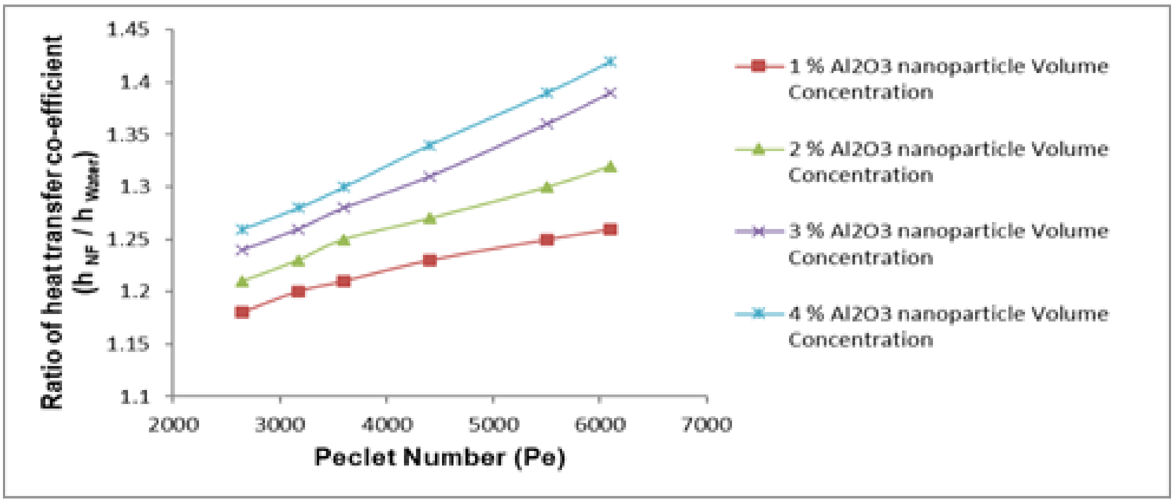

Fig.3. Variation of heat transfer coefficient with varying Peclet number & nanoparticles volume concentration

The research objectives of this study may have been most appropriate for examining the impact of different concentrations of a single type of nanoparticle, specifically Al_2O_3, on heat transfer parameters. By utilizing monofluids, the study could concentrate on assessing the effects of nanoparticle concentration within the environment of a cleanroom air handling unit.

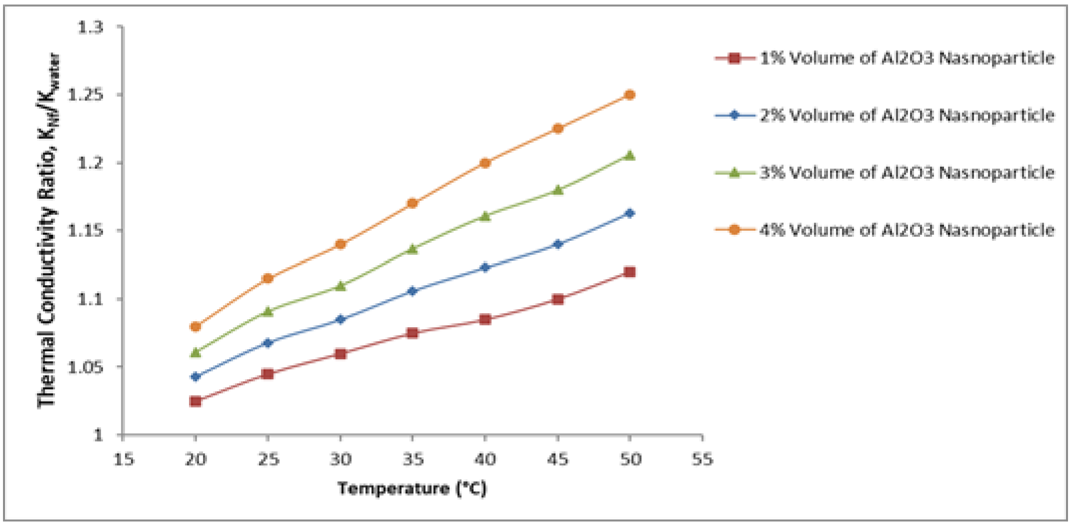

Fig.4. Effect on thermal conductivity ratio with variable temperature & Al_2O_3 nanoparticle volume concentration

Fig.4 illustrates the experimental findings indicate that the thermal conductivity ratio escalates with increasing nanoparticle volume concentrations and temperatures. At a nanoparticle volume concentration of 4%, the thermal conductivity ratio of Al_2O_3+water nanofluid by 11.61% at 50°C. This observed trend underscores the significant impact of both nanoparticle volume concentration and temperature on augmenting thermal conductivity in nanofluids. The superior thermal conductivity ratio for Al_2O_3+water nanofluid, emphasizing the necessity of considering both nanoparticle type and environmental conditions to optimize thermal conductivity in nanofluid-based heat transfer applications.

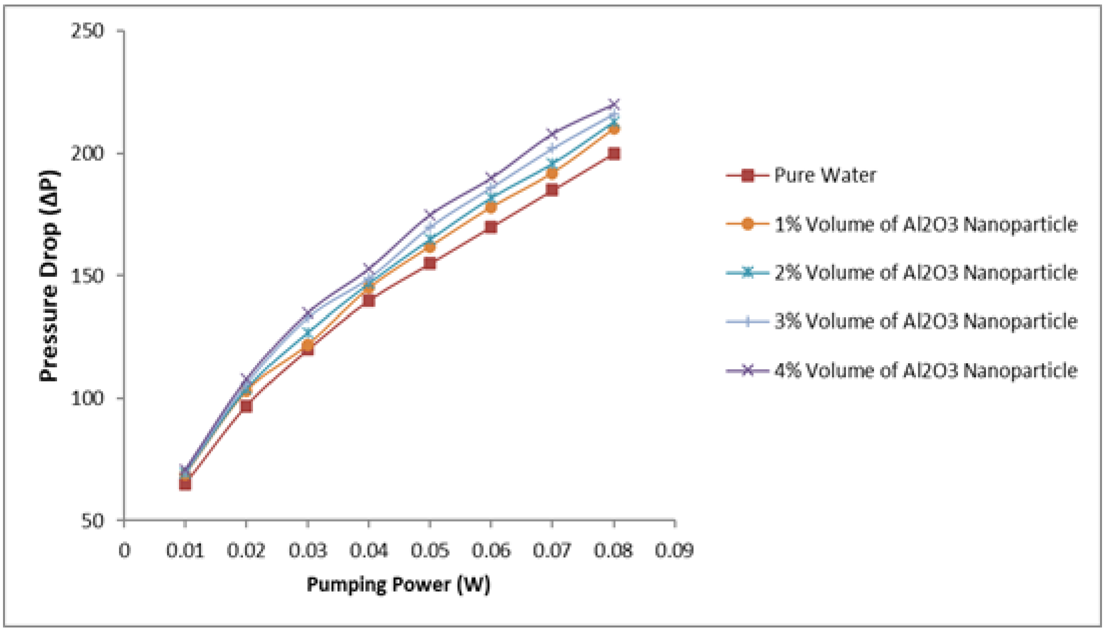

Fig.5 Pressure drop variations at variable pumping power & nanoparticle volume concentration

Fig.5 illustrates the experimental results indicate that both Al_2O_3+water nanofluid experienced increases in 10% pressure drop, compared to water at a 4% nanoparticle volume concentration in a prototype cleanroom air handling unit when subjected to higher pumping power. This observation suggests that heightened pumping power is associated with elevated pressure drop, and differences in nanoparticle properties contribute to the variations observed in pressure drop between different nanofluid compositions.

To summarize, while the current study opted for monofluids to maintain simplicity and control, future research exploring hybrid nanofluids could offer valuable insights into their potential advantages and drawbacks for improving heat transfer in cleanroom air handling units

IV.CONCLUSION

The experimental investigation aimed to analyze the effect of varying concentrations of Al_2O_3+Water nanofluids on heat transfer parameters within a cleanroom air handling chiller unit heat exchanger. The key findings of the study revealed significant improvements in the heat transfer coefficient when using nanofluids compared to pure water. Specifically, the heat transfer coefficient increased by 16.95% to 26.65%, 22.88% to 33.24%, 27.11% to 35.88%, and 34.74% to 50.39% as the Peclet number varied from 2750 to 6100 for nanoparticle volume concentrations of 1%, 2%, 3%, and 4%, respectively. Additionally, the ratio of the heat transfer coefficient of Al_2O_3+Water nanofluid to water ranged from 6.78% to 12.70% with variations in the Peclet number and nanoparticle volume concentrations. Experimental findings show that Al_2O_3+water nanofluid experiences a 10% increase in pressure drop compared to water at 4% nanoparticle volume concentration with higher pumping power, while exhibiting an 11.61% higher thermal conductivity ratio at 50°C. These results highlight the influence of nanoparticle properties on pressure drop and thermal conductivity, emphasizing the importance of nanoparticle type and environmental conditions in nanofluid-based heat transfer applications.

These experimental results provide valuable insights into the intricate relationship between nanoparticle concentration and heat transfer coefficient within the cleanroom air handling chiller unit heat exchanger. By comprehensively exploring this relationship, the study advances our understanding of how nanoparticle characteristics influence heat transfer properties, thereby facilitating further advancements in nanofluid-based heat transfer systems.

The novelty of this research lies in its thorough investigation of the influence of varying Al_2O_3+Water nanofluid concentrations, encompassing a range of nanoparticle volume concentrations, on heat transfer parameters within a cleanroom air handling unit. This comprehensive approach addresses a significant research gap in the field and offers insights into optimizing heat transfer efficiency in controlled and critical environments.

Furthermore, the study sets a foundation for future research endeavors by highlighting the need to address challenges related to pressure drop and exploring strategies to optimize nanoparticle size and concentration distribution within the fluid. Additionally, investigating the long-term stability and reliability of heat transfer systems utilizing nanofluids in real-world applications is essential for advancing their practical implementation.

In conclusion, this study lays the groundwork for further advancements in nanofluid-based heat transfer technologies, providing valuable insights into the complex interaction among nanoparticle characteristics, fluid dynamics, and heat transfer effectiveness. Future research efforts should build upon these findings to develop more efficient and sustainable solutions for heat transfer applications in cleanroom environments and beyond

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