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Performance Evaluation of Vapor Compression Refrigeration System Using Different Types of Condensers Cooling Medium

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ABSTRACT

This research investigates the performance of a vapor compression refrigeration system (VCRS) using different condenser cooling mediums: air, water, and nanofluid containing 0.02% (v/v) titanium dioxide (TiO_2) nanoparticles in water as base fluid. The primary objective is to comprehensively evaluate and compare the performance of these condenser types within the VCRS, aiming to identify the most efficient and eco-friendly condenser cooling medium. The research also explored different mass flow rates of air velocity in the evaporator, ranging from 0.7 to 2.7 m/s. The experimental results reveal that nanofluid-cooled condensers outperform water-cooled and air-cooled condensers in terms of coefficient of performance and cooling effect. This is due to the higher thermal conductivity of nanofluids, which results in a higher heat rejection rate in the condenser. The choice of cooling medium for the condenser depends on various factors such as cost, maintenance requirements, and operating conditions. This research reveals the potential for nanofluids, particularly those incorporating TiO_2 nanoparticles, to significantly enhance the cooling efficiency of VCRS. These findings have important implications for the design and optimization of VCRS systems, ultimately contributing to reduced energy consumption and environmental impact.

1. Introduction

Refrigeration systems play an important role in the modern era, where sustainability, energy efficiency, and environmental responsibility are most important, serving purposes ranging from food preservation to climate control and supporting various industrial processes. The condenser is a critical component responsible for the conversion of refrigerant from vapour to the liquid state and the release of heat. Condenser performance and efficiency are of rare importance as the world is dealing with challenges such as climate change, finite energy resources, and increased environmental consciousness. The search for optimal condenser designs and cooling methods is becoming more urgent as the globe struggles to combat global warming and conserve energy. A basic vapor compression refrigeration system consists of four main parts: the compressor, expansion valve,

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condenser, and evaporator. Since the condenser is the body's outermost component, changing its cooling medium will change the system's cooling capacity, refrigeration effect, and coefficient of performance (COP).

According to the studies, R134a has a higher COP and a lower GWP (Global Warming Potential) than R22 and R407C. Furthermore, R134a is non-toxic, inflammable, and has a low potential for ozone depletion, making it a popular choice for Vapor Compression Refrigeration System (VCRS) [1]. It is frequently observed that a refrigeration system's COP usually drops by 2–4% for every 1°C increase in condenser temperature [2]. Three types of condensers—evaporative, air-cooled, and water-cooled—were compared by Wang *et al.,* [3]. They discovered that the water-cooled condenser had the best cooling capacity and COP after maintaining constant temperatures. A water-cooled condenser's COP ranged from 1.5% to 10.2% higher than that of an air-cooled condenser, and an evaporative condenser was 14.3% higher. To verify mathematical models for forecasting the performance of air-cooled and water-cooled air conditioners in a residential building in Hong Kong, Lee *et al.,* [4] compared the coefficient of performance of these types of air conditioners. Chen *et al.,* [5] conducted a comparison between air-cooled and water-cooled air conditioners and found there may be advantages to adopting water-cooled air conditioners in subtropical cities, as demonstrated by the 17.4% higher average COP and estimated 8.7% decrease in electricity consumption of water-cooled systems. Evaporative cooling methods, such as water spraying or wet pads, can lower the external ambient temperature and increase the COP [6]. Harby *et al.,* [7] investigated evaporative condensers in residential cooling systems. By comparing various types of condensers, he concentrated on energy consumption and its complications. This means that the various authors compared all three condensers in terms of performance coefficient, energy consumption, refrigeration capacity peak power.

Mixing nanoparticles with a base fluid can alter its thermo-physical properties, given that nanoparticles typically have higher thermal conductivity than the base fluid [8]. Ahmed *et al.,* [9] investigated the use of nanofluids (Al_2O_3, TiO_2, and Al_2O_3/TiO_2 hybrid) in a chilled water air conditioning unit connected to a vapour compression refrigeration system and found that Al_2O_3/H_2O nanofluid outperformed TiO_2/H_2O in terms of cooling performance and coefficient of performance. Chandraprabu *et al.,* [10] investigated the use of Al_2O_3/water and CuO/water nanofluids in an air conditioning system at 1%, 2%, 3%, and 4% concentrations. These nanofluids are well-known for improving heat transfer. CuO/water outperformed Al_2O_3/water due to higher heat transfer coefficients, owing to increased nanoparticle concentration. Hussain *et al.,* [11] used Al_2O_3 nanofluid in distilled water to improve the VCRS COP. At different temperatures, they tested three Al_2O_3 concentrations (0.01%, 0.005%, and 0.001% by weight). At 28°C, the COP of the respective Al_2O_3 concentrations increased by 25.7%, 17.46%, and 11.74% when compared to the conventional fluid. In research by Nabil *et al.,* [12], the heat transfer coefficient was shown to be enhanced by the addition of TiO2 nanoparticles. The study also examined the friction factor and heat transmission of TiO2-SiO2 nanofluids in a water-ethylene glycol combination. Huang *et al.,* [13] investigated water-cooled and air-cooled condensers in residential refrigerators. The water-cooled condenser outperformed the air-cooled one in terms of COP, owing to improved convective heat transfer on the air side, which reduced the compressor's workload. According to the findings [14], combining O-DTs with a twist ratio of 1.5 and a nanofluid containing 0.21% TiO_2 results in a significant heat transfer improvement ranging from 9.9% to 11.2%. Furthermore, thermal performance improves by up to 4.5% when compared with the use of O-DTs independently. Typically, conventional liquids such as ethylene glycol, water, and various oils typically have low thermal conductivity [16]. However, adding various kinds of nanoparticles to the base fluid raises the fluid's potential for heat transfer and improves their thermal conductivity, which is directly related to stability [15-17]. Mishra [19] investigates that using Al_2O_3-water nanofluids as a secondary fluid can increase system performance by 17% to 20%. Such a form of analysis can be beneficial for comparing the thermal performance of several nanoparticle-based nanofluids (Cu, Al_2O_3, TiO_2, and CuO) as a secondary fluid in a VCRS. Various condenser types and techniques, such as sprays, subcooling, and hybrids, are used to improve efficiency in vapour compression refrigeration systems. The goal is to reduce power consumption while increasing the performance coefficient [20]. Preparing more stable and homogenous nanofluid is still one of the hardest things to do in the field of nanofluids because of the strong Van der Waals contact between particles [16–18]. Breaking down the agglomeration of nanoparticles is crucial for improving the stability of nanofluid. Yiamsawas *et al.,* [21], According to his findings, the application of surfactants is another approach for stabilizing nanofluids, which can play an essential role in lowering liquid surface tension. The impact of SDS and NP-9 surfactants on the aggregation and stability of titanium dioxide nanoparticles in various aqueous environments was investigated in this study. The results showed that both surfactants, especially SDS, decreased aggregation, suggesting that TiO2 nanomaterials' environmental behaviour may change [22]. Kakati *et al.,* [23] used deionized water and a 0.03% SDS solution to create an Al_2O_3 nanofluid with a volume content ranging from 0.1% to 0.8% and temperatures ranging from 10 to 50 degrees Celsius. As a result, the nanofluid was stable for a period of 4-5 days. However, in the absence of surfactant nanoparticles, it tended to sediment after just 1 hour of preparation.

According to a review of the literature, there is a research gap since there is presently no study that evaluates the performance of refrigeration systems using three distinct condenser types: air-cooled, water-cooled, and nanofluid-cooled. The experimental performance of systems with different types of condensers coupled to the same refrigeration cycle is investigated in this study. The same refrigeration cycle was coupled with each condenser type at a time and tested under the same conditions. The performance characteristics of the systems, such as refrigeration capacity, power consumption, coefficient of performance, and were then compared.

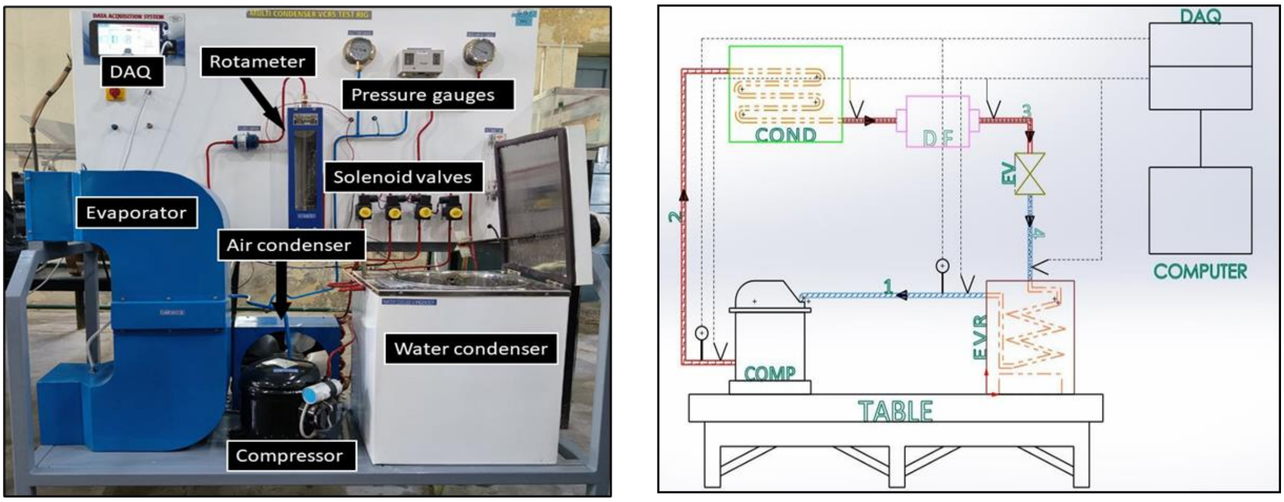
2. Methodology

2.1 Experimental Setup and Its Working

The experimental configuration comprises four fundamental components: the compressor, evaporator, expansion valve, and condenser. The condenser plays a pivotal role in this research. Three distinct types of condensers are utilized specifically air-cooled, water-cooled, and nanofluid-cooled condensers. In the case of the water-cooled condenser, a continuous circulation of water and nanofluid is maintained to optimize heat dissipation. It is important to note that the core components used in all experimental units are the same. Figure 1(a) illustrates the experimental setup, with clear labeling of all components and Figure 1(b) shows the schematic diagram of the experimental setup. Water condenser serves as nanofluid cooled condenser when nanofluid is used as the coolant. In all three units, R134a is used as a refrigerant.

2.2 Components and Specifications of Experimental Set-up

The experimental setup for the multi-condenser VCRS comprises an air-cooled condenser, a water-cooled condenser, a capillary tube expansion valve with the specification of a diameter of 0.55 inches, and a length of 7 feet which is double folded to enhance its efficiency, and a hermetically sealed reciprocating compressor with a 1/2 TR refrigerant capacity. The air-cooled condenser is designed with finned tubes featuring 11*12*3 rows, whereas the water-cooled condenser has a 12-liter capacity featuring immersed copper coils with a 3/8-inch pipe that spans 40 feet in length. The evaporator, duct outlet area of 0.160*0.160 m^2, is a duct-type unit with forced suction and an outlet. A digital anemometer measures the velocity of the air within the duct.



(a) (b)

Fig. 1. Experimental setup (a) Pictorial view of VCRS with multi-condenser and (b) Schematic diagram

The refrigerant flow cycle begins in the evaporator, where heat is absorbed and evaporated by the low-pressure, low-temperature vapour. Following that, the refrigerant is drawn into the compressor and compressed to a high pressure and temperature. The refrigerant then moves to the condenser, where it condenses into a high-pressure liquid after releasing heat. Following that, it flows to the expansion valve, which is throttled to low pressure and temperature, with some of it flashing (evaporating) to improve efficiency. The cycle is completed when the refrigerant returns to the evaporator. Electronically controlled solenoid valves regulate refrigerant flow between the air-cooled and water-cooled condensers, facilitating testing with different condenser types and coolants.

2.3 Measuring Instruments

The data acquisition system (DAQ) is the digital data analysis system used for capturing observational data. An array of precision measuring instruments is being used to collect relevant data. These instruments include a flow meter, which measures refrigerant flow rates. Pressure sensors strategically placed throughout the refrigeration cycle monitor pressure levels at critical junctions. Furthermore, thermocouples are used to measure temperature variations at various points throughout the system, which indicates the temperature distribution and changes during the cooling process. The data acquisition system is the central component of this system, an electrical control panel with a 7-inch touch display for measuring and controlling critical compressor input variables such as voltage and current. Furthermore, it monitors pressures and temperatures in real-time at key system points such as the compressor, condenser, evaporator, and expansion valve. This system is added by LabView-based PC software, which allows for precise control and graphical representation, as well as seamless data transfer via USB 2.0, providing a comprehensive and complex data capture solution for the research work.

2.4 Nanofluid and Its Preparation

The utilization of TiO_2 nanoparticles (Titanium Dioxide Rutile Nano-powder) in the preparation of nanofluids is motivated by several key advantages. Firstly, TiO_2 nanoparticles exhibit remarkable thermal conductivity, enhancing the efficiency of heat transfer in various applications such as cooling systems and heat exchangers. Moreover, the stability and dispersion of TiO_2 nanoparticles are noteworthy, especially when combined with Sodium dodecyl sulfate (SDS) surfactant, as they form stable and well-dispersed colloidal solutions, ensuring prolonged stability and effective utilization. Furthermore, the cost-effectiveness and abundance of TiO_2 as a material make it a highly favorable choice for nanofluid applications, offering an economical alternative when compared to more expensive options [21].

The preparation of TiO_2 nanofluid using water as the base fluid is a precise process, in which initially nanoparticles are measured accurately, considering the concentration and size of the nanoparticle, and then measured TiO_2 nanoparticles added to distilled water, properly mixed, or dispersed through sonication as shown in Figure 2. A surfactant is optionally added for stability, and finally, a homogeneity check is performed to ensure consistent distribution.

Fig. 2. Preparation of nanofluid in Sonicator

2.5 Properties of Nanofluid

It is important to find out the required weight of nanoparticles and surfactant for the correct preparation of nanofluid. The concentration of nanoparticles and surfactant used in nanofluid is 0.02% (v/v) and 0.02% (v/v) respectively which were calculated by using the properties of nanoparticle and surfactant mention in Table 1 below.

Table 1
Properties of nanoparticle and surfactant

Properties	Values
Density of nanoparticle	4175 kg/m^3
Molecular weight of nanoparticle	79.87 u
Size of a particle of nanoparticle	20nm
Density of surfactant	1010 kg/m^3

2.6 Performance Parameters

VCRS essential factors such as air duct area, air density, specific heat, power factor, refrigeration effect, compressor power, and COPs are evaluated in Eq. (1) – (4). The refrigeration effect is determined by the air mass flow and the specific enthalpy. These variables are critical for improving VCRS efficiency and cooling.

Outlet air duct area = 0.160 m * 0.160 m
Density of air ρ_w = 1.26 kg/ m^3
Specific heat of air C_p = 1.005 KJ/kg K
Power Factor cos φ = 0.8

Cooling effect, $CE = \mathrm{m_a} * \mathrm{C_p}(\mathrm{T_5} - \mathrm{T_6}) \frac{Kj}{Sec}$ (1)

Where, ma = mass flow rate of air in kg/s
= Inlet air Duct area x density of air x Velocity of air
= 0.160m*0.160 m*1.26 kg/ m3 * $\dot{V}$
= 0.032256*$\dot{V}$ (Kg/s)

Compressor Input, $CW_{Act} = \frac{V*I*\cos\phi}{1000}$ (KW) (2)

Where, V = Input voltage to the compressor in Volts
I = Input current in Ampere

Actual, $COP_{Act} = \frac{CE}{CW}$ (3)

Theoretical, $COP_{Theo} = \frac{RE_{Theo}}{CW_{Theo}} = \frac{h_1-h_4}{h_2-h_1}$ (4)

The specific enthalpies h_1, h_2 and h_3 can be determined by locating points 1, 2, and 3 on the Pressure-Enthalpy (P-h) diagram from a refrigeration chart. This involves using the corresponding pressure-temperature pairs (P_1,T_1), (P_2,T_2), and (P_2,T_3). Once these points are marked on the P-h diagram, the specific enthalpies h_1, h_2, and h_3 (where h_3=h_4 for a refrigeration cycle) can be read from the chart.

3. Results and Discussion

We have conducted a thorough comparison of three distinct condenser types: the air-cooled condenser, the water-cooled condenser, and the nanofluid condenser. In this study, the impact of varying air velocities and the choice of coolants within water condensers were observed and their consequential effects on crucial performance parameters of VCRS system. All the experimental data has been recorded when a steady state has been achieved.

3.1 Influence of Air Velocity on the Cooling Effect for Three Different Types of Condensers

The effect of evaporator air velocity on the cooling effect of a VCRS using different condenser cooling mediums: nanofluid, water, and air is shown in Figure 3. For all three mediums, the graph clearly shows a linear relationship between evaporator air velocity and cooling effect, but the increase in cooling effect is more pronounced with nanofluid.

At an evaporator air velocity of 2.2 m/s, the percentage increase in cooling effect with nanofluid condenser exceeds that with water by 28% and significantly outperforms air by 37%. Because nanofluids have higher thermal conductivity than conventional fluids, they can transfer heat from the condenser to the surrounding environment more efficiently. This lowers the condenser temperature, allowing the compressor to compress the refrigerant to a higher pressure. This higher-pressure refrigerant has a greater cooling capacity, resulting in the observed increase in cooling effect.

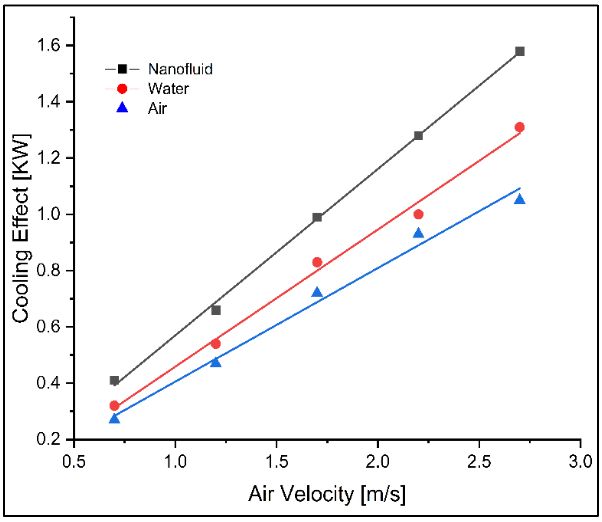


Fig. 3. Cooling effect *vs* air velocity

3.2 Influence of Air Velocity on Theoretical Coefficient of Performance (COP) for Three Types of Condensers

To improve the energy efficiency of air conditioning systems, an investigation into the effect of air velocity on theoretical COP was carried out. Figure 4 depicts the change in theoretical COP with changing air velocity. As shown in the graph, the COP of the air conditioner increases in direct proportion to the increase in air velocity passing over the evaporator coil. This observation can be attributed to increased turbulence in the airflow, which allows for more extensive interaction between air molecules and the surface of the evaporator coil. As a result of this increased interaction, the heat transfer rate between the evaporator coil and the incoming air accelerates, resulting in increased heat absorption capacity and, as a result, increased cooling capacity of the system.

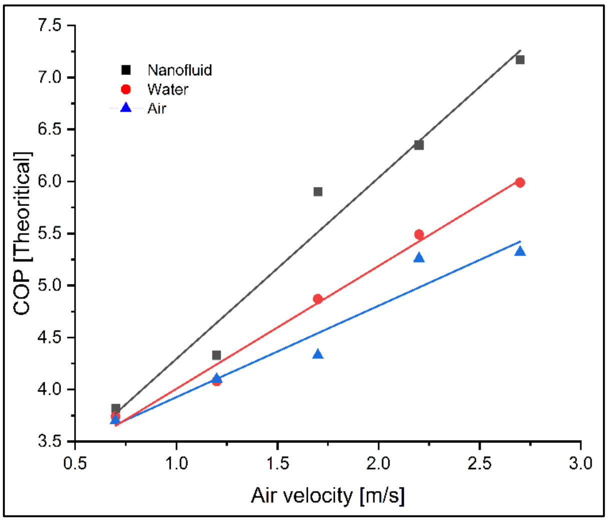


Fig. 4. Theoretical COP comparison for air, water and nanofluid as cooling medium

At an air velocity of 2.2 m/s, the COP when using nanofluid as the condenser cooling medium is 16% higher than when using water, and an impressive 20% higher than when using air.

3.3 Influence of Air Velocity on Actual Coefficient of Performance (COP) for Three Different Types of Condensers

Similarly, the effect of air velocity on actual COP was investigated, and the results are shown in Figure 5. The data show that as the air velocity over the evaporator coil increases, so does the actual COP. This phenomenon mirrors the effect of air velocity on theoretical COP, highlighting the importance of air velocity in system performance. However, the actual COP of the nanofluid-cooled condenser consistently outperforms that of the other two condenser types. This advantage is due to the nanofluid's significantly higher heat transfer coefficient when compared to traditional cooling media such as water and air. This increased heat transfer coefficient improves the efficiency of the refrigerant condensation process inside the nanofluid-cooled condenser.

At an air velocity of 2.2 m/s, the COP increase when using nanofluid as the condenser cooling medium is 37% greater than when using water, and 57% greater than when using air. This empirical findings confirm nanofluid's remarkable potential as a condenser cooling medium and highlight the importance of optimizing this critical component in air conditioning system design for maximum efficiency.

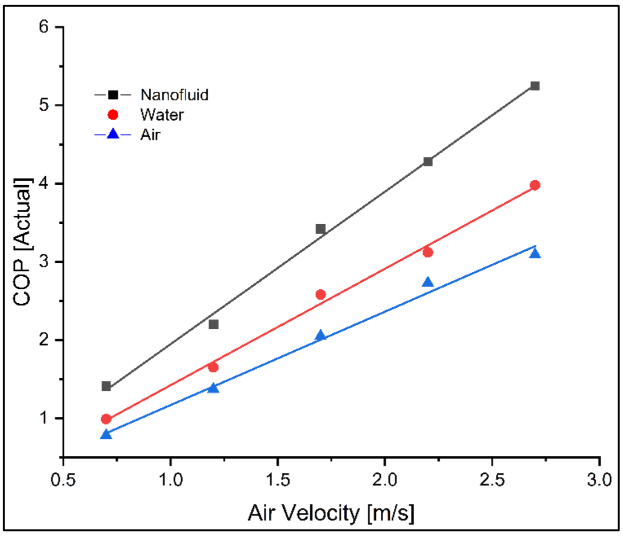


Fig. 5. Actual COP comparison for air, water and nanofluid as cooling medium

3.4 Influence of Air Velocity on the Power Consumption for Three Different Types of Condensers

Figure 6 shows a graphical representation illustrating how the power consumption of the compressor, measured in kilowatts (kW), changes with varying air velocities.

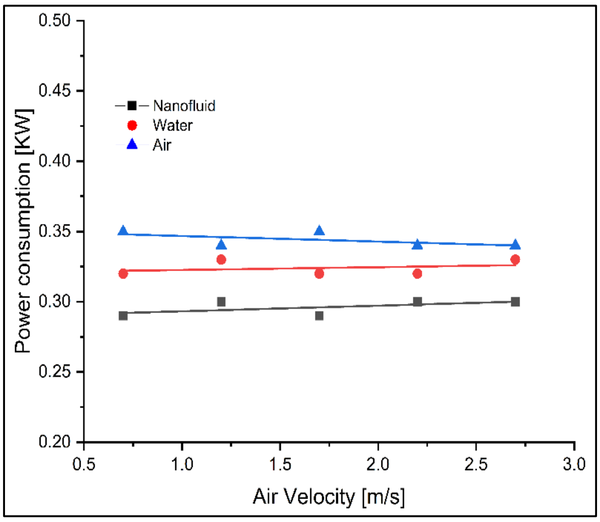


Fig. 6. Power consumption by compressor

The results show a consistent trend. It is evident that the condenser cooled with nanofluid consistently required less power compared to condensers using either water or air for cooling.This reduction in power consumption can be primarily attributed to the superior heat transfer properties exhibited by nanofluids. The use of nanofluids in the cooling process enhances the efficiency of heat transfer and heat rejection within the system. As a result, the compressor can operate with a reduced workload.

4. Conclusions

Our experimental study highlights the exceptional performance of nanofluid, which demonstrated superior heat transfer capabilities as compared to traditional air- and water-cooling methods. Following are the key points which are drawn from our work:

- The standout performance is attributed to nanofluid condensers, particularly those incorporating TiO_2 nanoparticles.
- At an air velocity of 2.2 m/s, nanofluid condensers demonstrated a remarkable 28% higher cooling effect compared to water and an impressive 37% improvement over air.
- Theoretical Coefficient of Performance (COP) saw a substantial 16% increase with nanofluid compared to water and an exceptional 20% increase compared to air at the same velocity.
- In the context of actual COP, nanofluid-cooled condensers consistently outperformed other condenser types, with a 37% increase over water and an impressive 57% increase over air at an air velocity of 2.2 m/s.
- The use of nanofluids led to a significant 12% reduction in power consumption when compared to water-cooled condenser and a remarkable 17% decrease when compared to air-cooled condenser, indicating improved energy efficiency.

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