

## EXPERIMENTAL ASSESSMENT OF COMPARATIVE R290VS. R449A REFRIGERANTS BY USING 3E (ENERGY, EXERGY AND ENVIRONMENT) ANALYSIS: A SUPERMARKET APPLICATION

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### ABSTRACT

Efficiency is becoming an increasingly important issue in cooling systems. It is important to use micro channel heat exchangers in order to increase the cooling system efficiency. In this study, performance analysis of refrigerants used in supermarkets was tested experimentally. Thermodynamic analyses of the refrigerants were examined. The compatibility of R290 and R449A refrigerants with the environment has been experimentally observed. Energy, exergy, and environmental analyses were performed using R290 and R449a refrigerants based on the test results for 24 hours using double inlet and double outlet evaporator. Accordingly, in the experiments using R290, the exergy efficiency and COP value are 43.52 % and 2.09, respectively. In experiments using R449A, these values were found to be 22.28 % and 1.59. Exergy efficiency was increased by 48.81 % in experiments using propane. In addition, an increase of 24.12% was observed in the Coefficient of Performance (COP) value. Considering the environmental analysis results, the amount of CO<sub>2</sub> emitted by the R290 refrigerant to the atmosphere during the test period was 3.14 kg/h and R449A was calculated as 3.97 kg/h. It was seen in this study that the R290 refrigerant emits 26.22 % less CO<sub>2</sub> to the atmosphere.

**Keywords:** Comparative R290vs. R449A, Refrigerant, Environmental Analysis, Energy and Exergy Analysis

### INTRODUCTION

The most common and efficient method for cooling is air-source heat pump systems with a vapour compression refrigeration cycle. Refrigerants used in heat pump systems have environmental impacts such as ozone layer depletion and increasing the global warming. This situation has led to the publication of many international regulations such as the Kigali amendment to the Montreal Protocol [1, 2] and the F-Gas Regulation [3].

Chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants, which were used as refrigerants in cooling systems for many years, were banned by the Montreal Protocol (1987) [1] upon understanding that the refrigerants damage the ozone layer [4]. As a substitute, hydrofluorocarbon (HFC) gases developed as an alternative for the CFC and HCFC refrigerants, due to global warming effects, and the use of these gases was restricted by the Kyoto Protocol and the European Union (EU) [5].

The refrigerant with the composition of R125/R143a/R134a (44%/52%/4%) is R404A which has low toxicity and is not flammable. R290 was widely used in low and medium temperature applications such as supermarkets. The use of this refrigerant has been restricted as of 2020 according to the EU Regulation No 517/2014 [5, 6]. R448A, R449A, R452A refrigerants have been used as an alternative to R404A. Makhnatch et al. [7] demonstrated that R449A can be used instead of R404A owing to its suitable thermodynamic properties and acceptable maximum discharge temperature in the supermarket refrigeration system. They confirmed that a 4% increase in refrigerant charge can provide a similar COP between R404A and R449A. Vaitkus and Dagilis [8] reported that the reduction 13% in cooling capacity and the decrease was 4% in energy consumption for R448A and R449A according to R404A. They showed that the components of R448A and R449A were very close; therefore, the performance criteria were the same.

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R290 is an inexpensive and easily available natural coolant. Additionally, R290 has zero ozone depletion potential (ODP) and low global warming potential (GWP) compared to HFCs, which are known as a short-term alternative to CFCs and HCFCs. Kyoto Protocol (1997) planned the phasing out of HFCs by 2025-2040. By 2050, HFCs are predicted to contain approximately 9–19% of projected global CO<sub>2</sub> emissions. Therefore, it is urgent to popularize refrigeration technology using hydrocarbons as refrigerants such as R290. In recent years, the application of the R290 in the commercial refrigeration and air conditioners area has increased, but the refrigerant charge is limited due to safety reasons and industry regulations [9, 10].

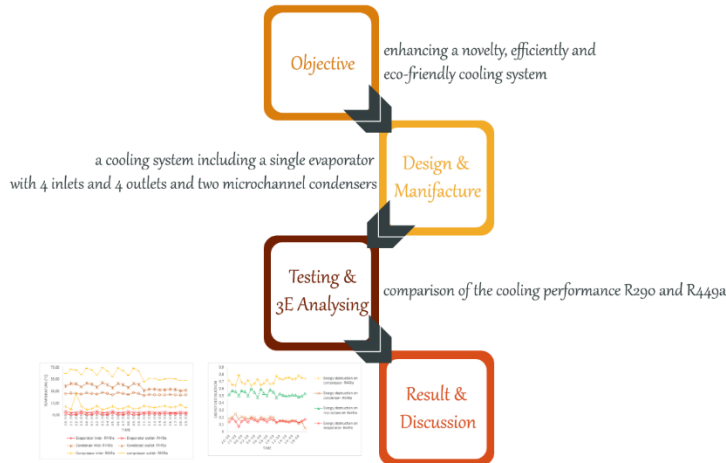
Among the refrigerants examined ref. [11], R290 was found to have global warming potential (GWP) and zero emission. R290 is regarded as an environmentally friendly, economical, and practical refrigerant with suitable cooling performance [12, 13].

Few studies have been found for R290 in two-circuit and two-temperature cycle refrigerant systems [14-16]. R290 is a natural refrigerant with a mass and volumetric cooling capacity of 87.7% and 54.2% higher than other refrigerants (R134a), respectively [6]. In other studies, R290 was used in air conditioning and heat pump systems [17, 18]. It was found that there was an improvement of 16.71% in the COP value in the steam compression refrigeration cycle, and it was observed that the cooling capacity increased by approximately 35% [15, 19]. Studies have proven that R290 can replace many refrigerants in domestic applications [20, 21].

Tian et al. [22] experimentally investigated the performance of the ACs operating with both R32/R290 and R410A. The experimental results indicated that the refrigerant charge amount of R32/R290 decreased by 30–35%. The cooling and heating capacities increased by 14–23.7%. For further decrease in the charge amount and flammability, a micro-channel heat exchanger (condenser) was employed to replace the finned tube one. Compared with R32/R290 system using the finned tube heat exchanger, the charge amount and power consumption of R32/R290 decreased by 34.1 and 0.4%, respectively; the cooling capacity and the COP increased by 6.4% and 6.8%, respectively.

When the literature is examined, it is seen that microchannel heat exchangers have many advantages. Microchannel heat exchangers have high heat transfer coefficients. They are lightweight due to their small size. Another advantage of its dimensions is that it can work with less amount of working fluid. Because of these advantages, microchannel heat exchangers are preferred as condensers and evaporators in cooling systems [23]. Xu et al. [24] experimentally and numerically analysed the performance of a microchannel condenser used in a domestic air conditioning system with R290 refrigerant. Results showed that the cooling capacity of the microchannel condenser system increased by 1.6%, and the system refrigerant charge decreased by 28.3%. Tosun et al. [25] examined the use of microchannel condenser in a household refrigerator with different amounts of refrigerant and the different sizes of capillary integration. As a result of experimental studies, the best combination of 50 g refrigerant and 3.25 m capillary for better performance was found. Cremaschi and Yatim [26] investigated the retention of oil in a microchannel condenser and evaporator of an R134a cooling system and the effect of circulating oil on heat transfer capacities and pressure drops in the microchannel heat exchangers. It was emphasized that the heat capacity of the evaporator varied between 5% and 12%, and the pressure drops increased significantly.

From the given literature, it is understood that various studies have been conducted on R290 and R449A, and microchannel condenser. The aim of this study is to design a novel, efficient, and eco-friendly cooling system especially for use in supermarkets. For this purpose, a cooling system consisting of a single evaporator with 4 inlets and 4 outlets and two microchannel condensers has been designed. This cooling system was experimentally tested with both R290 and R449A refrigerant. The variation of package temperatures in the cooling of this system was investigated, too. The experiments were carried out in the test room under at the 25 °C and 60% relative humidity. In the designed cooling system, 3E analysis for both refrigerants were made, their performances were evaluated, and the results were compared with each other. The structure of this study is summarized in Figure 1.

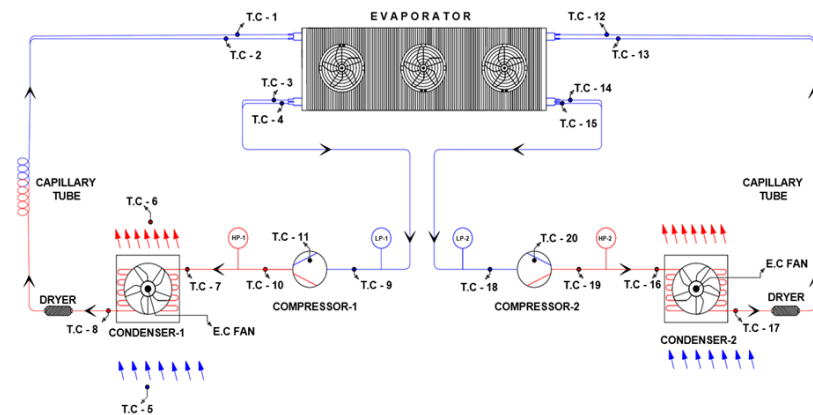


**Figure 1.** Structure of this study

## MATERIALS AND METHODS

### System Description

The schematic view of the designed cooling system is shown in Figure 2. This system mainly consists of a single evaporator, two microchannel condensers, two compressors, two capillary tubes, and other elements. This cooling system, which has a single evaporator, has two cooling cycles operating parallel to each other. The evaporator is designed so that the refrigerant coming from both cycles enters the evaporator through two inlets and exits the two outlets. The reason for this is to increase the cooling capacity by providing a homogeneous cooling in the evaporator. The dimension of the evaporator in the cooling system is 1.565x0.493x0.105 m, and the condenser dimension is 0.500x0.241x0.070 m. Thus, the size of the cooling system is 1.875x2x0.880 m. In addition, superheat was applied at 8 K temperature to prevent liquid refrigerant from entering the compressor.



**Figure 2.** The schematic view of the designed cooling system

The experiments were carried out in Nurdil Cooling Company's test room with calibrated test devices within the scope of TS EN ISO 23953-2 standard. The photographs of the experimental setup are shown in detail in Figure 3. In this system, energy consumption, temperature measurements, pressure measurements were performed throughout 24 hours. Temperature measurements were taken every minute by means of thermocouples from certain points of cooling systems equipment (compressor, condenser and evaporator inlet-outlet temperature values, cooled packing temperature).

Experimental setup and technical detail of the equipment is given Figure 3. Refrigerator where the temperature of the products is tested shown (Figure 3a). Dimension of the Test room (Figure 3b and Figure 3c) is measured as 1.88x2x0.88 m. Last figure is show the Compressors of the experimental setup (Figure 3d).



**Figure 3.** Photographs of the experimental setup

Some parameters were measured with energy analyzers in the test rooms. Parameters such as the energy consumption values of the system, pressure transmitters, low-high pressure values and the flow rate of the refrigerant are among these measured values. Information on measurement equipment used in experiments and tests are given in Table 1.

**Table 1.** Measuring instruments used in experiments

Device	Model	Measuring Range	Unit	Accuracy
Thermocouple	Omega, CL-23A	-40 / +150 °C	°C	± % 0.02
Pressure transmitter	Eliwell, HP	0-30 bar	bar	± 0.1 bar
Pressure transmitter	Eliwell, LP	0.5-8 bar	bar	± 0.01 bar
Thermohygrometer	Rotronic, M23W2HT-1X	0 / +50 °C 0-100 %RH	°C / %RH	± % 1.5 RH ± 0.03 °C
Anemometer	E+E Electronic, EE66-VA3 EE660-V7	0-2 m/s	m/s	± 0.01
Vacuum pump	Value, VP2200	0.04-0.8 Pa	Pa	±0.02
Digital scales	Value, VES-100B	0-100 kg	g	± % 0.05
Digital manifold	Testo, 550	-50 / +150 °C -1 / +60 bar	bar	± 0.1 °C ± 0.01 bar
Energy analyzer	Janitza, UMG508	-	Ampere Volt	Current ± % 0.2 Voltage ± % 0.1
Flowmeter	Siemens, SITRANS FC MASS 6000	0-1000 kg/h	kg/h	± % 0.1

### Energy and Exergy Analysis

To specify the exergy losses or destructions in the system, thermodynamic analysis is made. In this study, the following assumptions are made:

1. Steady state conditions remain in all the components.
2. Pressure losses in the pipelines are neglected.
3. Heat gains and heat losses from the system or to the system are not considered.
4. Kinetic and potential energy and exergy losses are not considered [27-29].

Details of the acceptance analysis for experiments is given in Table 2. It can be seen from Table 1 that the superheating and supercooling temperature are 8 K and 5 K, respectively.

**Table 2.** Acceptance details for the analysis

Parameter	(unit)	Value
Evaporation temperature	(K)	263
Condensation temperature	(K)	318
Superheating	(K)	8
Supercooling	(K)	5
Isentropic efficiency	(%)	83

The amount of heat transferred from evaporator is given Eq. (1) [27-29]:

$$\dot{Q}_{eva} = \dot{m} (h_1 - h_4) \quad (1)$$

The amount of heat transferred from condenser is given as Eq. (2):

$$\dot{Q}_{con} = \dot{m}(h_2 - h_3) \quad (2)$$

The compressor capacity and the electrical power of the compressor can be calculated using Eq. (3).

$$\dot{W}_{comp} = \dot{m}(h_2 - h_1) \quad (3)$$

The coefficient of performance (COP) corresponding to the energy consumed by the compressor per unit time and the heat transferred from the evaporator per unit time is given in the Eq. (4):

$$COP = \frac{\dot{Q}_{eva}}{\dot{W}_{comp}} \quad (4)$$

Exergy flow for each point is given Eq. (5):

$$\dot{E}_x = \dot{m} [h - h_0 - T_0(s - s_0)] \quad (5)$$

Exergy destruction on compressor is calculated by Eq. (6):

$$\dot{E}_{x,dest,comp} = \dot{m} [(h_1 - T_0s_1)] - [(h_2 - T_0s_2)] + \dot{W}_{comp} \quad (6)$$

Exergy destruction on condenser is calculated by Eq. (7):

$$\dot{E}_{x,dest,con} = \dot{m} [(h_2 - T_0 s_2)] - [(h_3 - T_0 s_3)] - \left[ \dot{Q}_{con} \left( 1 - \frac{T_0}{T_{con}} \right) \right] \quad (7)$$

Exergy destruction on evaporator is given by Eq. (8):

$$\dot{E}_{x,dest,eva} = \dot{m} [(h_1 - T_0 s_1)] - [(h_4 - T_0 s_4)] - \left[ \dot{Q}_{con} \left( 1 - \frac{T_0}{T_{eva}} \right) \right] \quad (8)$$

Microchannel exergy destruction is given by Eq. (9):

$$\dot{E}_{x,dest,mch} = \dot{m} [T_0 (s_3 - s_4)] \quad (9)$$

Finally, total exergy destruction can be defined as Eq. (10):

$$\sigma_{total} = \sigma_{ext,p} + \sigma_{ext,m} \quad (10)$$

It is important to perform energy exergy analysis in refrigerant systems. Therefore, the exergy balance for the steady flow control volume in this study is given Eq. (11) and Eq. (12):

$$\eta_{ex} = \frac{\dot{E}_{x,4} - \dot{E}_{x,1}}{\dot{W}_{comp}} \quad (11)$$

$$\eta_{ex} = \frac{\dot{m} [(h_1 - T_0 s_1)] - [(h_4 - T_0 s_4)]}{\dot{m} (h_2 - h_1)} = \frac{[(h_1 - T_0 s_1)] - [(h_4 - T_0 s_4)]}{(h_2 - h_1)} \quad (12)$$

### Environmental analysis

In this study, an environmental analysis was carried out to investigate how environmentally friendly R290 and R449A refrigerants were. However, the compressors in the system work with electricity. In the production of this electrical energy, carbon dioxide (CO<sub>2</sub>) emission is created depending on the fuel source of the power plant. In this part of the study, CO<sub>2</sub> emissions will be calculated for each refrigerant based on compressor power consumption. To perform this calculation, the system's compressor (for all refrigerant applications) is assumed to be running for 24 hours. However, only the compressor power consumption is evaluated. Fan etc. It is not taken into account in the power consumption analysis of the equipment.

Environmental economy analysis is based on the CO<sub>2</sub> emission price and the amount of carbon emitted. This analysis is valuable in obtaining a carbon price to reduce greenhouse gas emissions. The carbon price approach is a good approach for cost calculation of greenhouse gases. To prevent greenhouse gases being released into the atmosphere, having a price of CO<sub>2</sub> emitted will result in a reduction of the carbon emitted. This will also reveal the importance of renewable energy technologies. [30]. In another study, the average CO<sub>2</sub> equivalent density for electricity production from coal was stated as 960 g CO<sub>2</sub>/kWh [31]. Indeed, this rate will be 2.08 kg CO<sub>2</sub>/kWh, considering 40% transmission and distribution losses and 20% losses due to insufficient electrical appliances used [32]. Therefore, CO<sub>2</sub> reduction for refrigerant system is given in Eq. (13):

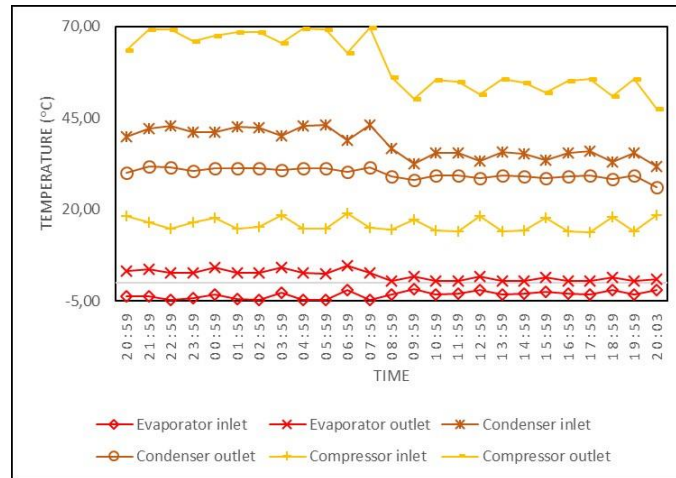
$$\Phi_{CO_2} = \Psi_{CO_2} \times \dot{W}_{comp} \quad (13)$$

where  $\Phi_{CO_2}$  represents the amount of CO<sub>2</sub> (kg CO<sub>2</sub>/h) reduced per hour and  $\Psi_{CO_2}$  indicates the average amount of CO<sub>2</sub> emissions (2.08 kg CO<sub>2</sub>/kWh) generated during the production of energy from coal.

## RESULTS AND DISCUSSION

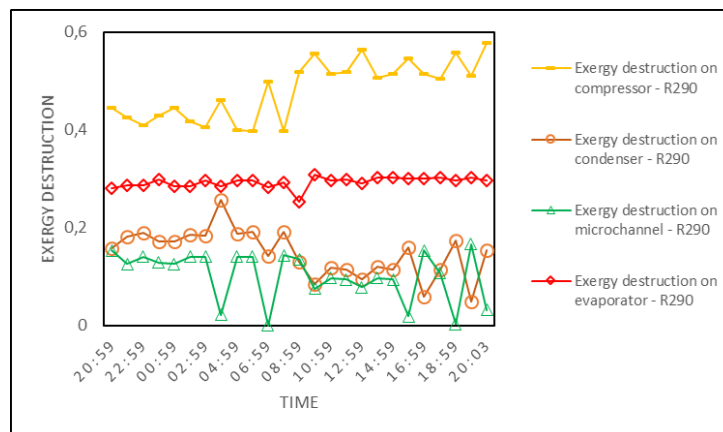
In the refrigerator system with an internal microchannel, the thermodynamic analysis of R290 and R449A refrigerants as an alternative refrigerator were analysed according to the first and second law of thermodynamics in this paper.

The temperature of the experiment using R290 as the refrigerant is given in the Figure 4 which shows the input-output temperatures of the system components. Compressor's maximum, minimum and average inlet-outlet temperatures were measured as 19.03-69.42 °C, 13.84-47.58°C, and 15.94-60.42°C, respectively. Condenser maximum, minimum and average temperature values were measured as 43.05-31.74°C, 31.80-26.06°C, and 37.98-29.85°C; evaporator temperature values were measured as -1.94-4.55°C, -4.78-0.50°C, and -3.33-1.99°C.



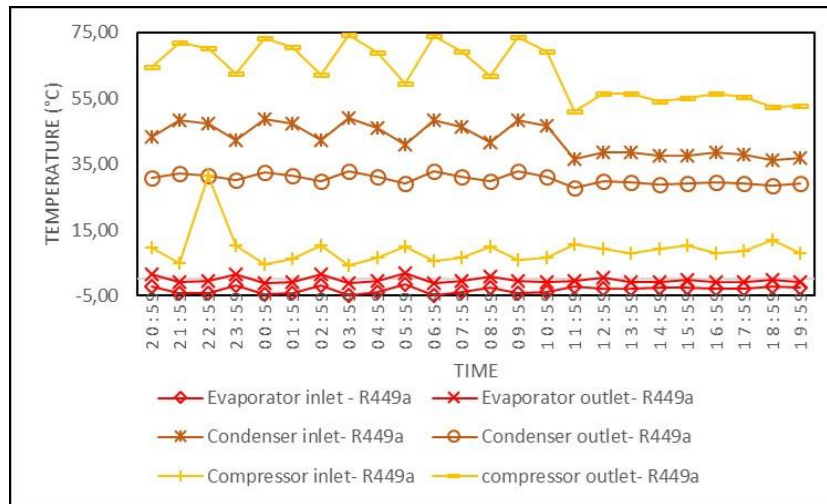
**Figure 4.** Temperature of the system components where R290 was used as refrigerant

The exergy destruction of the system elements according to the measurement moment is shown in Figure 5. According to Figure 5, the highest exergy destructions of the compressor, condenser, microchannel and evaporator are 0.5556 W, 0.2571 W, 0.1533 W and 0.3094 W; minimum values are 0.4090 W, 0.0480 W, 0.0031 and 0.2525; the average values are 0.4816 W, 0.1477 W, 0.102 W and 0.2930 W determined, respectively. It has been observed that the biggest exergy destruction in the system is in the compressor. It refers to exergy destruction irreversibilities or assessing the degraded resources and specifies the elements in the system where destruction is occurring. Thus, by improving the compressor in the R290 refrigerant cooling system, exergy destruction can be reduced and the system can operate more efficiently.



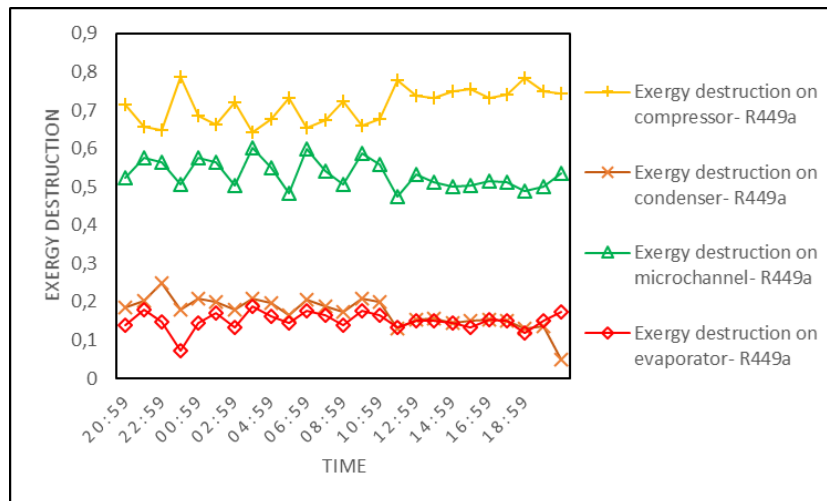
**Figure 5.** Exergy destruction of the system components where R290 was used as refrigerant

The temperature of the experiment using R449A as the refrigerant is given in Figure 6 which shows the input-output temperatures of the system components. Compressor's maximum, minimum and average inlet-outlet temperatures were measured as 19.03-69.42°C, 13.84-47.58°C, and 15.94-60.42°C, respectively. Condenser maximum, minimum and average temperature values were measured as 43.05-31.74°C, 31.80-26.06°C and 37.98-29.85°C; evaporator temperature values were measured as -1.94-4.55°C, -4.78-0.50°C and -3.33-1.99°C



**Figure 6.** Temperature of the system components where R449A was used as refrigerant

Figure 7 shows the exergy destruction of the components in the system where R449A was used. Accordingly, the highest exergy destructions of the compressor, condenser, microchannel and evaporator are 0.7857 W, 0.2489 W, 0.6007 W and 0.1765 W; minimum values are 0.6417 W, 0.1294 W, 0.4819 and 0.0719; the average values are 0.7126 W, 0.1764 W, 0.4695 W and 0.21503 W, respectively. Similarly, the exergy destruction of the compressor was the highest in the R449A refrigerant cooling system. With the improvement of the energy-consuming device compressor in the system or the reduction of energy consumption, the performance of the system will increase even more.

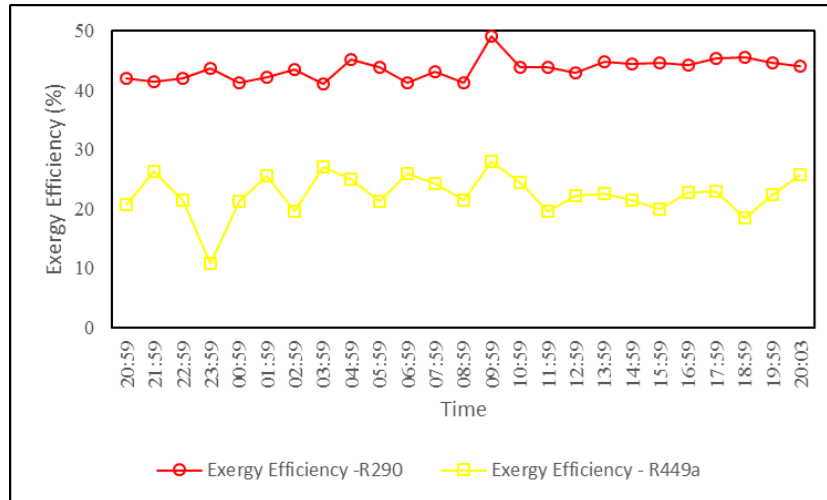


**Figure 7.** Exergy destruction of the system components where R449A was used as refrigerant

The comparative exergy efficiency of R290 and R449A refrigerants used in the experiments is given in Figure 8. Accordingly, in the experiments where R290 was used as refrigerant, maximum, minimum and average

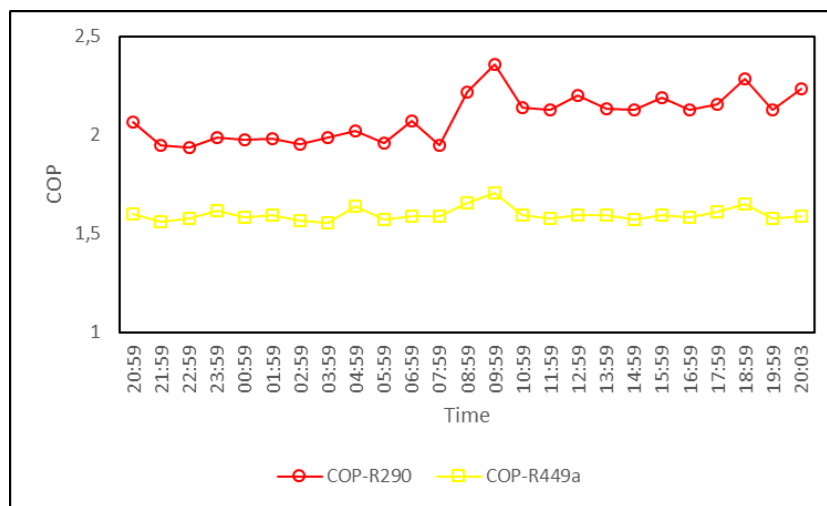


exergy efficiencies were calculated as 45.55%, 41.11% and 43.52%, respectively. On the other hand, in the experiments where R449A was used as refrigerant, these values were determined as 27.12%, 17.81% and 22.28%, respectively. Comparing average exergy efficiencies, it was observed that R290 produced 48.8% more useful energy than R449A.



**Figure 8.** Exergy efficiency of the system

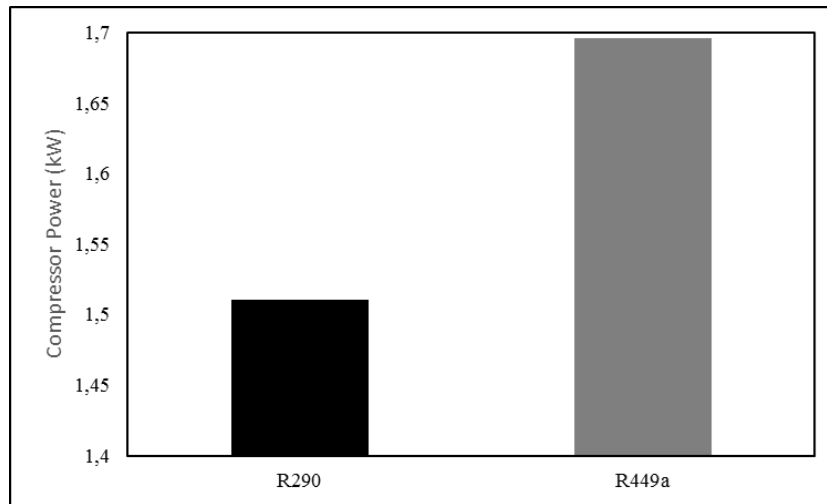
The comparative COP values of the system are given in the figure below (Figure 9). Accordingly, the maximum, minimum and average COP values obtained in the experiment using R290 refrigerant were determined as 2.36, 1.95 and 2.09, respectively, while these values were found to be 1.71, 1.53 and 1.59 for R449A refrigerant. It is known that in heat pump systems, when the heat transfer in the condenser is better or when the energy consumption in the compressor is decreased, the system increases the cooling performance. R290 refrigerant was calculated to be 23.92% more efficient compared to R449A.



**Figure 9.** COP value of the system

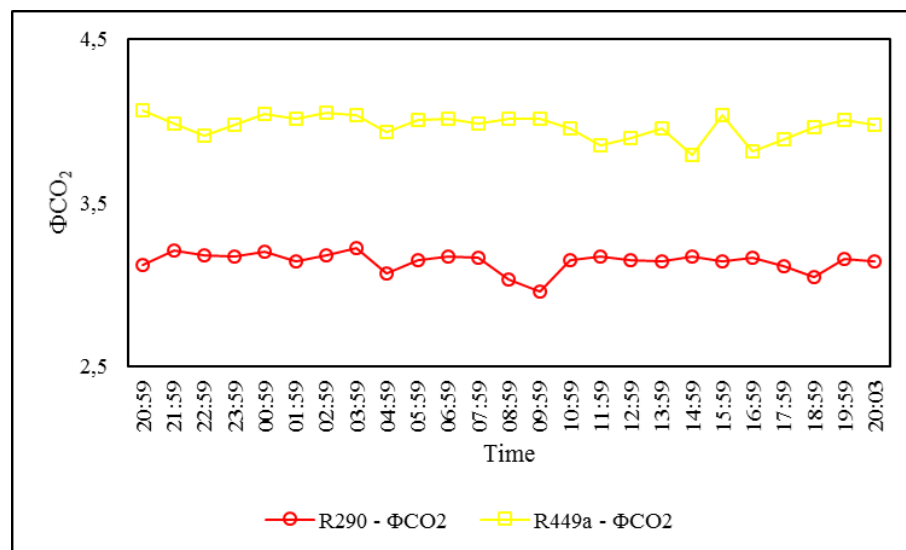
Figure 10 shows the power (kW) used by the compressor as a result of the use of refrigerant. Accordingly, while the power consumed by the compressor was 1.51 kW as a result of the use of R290, and 1.70 kW of power, as a result of the use of R449A. The high power consumed by the compressor in the R449A refrigerant system also

negatively affected the COP, exergy efficiency, and exergy destruction. As a result, was been observed that R290 was a more efficient refrigerant than R449A.



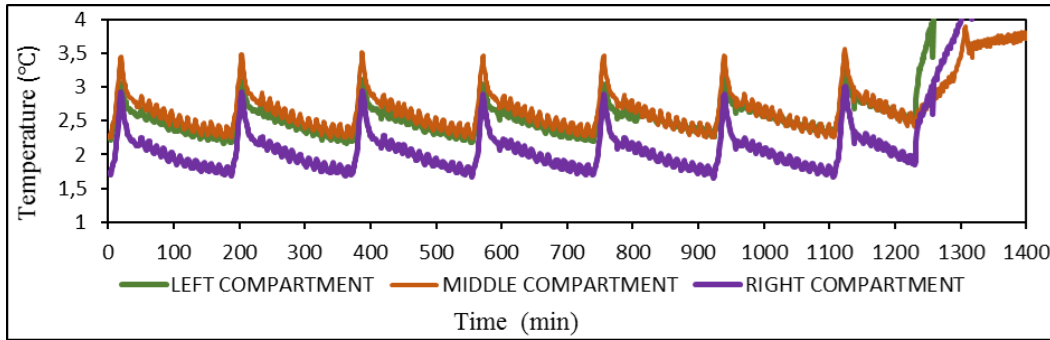
**Figure 10.** Comparison of the Compressor power (kW) value of R290 and R449A refrigerants

It is seen that the power drawn from the compressor is different as a result of the use of two different refrigerants used in the system. Accordingly, the difference in the amount of CO<sub>2</sub> emitted to the environment is shown in Figure 11. Accordingly, the maximum, minimum and average values of the amount of CO<sub>2</sub> emitted to the environment as a result of the use of R290 were calculated as 3.23, 2.96 and 3.14 kg/h. On the other hand, in the use of R449A, these values were calculated as 4.06, 3.85 and 3.97. As a result, 26.22% less CO<sub>2</sub> was released to the environment as a result of the use of R290 compared to R449A.



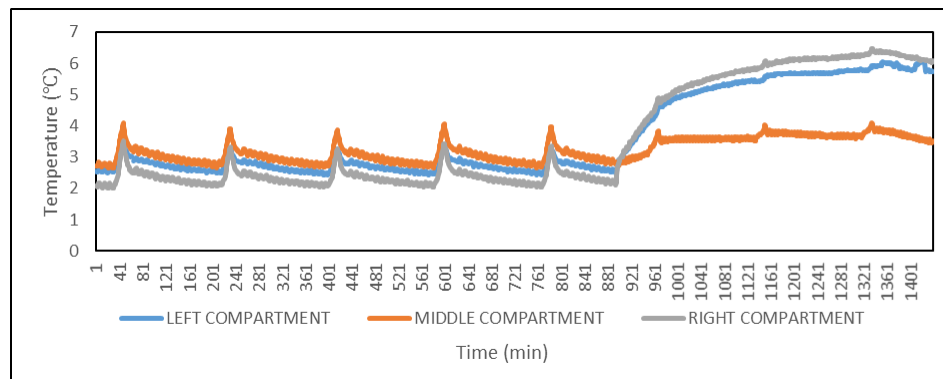
**Figure 11.** CO<sub>2</sub> emission value of the system

In the experiment, package temperatures of 48 products, which were located in different compartments of the industrial cooler, were measured with thermocouples. As a result of these measurements, the average temperature values of the products in the left, middle and right compartments were calculated as 3.05 °C, 2.778 °C and 2.44 °C, respectively, by using R290 as refrigerant (Figure 12).



**Figure 12.** Package temperature for refrigerant R290

For R449A package temperatures of 48 products calculated as 3.76 °C, 3.25 °C, 3.68 °C. As can be seen in Figure 13, it is observed that the temperature values of the products in different compartments in the industrial cooler increase overtime during the defrosting process and then decrease again. This temperature change was measured as an average of 3.066 °C on products.



**Figure 13.** Package temperature for refrigerant R449A

When the two systems with R290 and R449a refrigerant are compared in terms of COP, exergy efficiency, and CO<sub>2</sub> emission value, it is seen that the R290 refrigerant cooling system can provide a great advantage in terms of use in supermarkets. R290 refrigerant cooling system is both more performance and more environmentally friendly. The recommended cooling system with R290 refrigerant can be used reliably for many years in supermarkets.

## CONCLUSION

In this paper, the refrigerants R290 and R449A were thermodynamically analysed for a system with double inlet and outlet evaporators and microchannel heat exchangers. Based on the measured compressor energy consumption, energy-exergy analysis and environmental impact assessment were made for each refrigerant type. It is possible to list the results as follows:

- By using R290 refrigerant, it has been handled 48.8% more exergy efficiency.
- Using R290 higher 23.92% COP value obtained.
- It was observed that R449A consumed 11.18% more compressor power than R290.
- R290 emitted 26.22% less CO<sub>2</sub> than R449A.

According to these conclusion, R290 refrigerant has a better achievement compared to R449A. Both refrigerants are recommended to cooling in supermarket, R290 refrigerant is a good alternative when the environmental effects are considered together. In cases where R290 is used as the working fluid, it is important to make designs that will increase the performance of cooling systems (use of ejectors and use of internal heat exchangers, etc.).

## NOMENCLATURE

$\dot{E}_x$	Exergy, W
$h$	Enthalpy, kJ/kg
$\dot{m}$	Mass flow rate, kg/s
$\dot{Q}$	Heat transfer speed, kJ/s
$s$	Entropy, J/K
$T$	Temperature, K
$\dot{W}$	Electrical power capacity, kJ/s
$\Phi_{CO_2}$	Amount of CO <sub>2</sub> , kg CO <sub>2</sub> /h
$\Psi_{CO_2}$	Average amount of CO <sub>2</sub> emissions, 2.08 kg CO <sub>2</sub> /kWh

### Greek symbols

$\eta$	Efficiency
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### Subscripts

<i>comp</i>	Compressor
<i>con</i>	Condenser
<i>dest</i>	Destruction
<i>ex</i>	Exergy
<i>eva</i>	Evaporator
<i>mch</i>	Microchannel

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