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Exergy Based Performance of Hybridized-Nanofluids Zeotropic Blend as Refrigerant in Aircraft Cooling Systems

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Abstract: The vapour compression refrigeration (VCR) and air compression machine (ACM) exist and are currently in use in the aircraft cooling system, they were considered cheap and lightweight. However, the process results to stress on the aircraft, overheating, heat exchange fouling and in most cases, wear and tear on the aircraft. To curb the occurrence of these issues, the paper carried out an exergy-based analysis on the hybridized-nanoparticle zeotropic blend (HNZB) as a refrigerant to the aircraft refrigeration system to obtain the possibility of using the HNZB refrigerant as a suitable alternative to the exiting compressed air refrigerant. Aside from the exergy-based metrics such as exergy destruction, exergy efficiency and the coefficient of performance (COP) used in determining the performance of the refrigerants to the aircraft refrigeration systems, temperature during the cooling process, temperature of the refrigerants during the aircraft refrigerating process, entropy and the enthalpy during the cooling process were utilized in measuring the performance of the refrigerants. Postulates were made and the system was monitored for 14 minutes. From the results generated, the temperature of the cooling system at the 14th minute was 80.8^{0}C and 62.33^{0}C when air and HNZB refrigerants were utilized respectively. At the cooling process, the temperature of the air and HNZB refrigerants were 52.21^{0}C and 49.01^{0}C, entropy was 898.3kJ/^{0}C and 400.17kJ/^{0}C, enthalpy was 344.54kJ/kg and 151.21kJ/kg for the air and HNZB refrigerants respectively, which indicated the higher stability of HNZB than the air refrigerants. From the outcome of the exergy-based analysis carried out, at 14th minute of monitoring the aircraft cooling system, the COP was 0.992 and 1.19 when air and HNZB refrigerants were utilized respectively which showed that HNZB performed more efficiently. The trend of exergy distribution showed that the outcome with air as the refrigerant was higher than the exergy destruction with HNZB (669kJ and 452kJ respectively) which showed that air was more spontaneous and less stable than HNZB refrigerant and when measured with exergy efficiency, it was found that HNZB refrigerant performed better (78%) than the air refrigerant (62.44%), which implied that HNZF is more suitable and stable as an aircraft refrigerant than air. It was recommended that the optimum performance of HNZB when utilized in the aircraft refrigeration system should be determined using empirical model and optimization technique.
Keywords: *HNZB, air, refrigerants, exergy, analysis, COP, temperature, temperature, entropy, enthalpy*

I. Introduction

Hybridized-nanofluids zeotropic fluids (HNZF) is majorly used in the heat transfer and refrigeration systems and contains a mixture of two working fluids representing a distinct concept in thermal and aeronautical engineering. In aeronautical engineering, the HNZF is used as a coolant to the air-crafts. Hybridized Nanofluids can be defined as a new concept in heat transfer in fluid engineering as it contains two or more types of nanoparticles and the possible nano particles can be Al_2O_3, TiO_2 and CuO and other oxides of high affinity metals. The essence of carrying out a hybridization process is to obtaine a Synergistics effect that could possess a high thermal property such as improved heat transfer and improved thermal conductivity over the existing coolant fluids with single nanoparticles (Bigi& Cremaschi, 2019).

Currently, air cycle machines (ACMs) are the cooling systems in aircrafts with compressed air used as the refrigerant. To achieve this process, the air is sucked in the machine, compressed, cooled and expanded, with the intent of making air safe, lightweight and cheap. However, due to stress involved in utilizing air as the refrigerant to the aircraft, it usually results to overheating primarily due to low airflow, heat exchanger fouling leading to loss in efficiency as a result of particulates blocking the airflow, continuous occurrence of wear and tear and reduction in CoP (coefficient of performance). It must be indicated that the implementation of ACMs requires high running cost, high air flow but ensures reduction in cabin pressurization and weight savings (Merzvinskas et al., 2024).

Because of these issues existing in the utilization of air as refrigerant to the ACMs in an aircraft, the use of hybridized-nanofluid zeotropic blend was proposed and the exergy performance of the existing coolant and the proposed coolants was determined. Exergy based performance analysis is a thermodynamic concept that exceeds the known energy accounting of the first law of thermodynamics but details the usefulness and quality of the energy implemented in any process systems by determining the area that results to the highest form of exergy destruction (energy degradation) and obtain the thermodynamic irreversibility to be utilized as guidelines for the energy improvements. Exergy performance determination utilizes the second law of thermodynamics for the measurement of the work output, indicating how the process deviate from the ideal efficiency and this analysis is essential for the optimization of complex systems such as cooling systems, power plants and solar related thermal plants. The efficiency of exergy based analysis on complex systems made it essential for the determination of the efficiency of the hybridized nanofluids zeotropic fluids as coolants to the aircraft cooling systems.

Hence, in this paper, the level of exergy destruction and exergy efficiency of the HNZF and other coolant such as air were determined to obtain the level of the effective conversion of the coolants into useful energy products. Additionally, the coefficient of performance (COP) for the two refrigerants was determined.

II. Literature Review

Laboratory test has been carried out by various authors on the properties of the hybridized- nanofluid zeotropic blends (HNZB) and many findings discovered has been presented. According to Senthilkumar(2025), HNZB possesses a significant thermal conductivity increase with a Synergistic effect which was largely attributed to the combination two and more different nanoparticles which resulted to superior heat transfer capability. Ahmed(2021) found that the addition of nanoparticles increases the viscosity and concentration of the refrigerant which improves the flow parameters and pressure drop, needing a trade off for optimal performance. Pereira et al (2023) found that the density of the solid nanoparticles is always higher than that of the base fluids which results to increase in density of the refrigerant but maintained that the density of the refrigerant was dependent on the volume and type of the concentration of the nanoparticles. The experimentation carried out on the specific heat of the HNZB by Udofia& Ikpe(2024) showed that the specific heat of the refrigerant was lower than the specific heat of the base fluid. This was due to low specific heat possessed by the nano particles. Srouet al (2025) used surfactants and functionalization to test for the stabilization of the HNZB and found the refrigerant to be highly stable and is resistant to agglomeration. This implies that the HNZB is essential and can be utilized for a long duration of operation. The research carried out by Bigi& Cremaschi(2019) showed that as refrigerants, HNZB are energy efficient and also environmentally and atmospherically friendly making the blends suitable rather than the existing CFCs (chlorofluorocarbons) and the HCFCs (hydrochlorofluorocarbons) that are known to be harmful refrigerants. Generally, the use of HNZB as a refrigerant result to high system efficiency when applied especially as an aircraft refrigerant largely due to its convective heat transfer properties.

Ikpe et al (2023) noted that the properties of the HNZB can be adjusted by varying most of its factors such as the particle size, particle type, concentration of the volume and the zeotropic fluid blend compositions. The type of HNZB utilized in this paper was the optimal outcome projected in Udofia and Ikpe (2024) with outcome showing that the equal combinations of TiO_3/Al_2O_3/CuO blend with each of the component containing about 7.5grams. This was chosen because the author (Udofia and Ikpe, 2024) found the HNZB fluid to perform better than the VCRS (vapour compression refrigeration system). Furthermore, Bhattad et al (2018) reported the importance of HNZB when utilized as a refrigerant and other working fluids in system especially, in the area of cooling system, HNZB improves the thermal characteristics of cooling systems via efficient heat transfer coefficient, viscosity and thermal conductivity resulting to decrease in the level of energy intake of the cooling systems (in aircrafts). The exergy performance assessment of the HNZB as refrigerant replacement to the VCRS was carried out by Akanimo et al (2022), with optimum temperature of the evaporator achieved being -7^{0}C with consumption of 0.942kW and work input in compressor of 0.888kJ/kg. leading to the thermal conductivity performance heat transfer of 0.962W/m.K. All the outcome of the references utilized in the literature points to the fact that HNZB is reliable and is energy efficient when utilized as a refrigerant to the aircraft.

III. Methods

The exergy performance analysis of the HNZF and the air refrigerant on the aircraft cooling system were the major metrics utilized. Hence, the paper centers on the utilization of mathematical models for the determination of exergy-based performance analysis of these refrigerants. The following postulation were made.

i. The cooling process in the aircraft when the refrigerants were utilized was centered on the second law of thermodynamics, through Gouy-Stodola Theorem.
ii. The aircraft cooling system process was a steady state closed system.
iii. The relationship between the entropy (X) and the exergy (Ex) was constantly maintained.
iv. The cooling process in an aircraft is not a reversible process.

According to the second law of thermodynamics that states that the total disorder of the isolated system (entropy) always increases overtime which meant the energy flows from hotter to colder objects which remains a natural phenomenon. Hence;

$$\Delta X_{total} \geq 0 \tag{1}$$

And

$$\Delta X_{total} = \Delta X_{system} + \Delta X_{surroundings} \tag{2}$$

Since the cooling process in an aircraft is an irreversible process, it implies that;

$$\Delta X \neq 0 \tag{3}$$

Equation 3 is so because; the process of cooling is considered a highly spontaneous process.
In terms of heat transfer Qr, the entropy becomes;

$$\Delta X = \frac{Qr}{T} \tag{4}$$

Where T is the ambient temperature.
For mechanical works, entropy becomes;

$$\Delta X = Kb \ln W \tag{5}$$

Equation 5 is the boltzmann model formular, Kb represents Boltzmann constant and W represents work done.
Combining equation 4 and 5 generates;

$$dW = \exp \frac{Qr}{Kb}\, dT \tag{6}$$

Hence the COP of the system with respect to the heat removed Qr and the work required with respect to time and temperature was shown as;

$$CoP = \frac{dT}{dt}\left(\frac{Qr}{W}\right) \tag{7}$$

Equation 7 implied that the work W and energy Qr may increase or decrease depending on the temperature and time of operation of the air craft.
From the Gouy-Stodola theorem which states that exergy destroyed (Ex) in a process is directly proportional to the entropy (X) generated.
Hence;

$$Ex = X \times T \tag{8}$$

Hence the exergy balance (destroyed) considered in relation to the system at reference state (0) was shown in the equation below.

$$Ex = (U - U_o) + P(V - V_0) - T(X - X_o) + 0.5V^2 + gZ \tag{9}$$

Where U,V,X, represents the internal energy, velocity and entropy of the aircraft cooling system respectively, P and T represent the pressure and temperature of the environment.
Therefore, the exergy destroyed of the system considering the amount of the refrigerant (M) and the enthalpy (H) was as described.

$$Ex = M(H - XdT) \tag{10}$$

Where XdT represent the loss in entropy of the refrigeration system.
Hence from equations 9 and 10, it was deduced that the more the entropy generated, the more the exergy destruction.
H is the enthalpy whose equation was shown in the equation 11 below.

$$H = MCpdT \tag{11}$$

Where Cp represents the heat coefficient of both the HNZP and air.
The Cp and other parameters required were generated from hysys simulation application.
The exergy efficiency (N_{ex}) was obtained with the following equation;

$$N_{ex} = 1 - \left(\frac{Ex}{Ex(supplied)}\right) \tag{12}$$

Where Ex(supplied) can also be the amount of energy supplied in the system.
The summary of the procedure utilized for the determination of exergy based analysis of the HNZB and air refrigerants in aircrafts was outlined in the flow diagram shown in figure 1.

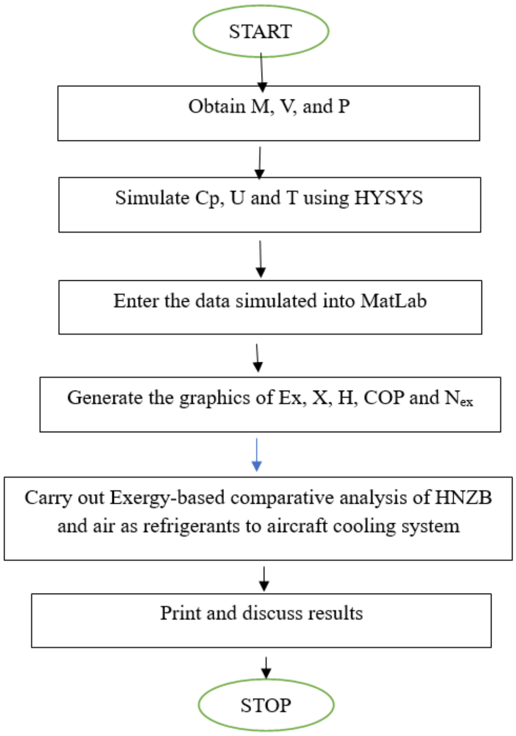

Figure 1; flow diagram of the paper procedure

IV. Results

The temperature of the heat transfer between the refrigerants (HNZB) and compressed air was monitored based on the model generated and the temperature of the aircraft cooling system with respect to time was shown in figure 2.

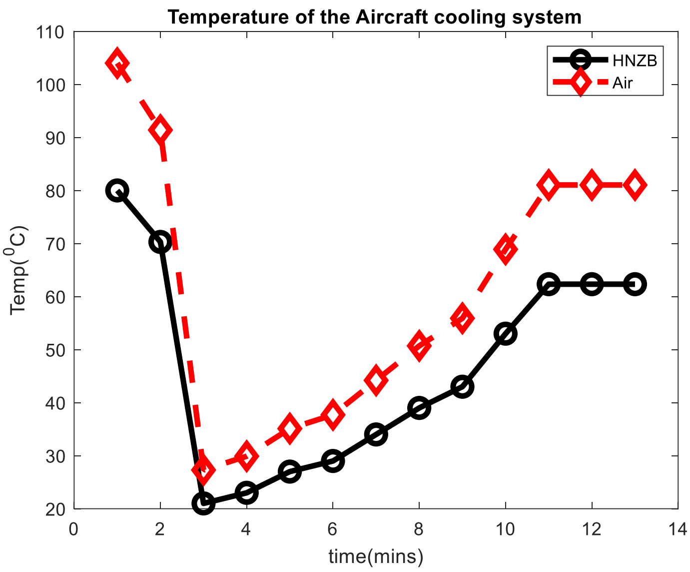

Figure 2; Temperature of the aircraft cooling system

In figure 2, the temperature of the aircraft cooling process using compressed air was higher than the process when HNZB was utilized. This implied that the cooling process with HNZB as the refrigerant was more effective and stable than when the compressed air was utilized. This can be attributed to the higher density and thermal conductivity possessed by the HNZB refrigerants above that of the compressed air.

The temperature of the refrigerant was shown in figure 3.

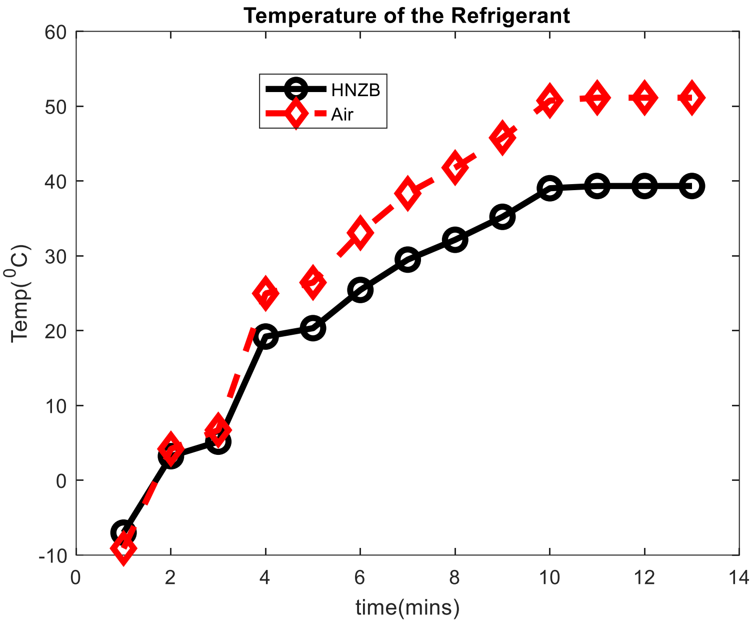

Figure 3; Temperature of the refrigerant

In figure 3, the temperature of the refrigerant increases during the cooling process as time variation increasing the spontaneity of the refrigerants. It was observed that the temperature of the compressed air refrigerant was higher than that of the HNZB which implied that the use of compressed air as the refrigerant was more spontaneous and HNZB was more stable. Hence, the use HNZB was more effective as a refrigerant than the use of compressed air due to low temperature stability and heat control.

The entropy of the cooling process with the refrigerants was shown in figure 4

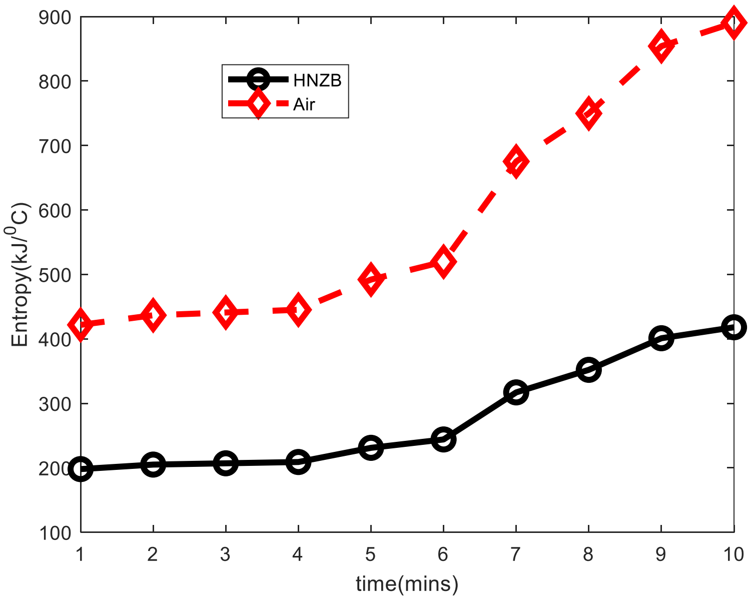

Figure 4; Entropy of the system

It was observed in figure 4 that the entropy of the aircraft cooling process was lower when HNZB was utilized as the refrigerant than when air was utilized. This implied that the utilization of HNZB as the refrigerant was more sustainable and stable as against the utilization of the compressed air that was more spontaneous because the lower the entropy of the cooling process, the more suitable the refrigerant utilized for the cooling process. This further proves that the use of HNZB as a refrigerant was more stable than the use of compressed air.

The enthalpy of the system during the cooling process was shown in figure 5.

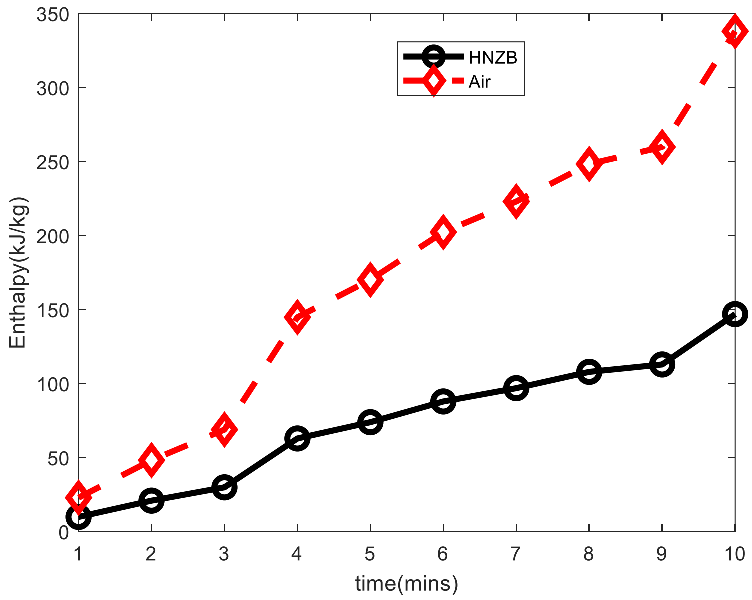

Figure 5; Enthalpy of the aircraft cooling system

The amount of enthalpy in the aircraft cooling process was higher with the implementation of compressed air as the refrigerant than when HNZB was utilized. Hence, greater amount of energy was lost when air was used than when HNZB was utilized. This simply showed that HNZB was more stable as an aircraft cooling refrigerant than the compressed air.

The COP of the HNZB and air refrigerants was shown in figure 6.

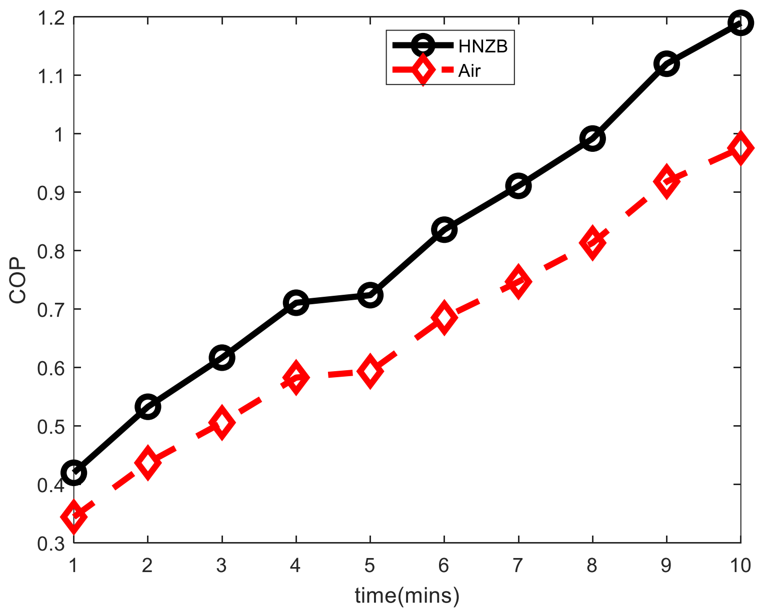

Figure 6; COP of the refrigerants

From the plot presented in figure 6, the COP of the implementation of HNZB refrigerant was higher in the aircraft refrigerating system than when compressed air was utilized as a refrigerant. This implies that the utilization of compressed air as the refrigerant would larger amount of work with larger amount of energy loss than the HNZB refrigerant which makes the HNZB more suitable and stable for the aircraft refrigerating process.

The exergy destruction of the aircraft process at various refrigerants was shown in figure 7.

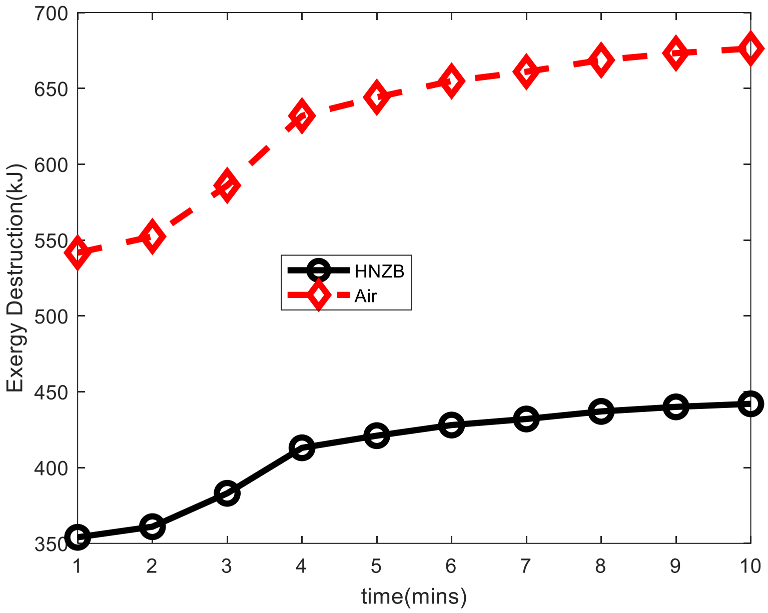

Figure 7; Exergy destruction at varying refrigerants

From figure 7. It was observed that the exergy destruction when compressed air was implemented as the refrigerant in the aircraft cooling system which higher than when HNZB was utilized as the refrigerant. This outcome of the HNZB refrigerant can be attributed to the higher amount of density than the compressed air, resulting in the presentation of useful work than when compressed air was utilized. The high level of entropy contained in compressed air also resulted to higher exergy distribution making HNZB more stable and suitable for the aircraft refrigeration system.

The exergy destruction of the aircraft process at various refrigerants was shown in figure 8.

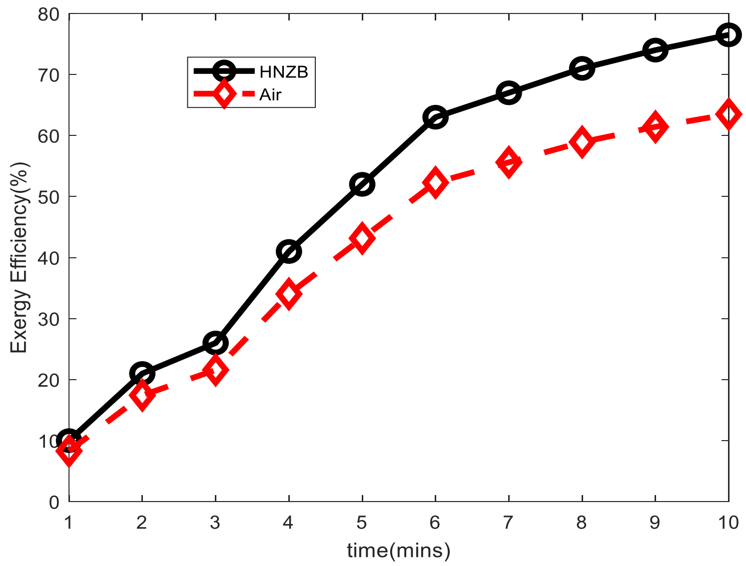

Figure 8; Exergy efficiency at varying refrigerants

In figure 8, it was observed that HNZB refrigerant had a higher exergy efficiency than the compressed air refrigerant. This can be attributed to higher density, stability, lower energy loss and adequate heat transfer process and HNZB refrigerant possesses more qualities than the compressed air refrigerant. Hence, based on the exergy efficiency which is the major metrics for characterizing the performance of the refrigerants, HNZB remains more suitable as a refrigerant to the aircraft cooling process than the compressed air that is currently in use.

V. Conclusion

The parameters involved in the exergy-based analysis of the refrigerants for the aircraft refrigerating system was done on HNZB and compressed air refrigerants. This was to determine the possibility of utilizing HNZB as a better alternative refrigerant than the existing compressed air refrigerant. Temperature of the heat exchange process, temperature of the refrigerant during the aircraft cooling process, enthalpy, entropy, exergy destruction, COP and the exergy efficiency were some of the metrics utilized in determining the performance analysis of the refrigerants. Based on the trends presented in the results, it was observed that the implementation of the HNZB refrigerant presented a better aircraft refrigerating performance than the compressed air refrigerants. This was attributed to higher density, lower entropy, cooling process temperature and higher COP, exergy efficiency and lower exergy destruction possessed by the HNZB refrigerant than the compressed air refrigerant.

Furthermore, it was recommended that a design of experiment process (DoE) using central composite design (CCD) should be carried on the aircraft refrigerating process with HNZB refrigerant and responsible surface methodology and an optimization technique should be utilized in further analyzing the characteristics of the HNZB refrigerant to obtain the optimum performance of the refrigerant during the aircraft refrigeration process.

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