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Performance investigation of a vapor compression refrigeration system with and without heat exchanger using mono and hybrid nanofluids and operated with R1234yf

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Buhar sıkıştırmalı soğutma sistemi
Hibrit nanoyağlayıcı
Termodinamik analiz
Çevresel analiz

Graphical/Tabular Abstract (Grafik Özet)

In this study, the performance of the vapor compression refrigeration system operated with R1234yf using mono and hybrid nanolubricants was investigated. As a result, the best results were obtained in 1 wt% TiO_2-B compared to pure POE and other nanolubricants in terms of thermodynamics and environmental aspects/Bu çalışmada mono ve hibrit nanoyağlayıcılar kullanılarak R1234yf ile çalıştırılan buhar sıkıştırmalı soğutma sisteminin performansı incelenmiştir. Sonuç olarak ağırlıkça %1 TiO_2-B'de termodinamik ve çevresel açıdan saf POE ve diğer nanoyağlayıcılara göre en iyi sonuçlar elde edilmiştir

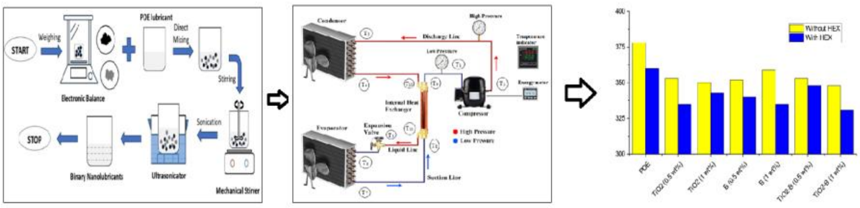

Figure A*: Vapor compression refrigeration system with and without heat exchanger using mono and hybrid nanolubricants /****Şekil A:****.Mono ve hibrit nanoyağlayıcı kullanılan ısı değiştiricili ve ısı değiştiricisiz buhar sıkıştırmalı soğutma sistemi*

Highlights (Önemli noktalar)

- *The performance of a vapor compression refrigeration system with and without heat exchanger using mono and hybrid nanolubricants was investigated/Mono ve hibrit nanoyağlayıcı kullanılan ısı değiştiricili ve ısı değiştiricisiz bir buhar sıkıştırmalı soğutma sisteminin performansı araştırılmıştır.*
- *The COP enhanced by 10.46% in the 1 wt% TiO_2-B hybrid nanolubricant in the experimental system with HEX/ COP ısı değiştiricili deney sisteminde, ağırlıkça %1 TiO_2-B hibrit nanoyağlayıcıda %10,46 artmıştır.*
- *A decrease of 8.06% was obtained with 1 wt% TiO_2-B hybrid nanolubricant in the experimental system with HEX compared to POE/Isı değiştiricili deney sisteminde POE'ye kıyasla ağırlıkça %1 TiO_2-B hibrit nanoyalayıcı ile %8,06'lık bir azalma elde edilmiştir*

Aim (Amaç): *In this study, the effects of different concentrations of mono and hybrid nanolubricants in vapor compression refrigeration systems with and without internal heat exchangers were investigated / Bu çalışmada farklı konsantrasyonlardaki mono ve hibrit nanoyağlayıcılar dahili ısı değiştiricili ve ısı değiştiricisiz buhar sıkıştırmalı soğutma sistemindeki etkileri incelenmiştir.*

Originality (Özgünlük): *In previous studies, nanolubricants were used separately in heat exchangers and vapor compression refrigeration systems. In this study, the performance of nanolubricants was evaluated when used together / Daha önce yapılan çalışmalarda ısı değiştirici ve buhar sıkıştırmalı soğutma sisteminde nanoyağlayıcılar ayrı olarak kullanılmıştır. Bu çalışmada birlikte kullanıldığında nanoyağlayıcıların performansları değerlendirilmiştir.*

Results (Bulgular): *As a result of the experiments, all nanolubricants were compared with pure POE within the results obtained / Deneyler sonucunda elde edilen sonuçlar dahilinde saf POE'ye göre tüm nanoyağlayıcılar karşılaştırılmıştır.*

Conclusion (Sonuç): *Hybrid nanolubricant TiO_2-B used in a vapor compression refrigeration system with heat exchanger showed better performance than other nanolubricants in terms of thermodynamics and environmental aspects / Isı değiştiricili buhar sıkıştırmalı soğutma sisteminde kullanılan hibrit nanoyağlayıcı TiO_2-B termodinamik ve çevresel açıdan diğer nanoyağlayıcılara göre daha iyi performans göstermiştir.*

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Abstract

In recent years, the world's energy needs have been increasing. Approximately one third of the world's energy consumption is carried out by buildings. Most of this rate is due to heating, cooling, and air conditioning systems. Compressors are the components that consume the most energy in heating, cooling, and air conditioning systems. Reducing the energy consumption of compressors is of great importance. The thermodynamic and environmental performances of mono and hybrid nanolubricants acquired from different nanoparticles (TiO_2 and B) used at different concentrations (0.5 wt% and 1 wt%) in vapor compression refrigeration systems (VCRS) with and without heat exchanger (HEX) were investigated in this study. Because of the experiments, the COP enhanced by 10.46% in the 1 wt% TiO_2-B hybrid nanolubricant in the experimental system with HEX. Compared to POE, exergy efficiency improved by 23.36% in the experimental system without HEX with 1 wt% TiO_2-B hybrid nanolubricant and by 28.48% in the experimental system with HEX with 1 wt% TiO_2-B hybrid nanolubricant. In the energy consumption of the compressor, a decrease of 7.94% was obtained with 1 wt% TiO_2-B hybrid nanolubricant in the experimental system without HEX and a decrease of 8.06% was obtained with 1 wt% TiO_2-B hybrid nanolubricant in the experimental system with HEX compared to POE. Compared to POE, 7.92% improvement in total exergy destruction was found in the 1 wt% TiO_2-B hybrid nanolubricant in the experimental system without HEX, and 8.72% improvement was found in the 1 wt% TiO2-B hybrid nanolubricant in the experimental system with HEX. The enviroeconomic value of 1 wt% TiO_2-B hybrid nanolubricants gave better results than POE and mono nanolubricant.

Mono ve hibrit nanoakışkan kullanılan ve R1234yf ile çalıştırılan ısı değiştiricili ve ısı değiştiricisiz bir buhar sıkıştırmalı soğutma sisteminin performansının araştırılması

Makale Bilgisi

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Öz

Dünyadaki enerji tüketiminin yaklaşık üçte biri binalar tarafından gerçekleştirilmektedir. Bu oranında büyük bölümünü ısıtma, soğutma ve iklimlendirme sistemlerinden kaynaklanmaktadır. Isıtma, soğutma ve iklimlendirme sistemlerinde en fazla enerji tüketen bileşen kompresörlerdir. Kompresörlerin enerji tüketimini azaltmak büyük önem arz etmektedir. Bu çalışmada ısı değiştiricisiz ve ısı değiştiricili buhar sıkıştırmalı soğutma sisteminde farklı konsantrasyonlarda (%0,5 wt ve %1 wt) kullanılan farklı nanoparçacıklardan (TiO_2 ve B) elde edilen mono ve hibrit nanoyağlayıcıların termodinamik ve çevresel performansları incelenmiştir. Deneyler sonucunda, ısı değiştiricili deney sisteminde COP değeri %1 wt TiO_2-B hibrit nanoyağlayıcıda %10,46 artmıştır. Kompresörün enerji tüketiminde POE'ye göre ısı değiştiricisiz deney sisteminde %1 wt TiO_2-B hibrit nanoyağlayıcıda %7,94'lük düşüş, ısı değiştiricili sistemde %1 wt TiO_2-B hibrit nanoyağlayıcıda %8,06'lık düşüş elde edilmiştir. Ekserji verimi POE'ye göre ısı değiştiricisiz deney sisteminde %1 wt TiO_2-B hibrit nanoyağlayıcıda %23,36'lık iyileşme, ısı değiştiricili deney sisteminde %1 wt TiO_2-B hibrit nanoyağlayıcıda %28,48'lik iyileşme gerçekleşmiştir. Toplam ekserji yıkımı POE'ye göre, ısı değiştiricisiz deney sisteminde %1 wt TiO_2-B hibrit nanoyağlayıcıda %7,92'lik iyileşme, ısı değiştiricili deney sisteminde %1 wt TiO_2-B hibrit nanoyağlayıcıda %8,72'lik iyileşme tespit edilmiştir. %1 wt TiO_2-B hibrit nanoyağlayıcılarda çevreekonomik değer POE ve mono nanoyağlayıcıya göre daha iyi sonuç vermiştir.

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1. INTRODUCTION (GİRİŞ)

The decreasing energy resources in the world day by day and the parallel increase in energy costs and the increase in demand for energy have forced countries to work on new energy sources and new solution methods to develop and use them [1]. Developed countries have become more sensitive about using energy more efficiently and are trying to reduce energy consumption to use existing resources more economically [2]. Focusing on energy saving and efficiency brings the importance and necessity of energy efficiency to the forefront [3].

Approximately 40% of the world's energy consumption comes from buildings [4]. A large portion of this rate consists of heating, cooling, and air conditioning systems [5]. The biggest contributor to these systems is the energy consumption of compressors [6]. For this reason, even the slightest improvement in energy efficiency and energy consumption in refrigeration and air conditioning systems will benefit serious energy savings worldwide [7].

In a refrigeration cycle, refrigerants are used to take heat from one environment and transfer it to another [8]. They generally provide heat exchange by converting from liquid to vapor and from vapor to liquid [9]. The heat transfer coefficient and viscosity of refrigerants affect the performance of heat exchangers (HEX) [10]. Different types of refrigerants such as chlorofluorocarbon (CFC) (R11, R12, R13, R114 and R115), hydrochlorofluorocarbon (HCFC) (R22, R124, R123), hydrofluorocarbon (HFC) (R134a) and hydrofluoroolefin (HFO) (R-1234ze, R-1234yf and R-513A) have been used from past to present [11]. In addition to the performance of these refrigerants, their environmentally friendly features have also gained importance over time with the effects of global warming and the Kyoto Protocol and the Paris Agreement. CFC and HCFC refrigerants cause environmental pollution, greenhouse effect, and ozone layer depletion [12]. Some types of refrigerants have been gradually banned because they damage the ozone layer in the stratosphere of the atmosphere and cause global warming [13]. Instead of these banned refrigerants, new generation refrigerants that are more environmentally friendly have begun to be used [14].

In addition to being environmentally friendly, it is very significant to enhance the performance of vapor compression refrigeration systems (VCRS) and save energy [15]. With the development and widespread use of nanotechnology in thermal energy systems (TES), there has been a significant enhancement in the use of nanoparticles [16]. Nanofluids are acquired by adding nanoparticles to the base fluid (water, oil, etc.) [17]. Nanofluids increase system performance by causing significant improvements in thermophysical properties such as heat transfer, thermal conductivity, and viscosity in the TESs in which they are used [18]. Nanofluids are generally prepared by a one-step or two-step method. The one-step method is applied by mixing the base fluid and nanoparticle at one time [19]. In the two-step method, the base fluid and nanoparticles are first blended with a magnetic stirrer for a specified time [20]. It is then subjected to an ultrasonic bath for a specified period [21]. Nanoparticles are also used as hybrid nanofluids by adding them into the base fluid as mono, binary, or ternary [22]. The use of hybrid nanofluids in TESs is also quite common [23].

There are some studies on the usage of mono and hybrid nanolubricants in VCRSs operating with R1234yf. Bibin and Gundabattini investigated the transfer characteristics and pressure drop of a VCRS using Copper oxide (CuO) nanoparticles and operating with R1234yf using mathematical and simulation methods. CuO nanofluid was used at a concentration of 0.2 to 1 vol%. The heat transfer coefficient and pressure drop of the nanofluid increased by 45.36% and 35.69%, respectively [24]. Sharif et al. conducted the effects of using Silicon oxide (SiO_2) and Aluminum oxide (Al_2O_3) nanoparticles in automotive air conditioning operating with R1234yf on system performance. Nanolubricants formed by adding nanoparticles into Polyalkylene Glycol (PAG) at different concentrations (0.01 vol% and 0.05 vol%) were obtained by a two-step method. The highest cooling capacity was determined with an average improvement of 15.7% in the system with SiO_2 nanolubricant at 0.01 vol% concentration. Additionally, the highest coefficient of performance (COP) increase and power consumption were obtained as 9.8% and 27.1% in 0.05 vol% Al_2O_3 nanolubricant, respectively [25]. Bibin and Gundabattini analyzed the liquid and vapor densities of Al_2O_3, Titanium oxide (TiO_2), and CuO nanoparticles in a VCRS operated with R1234yf. The experimental results showed that the liquid and vapor densities of CuO/R1234yf nanorefrigerant at 5% concentration were 10.3% and 62.93% higher than Al_2O_3/R1234yf, respectively. In terms of liquid vapor density, CuO/R1234yf was found to be superior to Al_2O_3/R1234yf and TiO_2/R1234yf [26]. Sharif et al. tested the impacts of Al_2O_3-SiO_2/PAG nanolubricant on system performance in a vehicle air conditioner operated with R1234yf. Hybrid nanolubricants were obtained at different concentrations by the two-step method. 12% performance increase was observed for the Al_2O_3-SiO_2/PAG nanolubricant at a concentration of 0.03%. Additionally, a 7.7% reduction in energy consumption was detected at the same concentration of nanolubricant [27]. Bibin and Gundabattini investigated the heat transfer and pressure drop of TiO_2 nanoparticle used in a VCRS operating with R1234yf by mathematical and other methods. Experiments were carried out by changing the TiO_2/POE nanolubricant at different concentrations (0.2 vol%-1 vol%) in the range of 10 ℃ to 40 ℃. The heat transfer coefficient and pressure drop of the nanolubricant were improved by 134.03% and 80.77%, respectively [28]. Li and Lu investigated the performance of VCRS by using four different refrigerants and adding Al_2O_3 nanoparticle. The COP enhancement of R1233zd(E)-Al_2O_3 nanorefrigerant is considerably higher than the other three nanorefrigerants. The maximum exergy efficiency was obtained as 38.46% for R1233zd(E)-Al_2O_3 [29]. Sharif et al. observed the enhancement of the system by utilizing hybrid nanolubricants in a vehicle air conditioner operated with R1234yf. It was observed that less energy was consumed in the experimental system using Al_2O_3-SiO_2/PAG nanolubricant compared to PAG. In addition, higher cooling capacity was achieved in Al_2O_3-SiO_2/PAG nanolubricant compared to PAG [30]. Pundkar and Chaudhari experimentally tested the performance of nanolubricants in VCRS operated with R1234yf and R134a. Nanoparticles (Al_2O_3 and TiO_2) added into POE were obtained as nanolubricants at different concentrations (between 0.5% and 1%). As a result, 18% and 15% increase in COP value were detected in 0.5% Al_2O_3 and 0.5% TiO_2 nanolubricants, respectively, and 23% and 19% decrease in energy consumption was determined, respectively [31].

In this study, the effects of mono and hybrid nanolubricants utilized in VCRS with HEX on system performance were investigated. Improvements in this area are needed to reduce the energy consumption of compressors in VCRSs in the global energy consumption of buildings. Therefore, the usage of nanoparticles with high heat transfer properties was preferred. Mono and hybrid nanolubricants obtained from different concentrations and different types of nanoparticles (TiO_2 and Boron (B)) were effective in increasing the performance and reducing the energy consumption of the VCRS with HEX. In addition, in a VCRS, liquid refrigerant entering the compressor reduces the efficiency and the compressor's life. To prevent this circumstance, the use of internal HEXs in the VCRS is preferred to perform the superheating process. Energy, exergy, and environmental analysis of the VCRS using mono and hybrid nanolubricants were performed and interpreted.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

In this section, mono and hybrid nanolubricants were tested in a VCRS with and without internal HEX. Theoretical explanations of thermophysical properties, and thermodynamic and environmental analysis utilized to evaluate the VCRS's performance with and without internal HEX used in the experiments are given.

2.1. Preparation of Nanolubricant (Nanoyağlayıcının Hazırlanışı)

Mono and hybrid nanolubricants were acquired by adding TiO_2 and B nanoparticles into POE. The obtained hybrid nanolubricants are formed by adding nanoparticles at a ratio of 50:50. Technical properties of nanoparticles used in nanolubricants are shown in Table 1. Scanning electron microscope (SEM) images of the nanoparticles in the nanolubricants used in the experiments are given in Figure 1.

Table 1. Technical properties of nanoparticles (Nanoparçacıkların teknik özellikleri)

Nanoparticle	Purity, %	Density, g/cm^3	Average Particle Size, nm	Morphology	Thermal Conductivity, W/m.K
TiO_2	+99.5	4.5	45	Nearly Spherical	8
B	+99.5	3.58	100	Nearly Spherical	27

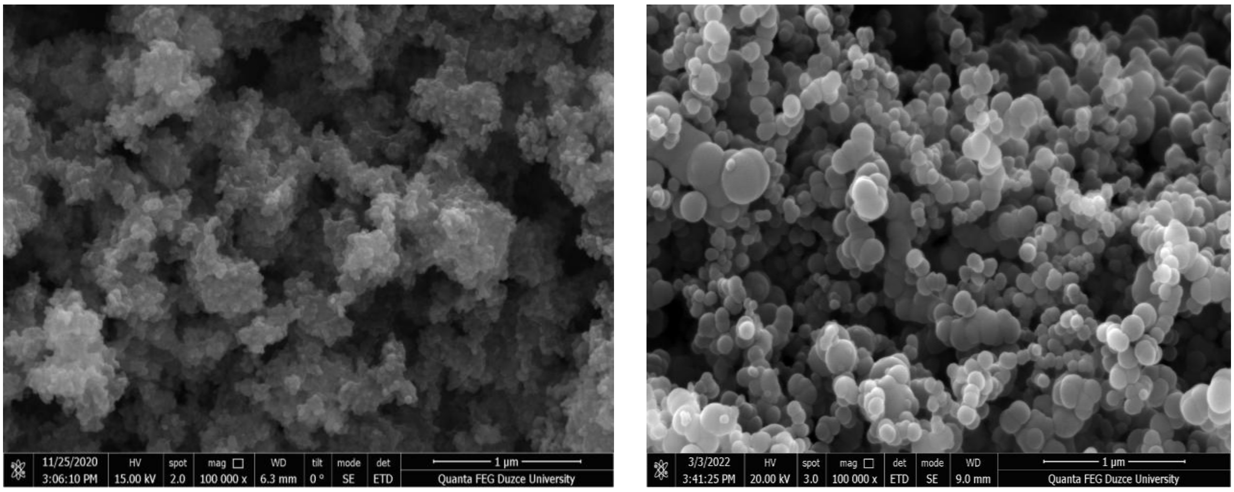

Figure 1. SEM images of nanoparticles used in the experiments a) TiO_2 and b) B (Deneylerde kullanılan nanoparçacıkların SEM görüntüleri a) TiO_2 ve b) B)

The weights of POE and nanoparticles were measured using a precision balance. To acquire mono and hybrid nanolubricants, nanoparticles are added to POE and then blended with a magnetic stirrer at 25 °C for 3 h. It is subjected to ultrasonic bath treatment at 50 Hz frequency and 250 W power for 2.5 h to ensure homogeneous distribution of nanoparticles in the POE. Preparation of all nanolubricants in this study is given in Figure 2.

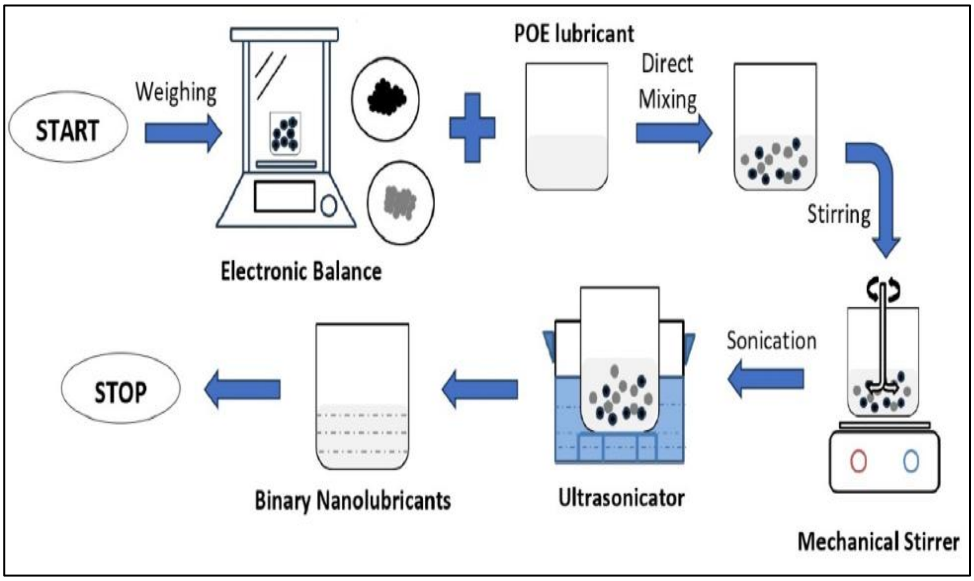

Figure 2. Steps of preparation of mono and hybrid nanolubricants [32] (Mono ve hibrit nanoyağlayıcıların hazırlanma aşamaları)

2.2. Experimental setup (Deney sistemi)

The performance of a VCRS with internal HEX using mono and hybrid nanolubricants was analyzed in the present study. Refrigerants are used to perform the cooling process in the experimental system. In this study, R1234yf, which is more environmentally friendly, was used as the refrigerant. The VCRS with internal HEX used in the experiments is shown in Figure 3. The P-h and T-s diagrams of the thermodynamic points of the refrigerant used in the experimental system for the system without and with a heat exchanger are given in Figure 4.

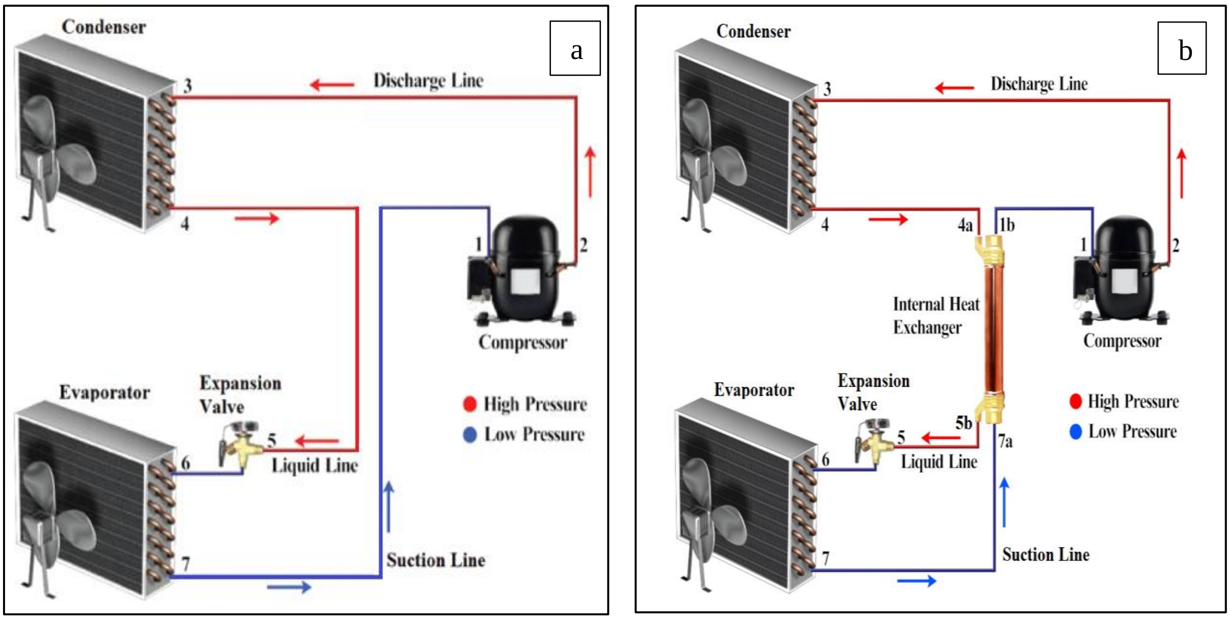

Figure 3. Schematic view of the experimental setup a) without HEX, b) with HEX (Deney sisteminin şematik gösterimi a) ısı değiştiricisiz, b) ısı değiştiricili)

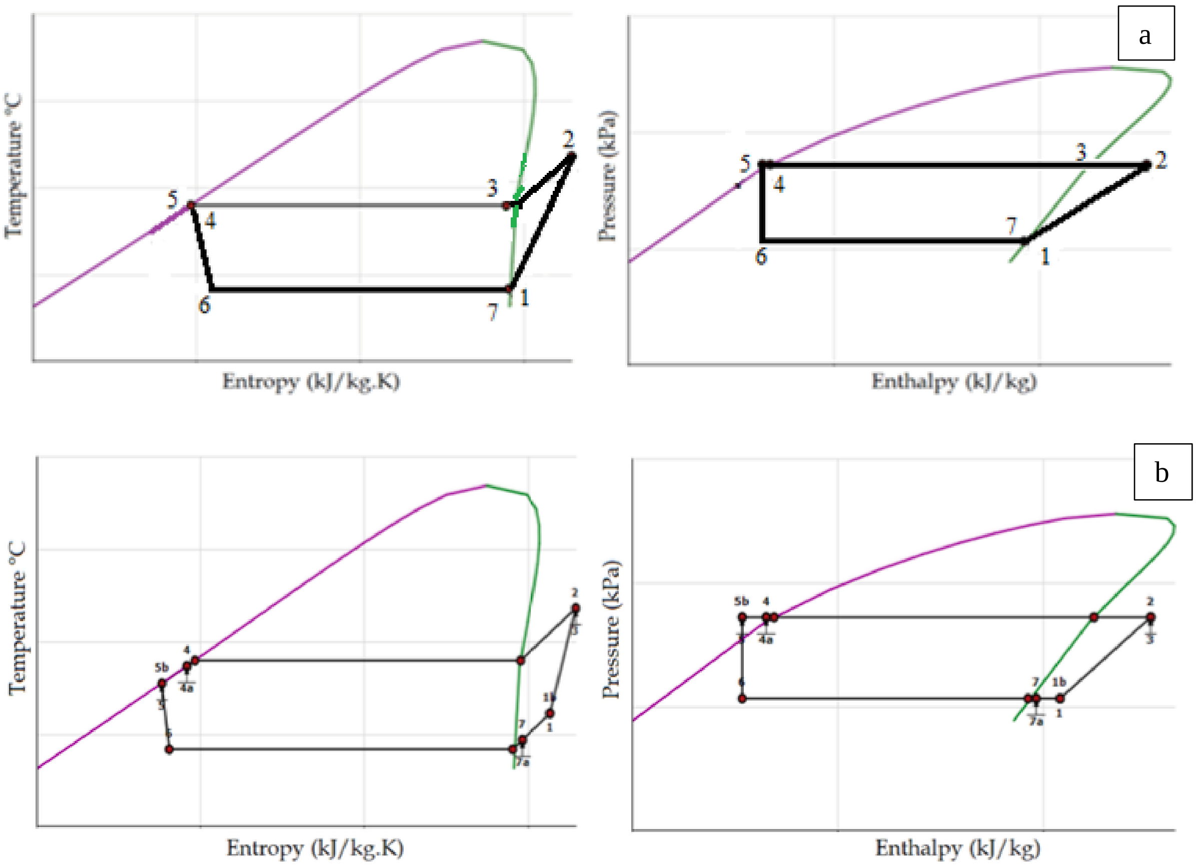

Figure 4. T-s and P-h diagrams of the experimental system a) without HEX, b) with HEX (Deney sisteminin T-s ve P-h diyagramları a) ısı değiştiricisiz, b) ısı değiştiricili)

Checks were made before starting the experiments in the VCRS with internal HEX. After the system was checked, 200 mL of POE was added to the VCRS with internal HEX. The air in the system is vacuumed with the help of a vacuum pump to prevent any air from remaining in the system. Then, 140 g of R1234yf refrigerant was charged. After the system was started, it was waited until it reached equilibrium conditions with the environment. When the system reached equilibrium conditions, data were taken from the system at 20 minute intervals for 1 h. The average of data taken at 5 different times during 1 h was used. The same procedures were followed in the usage of other mono and hybrid nanolubricants. The experiments were carried out at an average temperature of 23 °C and a relative humidity of 60%. While the nanolubricants were being replaced in the VCRS, the R1234yf in the system was completely evacuated. No matter how well the refrigerant is evacuated from the system, trace amounts of refrigerant will remain in the system. For this case, the system was purged with N_2 for 5 minutes at each nanolubricants change. R1234yf charging was done after the sweeping process. The technical specifications of the VCRS with internal HEX used in the experiments are given in Table 2. The view of pressure and temperature measurement points on the experimental system and the view of the experimental system are shown in Figure 5.

Table 2. Technical specifications of VCRS (VCRS'nin teknik özellikleri)

Components	Specifications
Compressor	Displacement: 4.05-9.09 cm^3 Cooling capacity: 325-970 W
Evaporator	Capacity: 1 kW
Condenser	Capacity: 1.4 kW
Thermostatic expansion valve	Temperature range: -40/10 °C Static superheat: 4 °C
Filter drier	Temperature range: -40/70 °C Net volume: 0.464 L
Heat exchanger	Type: Tube-in-tube heat exchanger Capacity: 1 kW Maximum working pressure: 28 bar Operating temperature: -60 °C to 120 °C

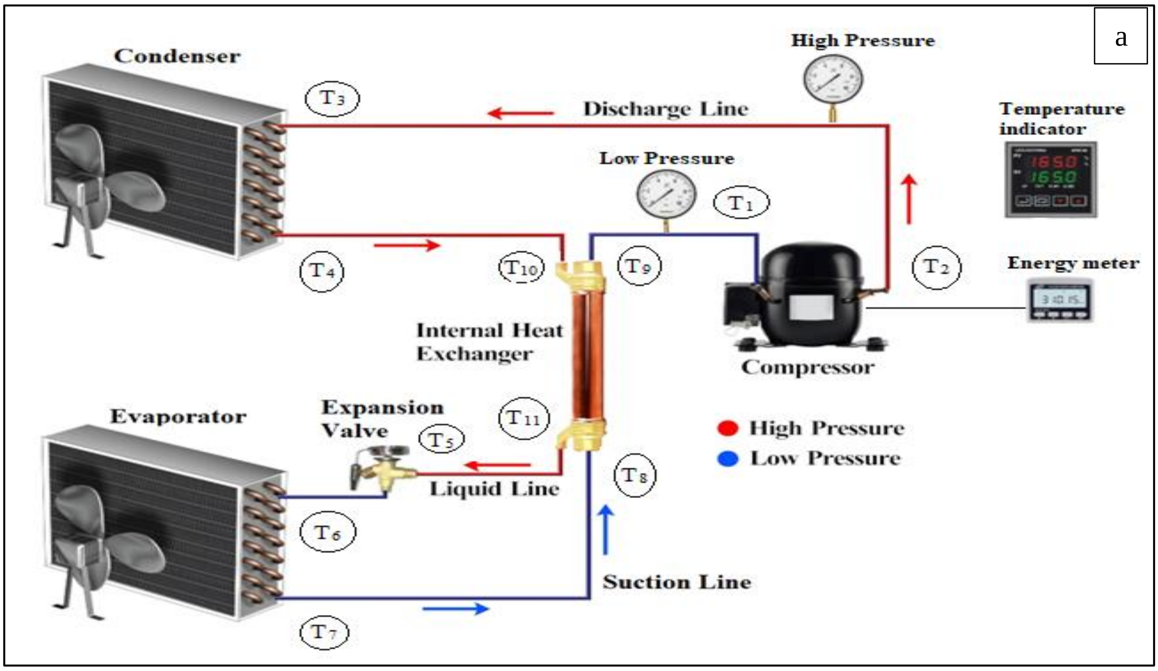

Figure 5. View of experimental system a) measurement points b) general view (Deney sisteminin görünümü a) ölçüm noktaları, b) genel görünüm)

2.3. Thermophysical properties (Termofiziksel özellikler)

Different thermal properties such as thermal conductivity and viscosity must be determined to determine some properties of a fluid. Thermal conductivities of fluids directly affect the heat transfer properties of the fluid. Thermal conductivity can be measured with measuring instruments, or it can be obtained through models produced from experimental data. The Maxwell model gives the best results in studies on mono nanofluids obtained from spherical nanoparticles. The Maxwell model is given in Equation 1. Likewise, a model for mono nanofluids was developed to calculate the thermal conductivity of hybrid nanofluids. The model used in the thermal conductivity calculation of hybrid nanofluids is given in Equation 2.

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np}+(n-1)k_{bf}-(n-1)\emptyset\left(k_{bf}-k_{np}\right)}{k_{np}+(n-1)k_{bf}-\emptyset\left(k_{bf}-k_{np}\right)} \tag{1}$$

$$k_{hnf} = k_{bf}\frac{(\phi_{np1}k_{np1}+\phi_{np2}k_{np2}/\phi_{np1}+\phi_{np2})+2k_{bf}+2(\phi_{np1}k_{np1}+\phi_{np2}k_{np2})-2(\phi_{np1}+\phi_{np2})k_{bf}}{\left(\phi_{np1}k_{np1}+\frac{\phi_{np2}k_{np2}}{\phi_{np1}}+\phi_{np2}\right)+2k_{bf}-(\phi_{np1}k_{np1}+\phi_{np2}k_{np2})+(\phi_{np1}+\phi_{np2})k_{bf}} \tag{2}$$

One of the most important thermal properties of fluids is viscosity. Mono and hybrid nanolubricants's viscosity utilized in experimental studies was obtained with the help of models according to the measured POE viscosity. These models are given in Equation 3 and Equation 4.

$$\mu_{nf} = \mu_{bf}\ (1 + 2.5\emptyset) \tag{3}$$

$$\mu_{hnf} = \frac{\mu_{bf}}{(1-\phi_{np1}-\phi_{np2})^{2.5}} \tag{4}$$

2.4. Thermodynamic analysis (Termodinamik analiz)

In this study, the performance of the VCRS with HEX using mono and hybrid nanolubricants was examined in terms of thermodynamics. The evaporator can be defined as the place where the cooling process takes place. The evaporator cools the environment by taking the heat of the refrigerant that reaches a temperature lower than the ambient temperature. The amount of heat drawn by the evaporator from the environment is given in Equation 5.

$$\dot{Q}_{evap} = \dot{m}_r(h_7 - h_6) \tag{5}$$

One of the main components of a VCRS is the condenser. The condenser releases the high heat created by the superheated vapor refrigerant coming from the compressor under pressure to the environment at a lower temperature. The heat released by the condenser to the environment is given in Equation 6.

$$\dot{Q}_{cond} = \dot{m}_r(h_4 - h_3) \tag{6}$$

The compressor compresses the refrigerant coming from the evaporator in theoretically saturated vapor form, increases its pressure and temperature, and sends it to the condenser in the form of superheated vapor. The power and electrical power consumed by the compressor while performing this compression process are given in Equation 7 and Equation 8.

$$\dot{W}_{comp} = \dot{m}_r(h_2 - h_1) \tag{7}$$

$$\dot{W}_{comp,el} = \frac{\dot{W}_{comp}}{\eta_{mec} \times \eta_{el}} \quad (8)$$

The COP is calculated to determine the performance of the VCRS. The COP is expressed as the ratio of the heat drawn by the evaporator from the environment to the power consumed by the compressor. The calculation of the COP value of a VCRS with an internal HEX is shown in Equation 9.

$$COP = \frac{\dot{Q}_{evap}}{\dot{W}_{comp,el}} \quad (9)$$

Exergy analysis provides detailed information about the usability of any system to increase its efficiency. Exergy analysis for a steady flow system is given in Equation 10. $E_{x,dest}$ in the equation represents exergy destruction. The first term in Equation 10 represents the flow exergy, the next term represents the heat transfer exergy, and the last term represents the work exergy.

$$E_{x,dest} = \sum \dot{E}_{x,in} - \sum \dot{E}_{x,out} + \sum \left[\dot{Q}\left(1 - \frac{T_0}{T}\right)\right]_{in} - \sum \left[\dot{Q}\left(1 - \frac{T_0}{T}\right)\right]_{out} + \sum \dot{W}_{in} - \sum \dot{W}_{out} \quad (10)$$

The flow exergy in each cycle in the HEX steam system is given in Equation 11. In Equation 11, $\dot{m}_r$ is the mass flow rate of the refrigerant, h_0 is the enthalpy at dead state conditions, T_0 is the ambient temperature for the dead state, and s_0 is the entropy for the dead state condition. The dead state conditions of the refrigerant are based on T_0 25 °C and P_0 101.325 kPa.

$$\dot{E}_x = \dot{m}_r[h - h_0 - T_0(s - s_0)] \quad (11)$$

Exergy destruction is the parameter that shows exactly how much exergy is lost in which component of the system. In this way, it provides information about which component needs to be improved. The exergy destruction for each major component in the experimental system is given in Equations 12-16.

$$\dot{E}_{x,dest,comp} = \dot{m}_r[(h_1 - T_0 s_1) - (h_2 - T_0 s_2)] + \dot{W}_{comp,el} \quad (12)$$

$$\dot{E}_{x,dest,cond} = \dot{m}_r[(h_3 - T_0 s_3) - (h_4 - T_0 s_4)] - \left[\dot{Q}_{cond}\left(1 - \frac{T_0}{T_{cond}}\right)\right] \quad (13)$$

$$\dot{E}_{x,dest,evap} = \dot{m}_r[(h_6 - T_0 s_6) - (h_7 - T_0 s_7)] + \left[\dot{Q}_{evap}\left(1 - \frac{T_0}{T_{evap}}\right)\right] \quad (14)$$

$$\dot{E}_{x,dest,exv} = \dot{m}_r T_0(s_6 - s_5) \quad (15)$$

$$\dot{E}_{x,dest,hex} = \dot{m}_r\big[[(h_{4a} - T_0 s_{4a}) - (h_{5b} - T_0 s_{5b})] + [(h_{7a} - T_0 s_{7a}) - (h_{1b} - T_0 s_{1b})]\big] \quad (16)$$

The total exergy destruction of all components in the VCRS with HEX is calculated according to Equation 17.

$$\dot{E}_{x,dest,ov} = \dot{E}_{x,dest,comp} + \dot{E}_{x,dest,cond} + \dot{E}_{x,dest,ev} + \dot{E}_{x,dest,exv} + \dot{E}_{x,dest,hex} \quad (17)$$

Exergy analysis of the VCRS with HEX is calculated by the ratio of the exergy difference of the evaporator to the compressor power.

$$\eta_{ex} = \frac{\dot{E}_{x,6} - \dot{E}_{x,7}}{\dot{W}_{comp,el}} \quad (18)$$

In the VCRS, an internal HEX is used to apply superheating to prevent liquid refrigerant from passing into the compressor. To evaluate the performance of the internal HEX used in the experimental system, the efficiency coefficient (ε_{hex}) is calculated in Equation 19.

$$\varepsilon_{hex} = \frac{T_1 - T_7}{T_4 - T_7} \quad (19)$$

2.5. Environmental analysis (Çevresel analiz)

Today, a significant portion of the energy needed is met by fossil fuels. In this energy production, high amounts of CO_2 emissions occur due to fossil fuels. High amounts of CO_2 emissions into the atmosphere cause environmental pollution and global warming. Research is being carried out with great effort around the world to reduce these effects. With these measures, environmental economic analysis has also become important. The electrical power consumed by the compressor is determined in Equation 20. $\dot{W}_{comp,el}$ is the power consumed by the compressor in unit time and t is the operating time of the compressor. The average operating time of the compressor used in this study was determined as 18 h. The amount of CO_2 released by the VCRS with HEX using mono and hybrid nanolubricants is calculated in Equation 21. φ_{CO_2} represents the amount of CO_2 reduced by the experimental system and ψ_{CO_2} represents the amount of CO_2 released by the operation of coal-fired power plants. The value of ψ_{CO_2} is taken as 2.08 $kgCO_2/kWh$.

$$W_{comp,el} = \dot{W}_{comp,el} . t \quad (20)$$

$$\varphi_{CO_2} = \psi_{CO_2} \times W_{comp,el} \quad (21)$$

The enviroeconomic value of the system used in the experiments is calculated in Equation 22.

$$Z_{CO_2} = z_{CO_2} \cdot \varphi_{CO_2} \quad (22)$$

In Equation 22, z_{CO_2} represents the international carbon price and varies between 13 and 16 $/t$CO_2$. The value of z_{CO_2} is taken as 14.5 $/t$CO_2$ in the calculations [33].

2.6. Uncertainty analysis (Belirsizlik analizi)

Uncertainty analysis provides a methodical approach to determining the sensitivity of the results obtained. A range of errors is determined with this approach. Uncertainty analysis has a distinct advantage over other analysis in that it helps identify the variable that causes the largest error.

$$W_R = \left[\left(\frac{dR}{dx_1}w_1\right)^2 + \left(\frac{dR}{dx_2}w_2\right)^2 + \cdots + \left(\frac{dR}{dx_n}w_n\right)^2\right]^{1/2} \quad (23)$$

Table 3. Technical specifications of measurement devices (Ölçü aletlerinin teknik özellikleri)

No.	Measurement Instrument	Range	Accuracy	Uncertainty
1	Thermocouple (K type)	(-30)-130 °C	0.5%	±0.45 °C
2	Radwag precision scales	0-220 g	0.001 g	±0.01 g
3	Energy meter	0.1-3680 W	0.1 W	±0.32 W
4	Pressure transmitter	0-30 bar	1 bar	±0.2 bar

3. RESULTS AND DISCUSSIONS (BULGULAR VE TARTIŞMA)

The performance of a VCRS with internal HEX operated with R1234yf using mono and hybrid nanolubricant at different concentrations is discussed thermodynamically and environmentally in this section.

The thermal conductivity of fluids utilized in TESs is an important parameter affecting system performance. The POE’s thermal conductivity increased significantly because of the effect of the nanoparticles added to it. This can be defined by the fact that solid nanoparticles have higher thermal conductivities than liquids, and liquids have higher thermal conductivities than gases. Nanoparticles with high thermal conductivity remain suspended in the base fluid to which they are added, creating a better heat transfer environment compared to the base fluid. POE’s thermal conductivities, and mono and hybrid nanolubricants depending on temperature are shown in Table 4. The POE’s thermal conductivity was determined as 0.1447 W/mK at 30 °C and 0.1455 W/mK at 50 °C. The thermal conductivities of mono and hybrid nanolubricants at the same temperature are higher than the POE’s thermal conductivity. The highest thermal conductivity value of 0.2249 W/mK at 50 °C was obtained in 1 wt% TiO_2-B hybrid nanolubricant. The lowest thermal conductivity value at the same temperature was obtained in POE as 0.1455 W/mK. Mono and hybrid nanolubricants have higher thermal conductivities compared to POE. This can be defined by the different sizes of nanoparticles. Smaller sized nanoparticles, mono, and hybrid nanoparticles have smaller surface-to-volume ratios. As seen in Table 4, there is a general increase in thermal conductivity with enhancing temperature. The change in POE’s thermal conductivities, mono and hybrid nanolubricants with enhancing temperature is parallel.

Table 4. Changes in thermal conductivity of nanolubricants with temperature (Nanoyağlayıcıların termal iletkenliklerinin sıcaklıkla değişimleri)

Temperature (°C)	POE	TiO_2 (0.5 wt%)	TiO_2 (1 wt%)	B (0.5 wt%)	B (1 wt%)	TiO_2-B (0.5 wt%)	TiO_2-B (1 wt%)
10	0.1413	0.1793	0.2104	0.1738	0.2012	0.1832	0.2185
20	0.1449	0.1838	0.2157	0.1782	0.2063	0.1879	0.2240
30	0.1447	0.1836	0.2154	0.1780	0.2061	0.1876	0.2237
40	0.1452	0.1842	0.2161	0.1786	0.2068	0.1883	0.2245
50	0.1455	0.1846	0.2165	0.1790	0.2072	0.1887	0.2249
60	0.1439	0.1826	0.2142	0.1770	0.2049	0.1866	0.2225
70	0.1434	0.1819	0.2135	0.1764	0.2042	0.1859	0.2217

An important parameter affecting the performance of fluids used in TESs is viscosity. As the fluid's viscosity used in the VCRS enhances, the amount of friction in the compressor increases. As this friction increases, the temperature inside the compressor increases. Viscosity changes of POE, mono, and hybrid nanolubricants with increasing temperature are shown in Table 5. The mono and hybrid nanolubricants' viscosity at the same temperature is higher than POE. When comparing POE, mono, and hybrid nanolubricants at the same temperature, POE has the lowest viscosity value. The mono and hybrid nanolubricants' high viscosities compared to POE can be defined by their large surface area to volume ratio. Therefore, the surface area of mono and hybrid nanolubricants increases and the resistance to flow in the system increases. Additionally, it is observed that the viscosity reduces with rising temperature. This allows the flow to be freer as the cohesive forces between molecules are reduced. Thus, a significant decrease in viscosity is observed in POE, mono, and hybrid nanolubricants as the temperature rises because of the reducing cohesive forces. In the experimental system, the highest viscosity value was obtained as 1.8098 Pa.s in 1 wt% TiO_2-B hybrid nanolubricant at 10 °C, and the lowest viscosity value was obtained as 0.0170 Pa.s in POE at 70 °C. As the temperature increases, the viscosity values of POE, mono, and hybrid nanolubricants reach values very close to each other after 60 °C.

Table 5. Changes in viscosity of nanolubricants with temperature (Nanoyağlayıcıların viskozitelerinin sıcaklıkla değişimleri)

Temperature (°C)	POE	TiO_2 (0.5 wt%)	TiO_2 (1 wt%)	B (0.5 wt%)	B (1 wt%)	TiO_2-B (0.5 wt%)	TiO_2-B (1 wt%)
10	0.4420	0.5746	0.7072	0.5475	0.6531	0.8108	1.8098
20	0.2050	0.2665	0.3280	0.2539	0.3029	0.3761	0.8394
30	0.1080	0.1404	0.1728	0.1338	0.1596	0.1981	0.4422
40	0.0600	0.0780	0.0960	0.0743	0.0887	0.1101	0.2457
50	0.0380	0.0494	0.0608	0.0471	0.0561	0.0697	0.1556
60	0.0240	0.0312	0.0384	0.0297	0.0355	0.0440	0.0983
70	0.0170	0.0221	0.0272	0.0211	0.0251	0.0312	0.0696

The energy consumption by the compressor in a VCRS with an internal HEX using mono and hybrid nanolubricants at different concentrations is indicated in Figure 6. As the concentrations of nanolubricants increase compared to POE, a decrease in the compressor's energy consumption is observed. Energy consumption is lower in VCRSs using HEXs than in VCRSs without HEXs. This circumstance can be explained as the refrigerant entering the compressor in the form of almost superheated vapor, as the superheating process takes place in VCRSs using a HEX. While the energy consumption in VCRSs with internal HEXs is already lower than in VCRSs without HEXs, the usage of mono and hybrid nanolubricants in the experimental system with HEX has further reduced energy consumption. In the VCRS without HEX, the highest energy consumption was obtained as 378 W in POE, and the lowest energy consumption was obtained as 348 W in 1 wt% TiO_2-B hybrid nanolubricant. In the VCRS with HEX, the highest energy consumption was obtained with POE as 360 W, while the lowest energy consumption was obtained with 1 wt% TiO_2-B hybrid nanolubricant as 331 W. This is due to the spherical shape of the nanoparticles used in the nanolubricants utilized in the experiments. Nanoparticles with spherical shapes create a rolling effect in the base fluid. As the friction between mating surfaces decreases due to the rolling effect, energy consumption in the compressor decreases. Additionally, since nanolubricants have higher thermal conductivity than POE, heat transfer between fluids is increased.

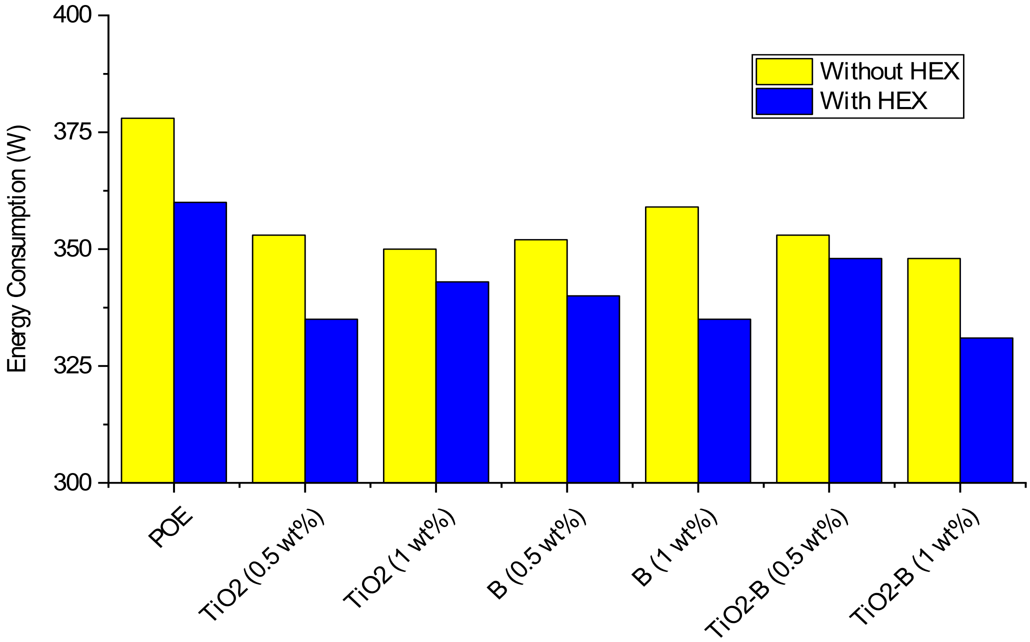

Figure 6. Energy consumption in the experimental system with and without HEX using mono and hybrid nanolubricants (Mono ve hibrit nanoyağlayıcı kullanılan ısı değiştiricili ve ısı değiştiricisiz deney sistemindeki enerji tüketimleri)

The COP changes of VCRS with internal HEX using nanolubricants at different concentrations are shown in Figure 7. The COP value increases in a VCRS with a HEX compared to an expected result in a VCRS without a HEX. However, when mono and hybrid nanolubricants are utilized in a VCRS with and without HEX, the POE of the system is observed to increase. This can be explained by the fact that mono and hybrid nanolubricants directly enhance VCRS performance due to their high thermal conductivity value. Additionally, COP values increase as the concentrations of mono and hybrid nanolubricants utilized in refrigeration systems with and without HEXs increase. In the experimental system without HEX, the lowest COP was determined as 2.63 in POE, and the highest COP was determined as 2.91 in 1 wt% TiO_2-B hybrid nanolubricant. In the experimental system with HEX, the lowest COP was obtained as 2.85 in POE, and the highest COP was obtained as 3.14 in 1 wt% TiO_2-B hybrid nanolubricant. Compressor energy consumption given in Figure 6 is effective on the COP value. Since the nanolubricants' energy consumption utilized in VCRS is low due to their high thermal conductivity, their COP values are higher than POE. As a result, hybrid nanolubricants used in VCRSs with and without HEXs have higher COP values than POE and mono nanolubricants with increasing concentrations. Additionally, the HEX used in the VCRS positively affected the system performance.

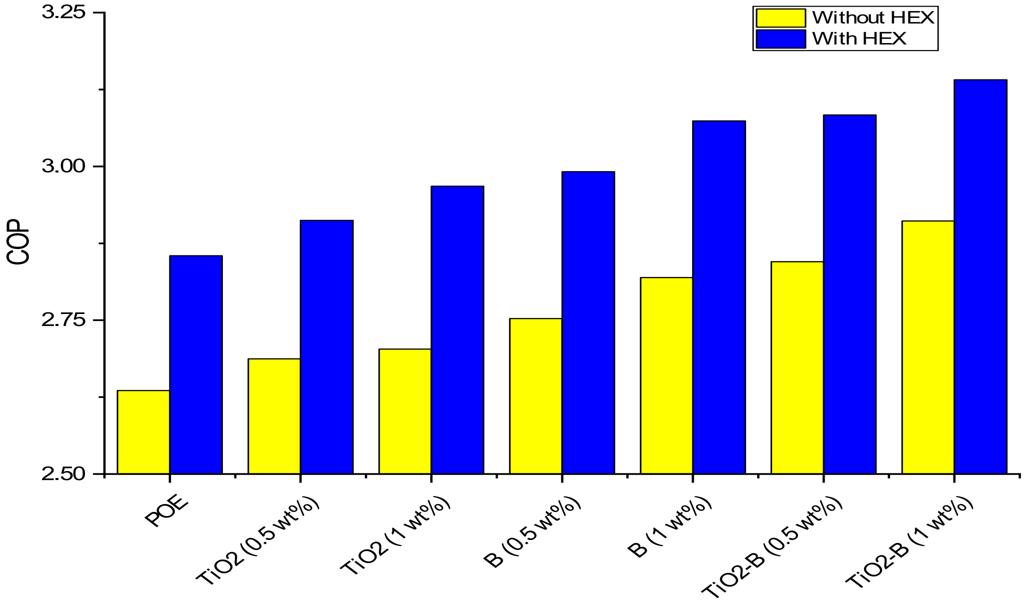

Figure 7. COP changes of the experimental system with and without HEX using mono and hybrid nanolubricants (Mono ve hibrit nanoyağlayıcı kullanılan ısı değiştiricili ve ısı değiştiricisiz deney sistemindeki COP değişimleri)

Mono and hybrid nanolubricants' total exergy destruction used in VCRSs with and without HEXs are shown in Figure 8. The mono and hybrid nanolubricants' exergy destruction decreases as the concentration enhances compared to POE. This can be defined by the fact that mono and hybrid nanolubricants with higher COP have lower total exergy destruction. The lowest total exergy destruction obtained in the experimental system without HEX was 451.24 W in 1 wt% TiO_2-B hybrid nanolubricant, and the highest total exergy destruction was 490 W in POE. In the experimental system with HEX, the lowest total exergy destruction is determined as 437.12 W in 1% TiO_2-B hybrid nanolubricant, and the highest total exergy destruction is calculated as 478.87 W. The usage of mono and hybrid nanolubricants in the experimental system with HEX led to significant improvement in the system.

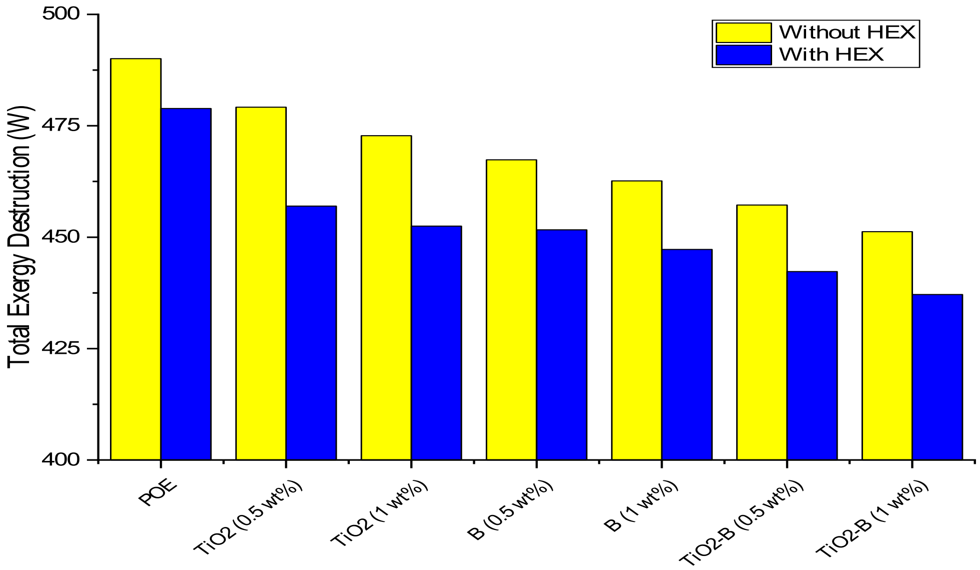

Figure 8. Total exergy destruction of the experimental system with and without HEX using mono and hybrid nanolubricants (Mono ve hibrit nanoyağlayıcı kullanılan ısı değiştiricili ve ısı değiştiricisiz deney sisteminin toplam ekserji yıkımları)

The exergy efficiencies of the VCRS with and without HEX for nanolubricants used at different concentrations are shown in Figure 9. The exergy efficiency of mono and hybrid nanolubricants compared to POE increased as the concentration increased. Exergy efficiency is inversely proportional to the total exergy destruction, which indicates the usability of the system. Exergy efficiency is generally parallel to the COP values of the experimental system using nanolubricants. This shows the importance of nanoparticles since heat transfer increases with increasing concentration. In the experimental system without HEX, the lowest exergy efficiency was obtained at 27.84% in POE, and the highest exergy efficiency was obtained at 34.43% in 1 wt% TiO_2-B hybrid nanolubricant. In the experimental system with HEX, the lowest exergy efficiency is 33.76% and the highest exergy efficiency is 43.37% in 1 wt% TiO_2-B hybrid nanolubricant. It is observed that hybrid nanolubricants used in VCRSs with and without HEXs have better exergy efficiency than POE and mono nanolubricants. This can be defined by the fact that the thermal properties of hybrid and mono nanolubricants should be taken into account at high concentrations.

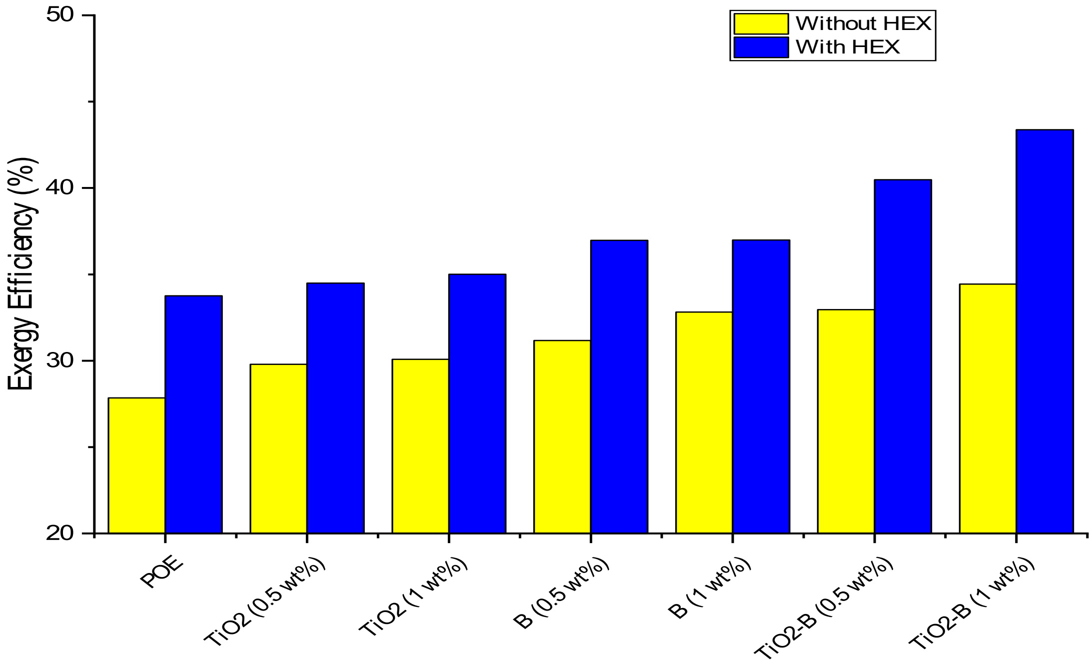

Figure 9. Exergy efficiency change of the experimental system with and without HEX using mono and hybrid nanolubricants (Mono ve hibrit nanoyağlayıcı kullanılan ısı değiştiricili ve ısı değiştiricisiz deney sisteminin ekserji verimi değişimleri)

The performance of VCRS using a counterflow tube-in-tube internal HEX is significantly increased. The efficiency of the internal HEX utilized in the VCRS also has great importance in the COP value of the VCRS. The efficiency coefficient of the counter-flow concentric tube HEX using mono and hybrid nanolubricants is given in Figure 10. As seen in Figure 10, higher efficiency values were obtained in the internal HEX using mono and hybrid nanolubricants compared to POE. As the concentrations of nanolubricants enhance, the efficiency of the HEX also enhances. The lowest efficiency value obtained in the internal HEX was 0.9367, while the highest efficiency value was 0.9843 obtained in 1 wt% TiO_2-B hybrid nanolubricant. By using mono and hybrid nanolubricants, the efficiency of the internal HEX was better than POE, which significantly affected the COP increase (See Figure 7). The positive effects of using nanofluids in tube-in-tube counter-flow HEXs are well known.

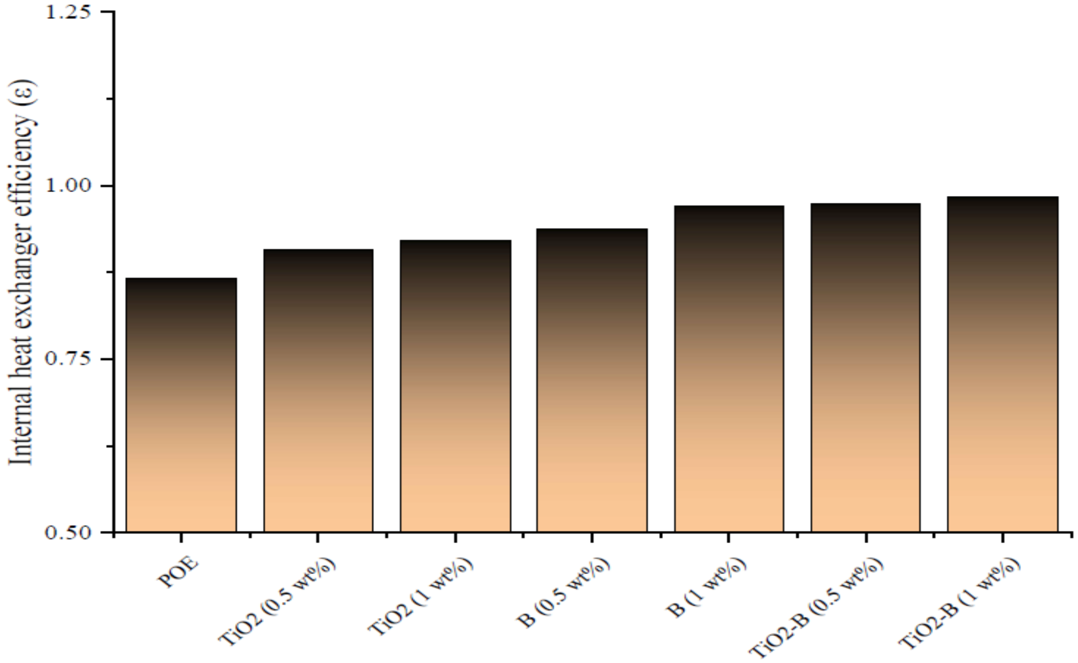

Figure 10. Efficiency changes of the internal heat exchanger (Dahili ısı değiştiricinin verimlilik değişimleri)

Today, while it is important to ensure efficiency in TESs, the environmental impacts of TESs and the reduction of these impacts are equally important because of the increase in global warming and the greater risk it poses in the future. The environeconomic analysis results are given in Table 6 to show the environmental effects of the experimental system with and without HEX of nanolubricants used at different concentrations. In the experimental system without HEX, the lowest amount was obtained as 0.18892 ¢/h in 1 wt% TiO_2-B hybrid nanolubricant, and the highest amount was obtained as 0.20521 ¢/h in POE. In the experimental system with HEX, the lowest amount was obtained as 0.17969 ¢/h in 1 wt% TiO_2-B hybrid nanolubricant, and the highest amount was obtained as 0.19544 ¢/h in POE. The most effective parameter in calculating environmental values is the energy consumption of compressors. Since lower energy consumption was achieved in the experimental system with and without HEX using mono and hybrid nanolubricants compared to POE, better environmentally friendly results were obtained in the experimental system using 1 wt% TiO_2-B hybrid nanolubricant. Hybrid nanolubricants were effective in increasing performance and contributed to the experimental system being more environmentally friendly.

Table 6. Processing parameters (İşleme parametreleri)

	Without HEX	With HEX
POE	0.20521	0.19544
0.5 wt% TiO_2	0.19164	0.18186
1 wt% TiO_2	0.19001	0.18621
0.5 wt% B	0.19109	0.18458
1 wt% B	0.19489	0.18186
0.5 wt% TiO_2-B	0.19164	0.18892
1 wt% TiO_2-B	0.18892	0.17969

4. CONCLUSIONS (SONUÇLAR)

Thermodynamic and environmental analysis of the VCRS with and without HEX were applied and interpreted using mono and hybrid nanolubricants at different concentrations (0.5 wt% and 1 wt%) in this study. Key improvements from the experimental system are presented below:

- In the experimental system used with and without HEX, mono and hybrid nanolubricants reached higher thermal conductivity values compared to POE. The highest thermal conductivity was determined as 54.57% increase in 1 wt% TiO_2-B hybrid nanolubricant compared to POE. In general, increases in thermal conductivity values were observed with increasing temperature and increasing concentration.

- Higher system performance was obtained with mono and hybrid nanolubricants utilized in the experimental system with and without HEX compared to POE. Compared to POE, there was an increase of 10.46% in 1 wt% TiO_2-B hybrid nanolubricant in the experimental system with HEX. It was determined that the COP value increased as the concentration of mono and hybrid nanolubricants increased compared to POE in the experimental system with and without HEX.

- Mono and hybrid nanolubricants utilized in the experimental system with and without HEX reduced the compressor's energy consumption. Energy consumption was reduced by 7.94% in the experimental system without HEX with 1 wt% TiO_2-B hybrid nanolubricant, and by 8.06% in the experimental system with HEX with 1 wt% TiO_2-B hybrid nanolubricant compared to POE. This can be defined by the fact that mono and hybrid nanolubricants reduce friction in the compressor and reduce the load on the compressor. Thus, the use of mono and hybrid nanolubricants in experimental systems with and without HEXs increases the performance of the compressor.

- Significant changes were observed in the mono and hybrid nanolubricants' total exergy destruction at different concentrations utilized in the experimental system with and without HEX. In the experimental system with and without HEX where mono and hybrid nanolubricants were used, total exergy destruction decreased as the concentration increased. According to the total exergy destruction POE, an improvement of 7.92% was obtained in the experimental system without HEX with 1 wt% TiO_2-B hybrid nanolubricant and 8.72% in the experimental system with HEX with 1 wt% TiO_2-B hybrid nanolubricant. This shows that the mono and hybrid nanolubricants utilized in the experimental system without and with HEX help the improvement of the system.

- In parallel with the COP of mono and hybrid nanolubricants utilized in experimental systems with and without HEXs, exergy efficiency also increases with increasing concentrations. In exergy efficiency, compared to POE, an improvement of 23.36% was achieved with 1% wt TiO_2-B hybrid nanolubricant in the experimental system without HEX and 28.48% with 1% wt TiO_2-B hybrid nanolubricant in the experimental system with HEX.

- It is observed that mono and hybrid nanolubricants at different concentrations utilized in the experimental system with and without HEX are more environmentally friendly than POE. This can be defined by the fact that mono and hybrid nanolubricants provide lower energy consumption compared to POE. Therefore, using mono and hybrid nanolubricants, less energy is used and less CO_2 will be released into the atmosphere by the compressor. The enviroeconomic value was improved by 7.94% with 1% wt TiO_2-B hybrid nanolubricant in the experimental system with HEX, and it was improved by 8.06% with 1% wt TiO_2-B hybrid nanolubricant in the experimental system without HEX.

Significant improvements in system performance, and thermodynamic and environmental performances were observed by using mono and hybrid nanolubricants in VCRSs with and without HEXs. In particular, using an internal HEX in the VCRS increases the system's performance, and mono and hybrid nanolubricants positively contribute to both performance and environmental aspects. In addition, the use of R1234yf as a refrigerant in the VCRS with and without internal HEX has made the system more environmentally friendly since its global warming potential and ozone depletion potential are lower than other HFC group refrigerants.

Nanofluids significantly help enhance the performance of TESs. However, they have some advantages as well as some disadvantages. One of the most important disadvantages is that the nanofluids obtained by two different methods undergo precipitation in the base fluid after a certain time. For this reason, the use of nanofluids cannot be used commercially in the refrigeration sector. Moreover, although mono nanofluids were widely used in past studies, the number of studies on binary and ternary combinations of nanoparticles is quite low. It would be more beneficial to increase the number of studies in this area.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The authors of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarları çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Kemal SARIOĞLU**:** He conducted the experiments, analyzed the results.

Deneyleri yapmış ve sonuçları analiz etmiştir.

Gökhan YILDIZ**:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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Nomenclature

Al_2O_3	Aluminum oxide	SEM	Scanning electron microscope
B	Boron	T	Temperature, K
CO_2	Carbon dioxide	TiO_2	Titanium oxide
COP	Coefficient of Performance	TES	Thermal energy system
CuO	Copper oxide	VCRS	Vapor compression refrigeration system
S	Entropy, kJ/K	$\dot{W}$	Power, kW
$\dot{E}x$	Exergy rate, kW	W_n	Uncertainties in the independent variables
h	Specific enthalpy, kJ/kg	w	Dimensional function
k	Thermal conductivity, W/m.K	W_R	Total uncertainty
$\dot{m}$	Mass flow rate, kg/s	z_{CO_2}	International carbon price
P	Pressure	Z_{CO_2}	Environmental cost
$\dot{Q}$	Heat transfer rate, kW	η	Efficiency, %
R	Uncertainty function	$\emptyset$	Particle volume fraction, wt.%
N_2	Nitrogen	μ	Viscosity of base fluid, Pa.s
PAG	Polyalkylene Glycol	ρ	Density
POE	Polyol ester oil	ψ_{CO_2}	Amount of CO_2 produced by the operation of coal-fired power plants
s	Specific Entropy, kJ/kg.K	φ_{CO_2}	CO_2 emissions' amount decreased by the VCRS
SiO_2	Silicon dioxide		

Subscript

bf	Base fluid	hnf	Hybrid nanofluid
comp	Compressor	in	Inlet
cond	Condenser	mec	Mechanical
dest	Destruction	nf	Nanofluid
el	Electrical	out	Outlet
evap	Evaporator	np	Nanoparticle
ex	Exergy	r	Refrigerant
exv	Expansion valve		