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R290 Refrigerant Performance in a Commercial Refrigerator

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Abstract

In this study, we investigated the impact of the environmentally friendly R290 refrigerant, which has a higher Coefficient of Performance (COP), on the operating performance of the cooling system, as an alternative to the commonly used R404A refrigerant, which has a negative effect on global warming. The boundary conditions in the refrigeration cycle were designed to be -10°C evaporation and +45°C condensation, and the performance of the system referenced in the TS EN ISO 23953-2 standard was experimentally compared for both refrigerants. The temperature and energy consumption values of the M-packs, whose location and quantity are specified in the relevant standard, have been evaluated in terms of the cooling performance of the cabinet. As a result of the study, the heat removal performance of the system using R290 fluid in the condenser showed better results compared to R404A. According to the relevant standard, the system using R290 is in the C and D classes in the energy consumption evaluation.

Keywords: Global warming, R290, R404A, Cooler liquid, Cooling performance

Ticari Buzdolabında R290 Soğutucu Akışkan Performansı

Öz

Bu çalışmada, küresel ısınma üzerinde olumsuz etkisi olan ve yaygın olarak kullanılan R404A soğutucu akışkanına alternatif olarak, daha yüksek Performans Katsayısına (COP) sahip çevre dostu R290 soğutucu akışkanının soğutma sisteminin çalışma performansı üzerindeki etkisi araştırılmıştır. Soğutma çevrimindeki sınır şartları -10°C buharlaştırma ve +45°C yoğunlaştırma olacak şekilde tasarlanarak TS EN ISO 23953-2 standardı referans alınan sistemin performansı her iki soğutucu akışkan için deneysel olarak karşılaştırmıştır. İlgili standartta konumu ve miktarı belirtilen M-paketlerinin sıcaklık ve enerji tüketim değerleri dolabın soğutma performansı yönünden değerlendirilmiştir. Yapılan çalışma sonucunda R290 akışkan kullanılan sistemin R404A'ya göre kondenserde ısı atma performansı daha iyi sonuçlar sergilemiştir. İlgili standarda göre R290 kullanılan sistem enerji tüketimi değerlendirmesinde C ve D sınıfında yer almıştır.

Anahtar Kelimeler: Küresel ısınma, R290, R404A, Soğutucu akışkan, Soğutma performansı

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1. INTRODUCTION

The studies that started with the Montreal Protocol in 1987 to protect the ozone layer from the negative effects of refrigerants, reduce the greenhouse effect, and regulate the production and usage conditions continued with the 1990 London and 1992 Copenhagen meetings. These issues have been the subject of international agreements with the 1997 Kyoto Protocol and the United Nations Framework Convention on Climate Change in 2015. As a result of these protocols and agreements, it has been adopted to use refrigerants with 0 or lower Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) values.

Cooling, which we often use in our daily life and in industrial areas, can be performed physically, chemically or mechanically in three different methods. Mechanical refrigeration systems operating according to the principle of reverse Carnot cycle are used for food, cold storage, supermarket refrigeration, ice rinks, etc. it is used in many areas such as. Perishable food products are stored and displayed for a certain period of time in display cabinets. In these cooling systems, 60-70% of the energy is spent in the compressor and condenser. For this reason, it is necessary to reduce the energy consumption costs of cooling systems, improve the parts that consume too much energy and reduce their negative effects on the environment [1].

The studies for cooling and heating systems, which started with the Montreal Protocol in 1987, have been the subject of international agreements with the Kyoto Protocol of 1997 and the United Nations Framework Convention on Climate Change of 2015. These regulations are aimed at reducing the use and production of refrigerants with high GWP and ODP. The refrigerant most often used in supermarket cabinets is R404A. The ODP value of R404A refrigerant is zero, but the GWP ratio is high [2].

Scientists are giving priority to refrigerants with low GWP values and systems that will reduce the amount of charging in order to reduce the impact of refrigerants on global warming [3].
Trying to protect nature with laws and laws can only be within the scope of priorities and possibilities. Although there are quite a large number of refrigerants that can be used in market-type refrigerants, their effects on nature in terms of ODP and GWP ratio, usage quantities, suitability to the existing system and costs constitute their limitations in terms of usage. Today, the low cost of industrial cooling cabinets, the easy availability of cooling equipment and the fact that it is an environmentally friendly refrigerant make R290 gas an advantageous position for manufacturers to choose.

According to Devotta et. al., in their study, they compared the refrigerants R410A, R134a, R407C, R290, R32, R135 and R134a, which can be an alternative to R22 refrigerant for air conditioners, with experimental data. In the comparison made according to the COP value, it was concluded that the refrigerant R134a is close to the R22 gas, but large compressor selections should be made to ensure the capacity. R290 refrigerant has similar properties to R22, but in the study, where it was stated that the compressor variety is low, it was stated that R407C is the most suitable and useful refrigerant instead of R22 gas [4].

In their study, Spatz and Motta examined the efficiencies of R290 and R410A refrigerants by comparing them with R22 refrigerant. It has been experimentally shown that R290 refrigerant gives 5% better results than R22 [5].

In a study conducted by Kaya [6], the efficiency of the system in the steam compression refrigeration cycle was examined by using R404A refrigerant with zero ODP value instead of R22 refrigerant. As a result of this research, an increase in cooling capacity by 2.32% was achieved by using R404A refrigerant instead of R22 gas. In addition, the COP values of R22 and R404A refrigerants were found to be 2.12 and 1.91, respectively.

Bortolini et. al., in their study, they examined the availability and performance of R410A and R407F refrigerants that can be used instead of R404A refrigerant used in industrial refrigeration systems. In the cooling system at medium temperature values (10°C, -5°C), it has been calculated that the cooling capacity and COP values of R410A and R407F refrigerants are high compared to R404A gas. The cooling capacity and COP values calculated in the study were calculated as 1297 W and 1.47 for refrigerant R404A, 1417 W and 1.51 for R407F, 1342 W and 1.75 for R410A, respectively [7].

Llopis et. al. analysed five different refrigerants (R717, R744, R290, R1234ze and R152a) that can be used as a substitute for R404A and R134a refrigerants, and compared the energy analysis and environmental effects of refrigerants that can replace R404A and R134a gases with high GWP values. R717, R744, R290, R1234ze and R152a refrigerants were tested in the same system instead of R404A and R134a, which are often used in refrigeration systems. The best performance in the test results was given by a two-stage system using R404A refrigerant. However, due to the high GWP value, it has been stated that the choice of cascade cycle using R744 refrigerant, which has a low GWP value and is environmentally friendly, will be more appropriate [8].

In the study conducted by Kızılkan [9], the performances of seven refrigerants were compared for cold storage application. As a result of the study, the COP values of refrigerants R170, R744, R1270, R290, R600a, R717 and R600, respectively 1.463, 1.482, 2.366, 2.369, 2.448, 2.462 and it was found to be 2.5.

According to Makhnatch et. al. examined the use of R449A refrigerant instead of R404A in their study related to cooling systems. Due to its favourable thermodynamic properties and the maximum acceptable discharge temperature, it has been stated that R449A can be used in the cooling system designed for R404A with a slight expansion adjustment and a 4% coolant charge increase. Although the COP value of the R449A has a cooling capacity that is about 13% lower, it is almost the same as the COP value of the R404A. When it is desired to use R449A instead of R404A, it has been stated that it will be sufficient to adjust only the amount of refrigerant and the thermostatic expansion valve in the cooling system designed for R404A [10].
Sapali and Choudhari, analysed the use of R290 instead of refrigerant R22 in their study. As a result of the analyses carried out using the vapor compression cooling cycle, the performance of the R290 was lower than that of the R22. Due to the low GWP and ODP values, it was stated that it would be appropriate to use it as an alternative to R22 [11].

Yıldırım et. al. in their study, they analysed the energy analysis and environmental effects of R404A and its alternative R454C refrigerants in the refrigeration system. The analyses were performed for five different evaporator and condenser temperatures. As a result of the study, it was found that the COP value of R454 is about 4% higher than R404A [12].

Biçen, examined the use of R290 refrigerant instead of R404A in commercial type freezers. As a result of the examination, it has been concluded that R290 refrigerant does a better job for the condenser of the same size compared to R404A [13].

When the studies were examined, it was observed that the environmental effects of the refrigerants used in cooling systems, energy analyses and cooling performances were measured. Although the refrigerant used in supermarket cabinets in general is R404A, its use in refrigeration systems is prohibited according to the F gas regulation because its effect on global warming is too great.

In this study, which will support these studies and enrich the literature with a different perspective, the effects of R404A and R290 refrigerants on the availability and cooling performance in supermarket product display cabinets were experimentally investigated. In the experimental study, in order to compare the performance of refrigerants, no design changes were made to the cooling system, only compressor changes suitable for the fluids were made and cooling performance, energy consumption values and energy efficiency were compared.

2. MATERIALS AND METHODS

Refrigeration systems used in the field of industrial air conditioning are a closed circuit consisting of compressor, condenser, expansion valve, capillary tube and evaporator elements connected to each other in series [14]. The properties that refrigerants, which are the intermediate that provide heat transfer in the vapor compression refrigeration cycle, are required to have and expected from repair are too many. Decontamination. On this issue, Koyun et al. (2005); Calm, (2008); Abas et al., (2018); Demirci et al. (2020) and Araz et al. (2013) have provided detailed information in their studies [14-18].

The imitation elements used to simulate the operating conditions of the cabinet and to measure the cooling performance are called M-packages. In order to measure the temperatures of the M-packages placed in the cabinet, temperature sensors are installed in such a way that they directly contact the packages in accordance with the standard. A M-pack is an odorless solid rubber container with a density of 1 g/ml and is composed of 23% oxyethylmethylcellulose, 72-76% (vol.) water and the rest sodium chloride and 6-chloro-m-cresol. In the experiments conducted in accordance with TS EN ISO 23953-2 “Refrigerated Display Cabinets” standard, the way the M-packages are loaded into the cabinet and the temperature measurement points of the packages, the thermocouple placements, the interpretation of the performance criteria were made according to the conditions and rules specified in this standard [19].

The list of M-packs used in filling the cabinet are;

- 18 pieces 50x100x100 cm Thermocouple installed package
- 21 pieces 50x100x100 cm Standard package (500 g)
- 60 pieces 50x100x200 cm Standard package (1000 g)
- 12 pieces 50x50x200 Standard package (500 g)

The temperatures of the M-packages used for the cooling performance test in the cabinet, evaporator inlet-outlet temperatures and condenser suction-blowing temperature measurements were made with a T-type thermocouple. T-type thermocouple has ranges 150 to 400 °C, sensitivity 0.02 °C and limits of error ±0.5°C. 18 Thermocouples for test packages, 2 thermocouples for evaporator and 2 thermocouples for condenser are placed in the cabinet. The placement of the M test packages, and the temperature sensor numbers are shown in Fig-1. The test chamber is heat-insulated, the internal environment is set to be at a temperature of 25 ±1°C and relative humidity of 60 ±3%, and the air flow in the test chamber is December 0.1-0.2 m/s from the front face of the cabinet. The test chamber where the experiment was conducted covers Class-3 according to the standard.

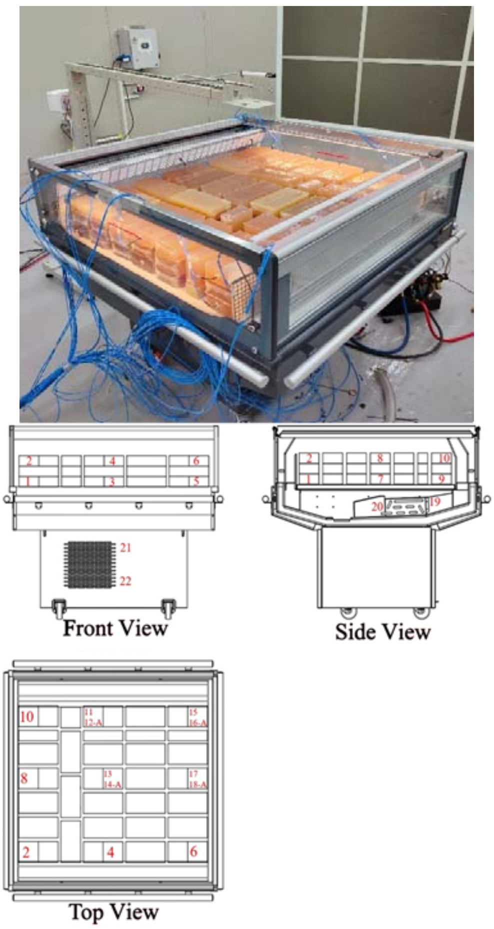

Figure 1. Placements of M test packages in the cabinet and thermocouple placements

The cabinet in the test assembly was tested under -10°C evaporation and +45°C condensation hot conditions. In the commercial display product cabinet, R404A refrigerant is usually used in low and medium temperature refrigeration applications, while R290 refrigerant is suitable for use in low temperature refrigeration applications, so it has been mandatory to use hermetic type compressors with different properties in the refrigeration system. In addition, in accordance with the relevant standard, R404A gas 630 g was used in the system, while R290 gas was charged to the tank in an amount of 90 g due to its A3 safety rating, flammable and explosive properties. The compressor characteristics according to the refrigerant used in the system are given in Table 1.

When the energy classification of the display cabinet is made, the type of cabinet, the volume and the temperatures of the M-packages are evaluated as criteria in addition to the energy consumed by the cabinet on a daily or annual basis. Within the scope of the study, these criteria and the display area of the cabinet are in accordance with TS EN ISO 23953-2 standard and were calculated in detail in the study by Saraç [20]. As a result of the calculations, the energy classes of R290 and R404A refrigerant systems were found to be C and D, respectively.

Table 1. Compressor specifications

	R290	R404A
Cooling Capacity (W)	396	465
Input Power (W)	162	276
COP Value	2.44	1.69
Evaporation Temperature (°C)	-10	
Condensation Temperature (°C)	45	

The performance tests of the refrigerants in the cabinet were carried out according to TS EN ISO 23953-2 standard. The types of M packages, their number and the positions of the packages and T-type thermocouple sensors have been adjusted as specified in the standard. The temperature values of the compressor's pressure-suction line, evaporator inlet-outlet pipes and the suction-blowing zone of the condenser fan were measured with the T-type thermocouple sensor. The evaluation was made according to the lowest – highest temperature M-packages. Since no design changes were made in the cabinet except for the mandatory compressor change, the lowest and highest temperature values of both fluids were obtained from the same numbered sensors.

Experimental data were obtained after the cabinet was operated for 24 hours before the experiments to ensure that the core temperatures of the M-packages placed in the cabinet reached equilibrium and to capture the necessary temperature values before starting the test. Data were taken from 22 temperature sensors placed in M packages every 60 seconds and their graphs were plotted. With the help of the analyser, the electrical forces attracted by the cabinet for both fluids were measured, and the energy class of the cabinet was determined.

Datascan 7020 was used to record the experimental data on the computer. Main features are direct sensor connection for DC voltages, Thermocouples, strain gauges, RTD's, resistance, and I6 bit measurement performance with 0.625µV sensitivity, and Accuracy +/-0.02% rdg +0.01%range+1bit. Entes brand MRP-26S-21 model analyser was used to evaluate the commercial cabinet used in the study according to its energy consumption value (Table 2).

Table 2. Entes analyser specifications

Measurement Range	10-300 VAC, 10-480 VAC
Communication Interface / Protocol	RS 485 / Modbus RTU
Operating Voltage	95-270 VAC/DC
Operating Frequency	50/60 Hz
Power Consumption	< 6 VA
Transfer Speed	2400 - 115200 bps
Nominal Current	In: 5A / 1A
Lowest Current	5 mA
Measurement Range	50 mA – 5.5 A
Accuracy	± 0.5%
Protection Class Terminal	IP20, IP40

Uncertainty analysis is needed to easily identify the variable that causes the most errors, to prove random errors or the accuracy of experiments. Even if the instruments used in the experiments are metrologically approved, the measurements contain different levels of errors. Uncertainty analysis gives us a methodological approach to the sensitivity of the results. The measurement errors caused by the test device is defined as the difference between the measured value and the real value and they are divided into two groups: random and systematic error. Random error is the difference between a single measured value and the average value of many individual measurements. The difference between the mean value of individual measurements and the true value is defined as systematic error. Errors that may occur in temperature measurement vary depending on the measuring instruments used in the experiments [21, 22].

The uncertainty (W_R) of the measured magnitude (R) in the system with respect to each independent variable (w_1, w_2, ..., w_n) can be calculated from the following Equation-1 [23, 24].

$$W_R=\sqrt{(\frac{\partial R}{\partial x_1}w_1)^2+(\frac{\partial R}{\partial x_2}w_2)^2+...+(\frac{\partial R}{\partial x_n}w_n)^2} \quad (1)$$

Table 3. Average uncertainties of some measured and calculated parameters

Parameter	Uncertainty (%)
Connection elements	0.1
Time measurement	0.1
Length and diameter	0.1
Temperature measurement	5.1
Energy consumption	7.1
Energy class determination	7.3

3. RESULTS

The temperature changes of the M-packages, temperature changes of the M-packages at the lowest and highest temperature, evaporator inlet-outlet temperatures, condenser suction-blowing temperatures and energy consumption data were examined in accordance with the TS EN ISO 23953-2 standard without any other changes in the cooling system except the compressor, which was changed compulsorily due to the properties of the fluid used, the humidity and temperature of the test chamber were kept under constant control in this study. The experiments were carried out over a 24-hour period, during which the average temperature value of the test chamber was measured as 57.2 °C and the humidity value was measured as 23.5%, and these values comply with the Climate Class-3 requirements of the TS EN ISO 23953-2 standard.
As a result of the 24-hour operation of the test cabinet, the average temperatures of the M-packages installed with the sensor are shown in the graph in Figure 2. The average temperature values for both refrigerants in the cabinet were calculated as 2.16 °C for R290 and 3.73 °C for R404A. As a result of the visualized and calculated data, it has been obtained that the cooling environment is 73% cooler in the system operated with R290 refrigerant.

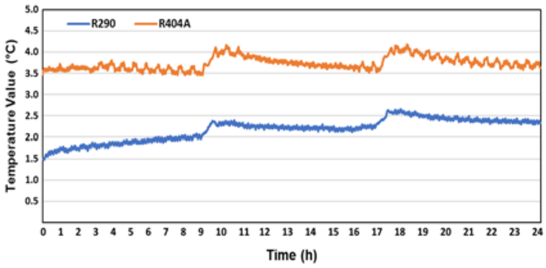

Figure 2. Average temperature graph of M packages

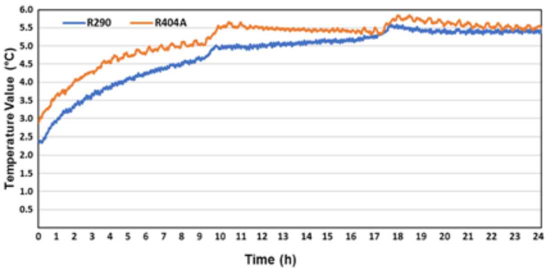

Figure 3. Temperature change graph of No.8 M-packages for R404A and R290

In Figure 3, the temperature change of the M-package to which the sensor No. 8, which has the highest temperature value during the cooling process with refrigerants R404A and R290, is connected, is graphically given. In the performance evaluation performed according to the cooling of M-packages, the highest temperature values for R404A and R290 gases were taken from the M-package in which the sensor No. 8 was installed, and these values were measured as 5.69 °C and 5.85

°C respectively. The reason why M-package No. 8 is the highest temperature product in both fluids is that the design of the cabinet has not been changed. When the two refrigerants are compared for the hottest products, there does not seem to be a significant temperature difference. But 8 hours after the start of the experiment, M-package No. 8 reached a temperature of 5 °C with R404A gas and then remained stable at a temperature of 5.5°C for 7 hours. Reaching a temperature of 5°C with R290 gas took about 10 hours, and then reached a temperature of 5.5°C only in 8 hours. the highest temperature value reached in R404A gas for M-package No. 8 was measured as 5.85°C, while R290 was measured as 5.69°C.

When the cooling performance of M-packages on the side of different refrigerants is examined, the M-packages to which sensor number 13 is connected are the ones with the lowest temperature. according to the data obtained from sensor No. 13, the temperature values for refrigerants R404A and R290 were obtained as 0.97°C and -1.36°C. Due to the fact that the difference between the lowest temperature values of the two refrigerants is 2.33°C and the cooling curve graphs are smoother, as shown in Figure 4, the cooling performance of the R290 has been interpreted as better. In the first stage of the cooling experiment in both fluids, thanks to the compressor, it provided a temperature drop of about 2°C, while in other studies it provided a temperature drop of 1°C each.

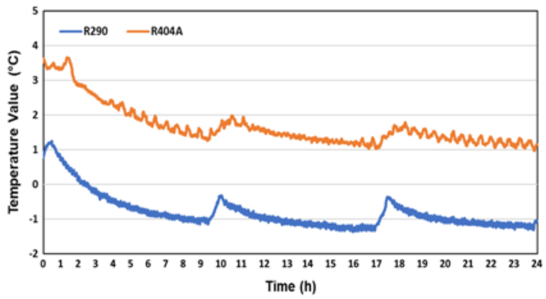

Figure 4. Temperature change graph of No.13 M-packages for R404A and R290

The graph in Figure 4 shows that the temperature of the M-package increases after the compressors stop automatically. With the R290, the temperature increase is linearly fast, and then the compressor is activated, significantly reducing the temperature of the product. When the compressor stops in the R404A fluid, the temperature increase draws a parabolic curve, while the temperature decrease was not much when the compressor was activated.

The graphs drawn according to the data obtained from the thermocouple sensors in the evaporator inlet and outlet pipes of the refrigeration system using R404A and R290 refrigerant are shown in Figure 5. It is ideal that the difference between the evaporator inlet and outlet temperature is 10°C, and it is desirable that the refrigerant should be at a temperature close to -10°C at the evaporator inlet and 0°C at the outlet. Dec. While these desired conditions could be achieved with R290 gas, they could not be achieved with R404A gas.

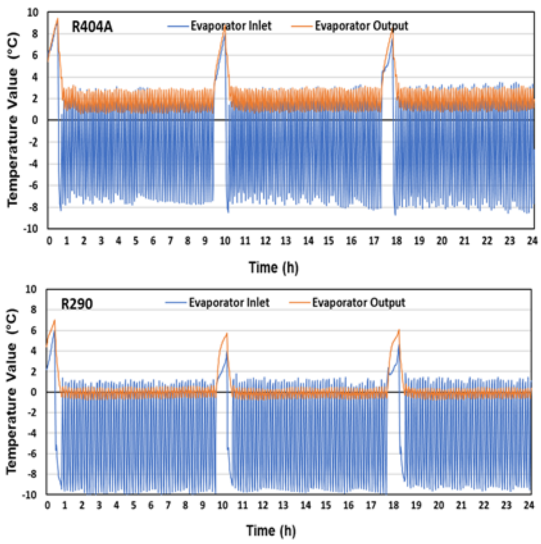

Figure 5. Graphs of evaporator inlet and outlet temperatures for R404A and R290

The evaporator inlet temperature values were measured as -8.73 and -10.38°C for R404A and R290, respectively. According to these values, R290 refrigerant is 18% more efficient than R404A. In order to obtain the desired operating values with R404A gas, it is necessary to make changes in the design and cooling elements of the cooling system.

During the experiments, the ambient temperature at which the cooling system was operating was approximately 25°C, while the fan blowing temperature value was measured as 29.8°C.

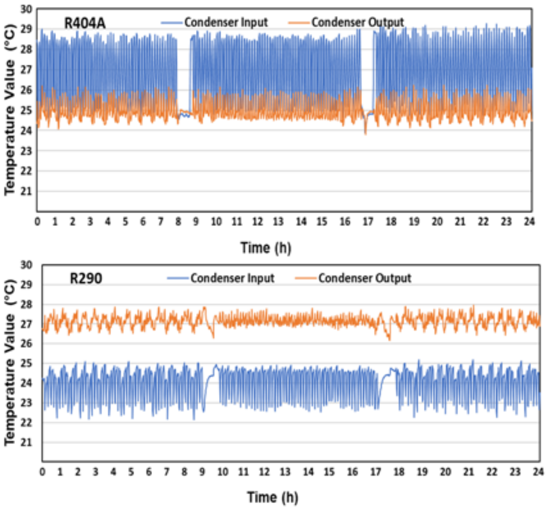

Figure 6. Condenser suction and blowing temperature graphs for R404A and R290

The result of the measurements made by placing thermocouple sensors in the suction and blowing areas of the condenser is shown in Figure 6. With this graph, it is possible to decide whether the condenser is sufficient for the system. In the system using R290 refrigerant, the air absorbed from the environment at a temperature of 25°C is expelled from the condenser as a maximum of 28°C (ΔT= 3°C), similarly, in the system using R404A refrigerant, ΔT= 4.8°C was measured. No heat was observed in the condenser in both refrigerants.

According to these graphs, it can be concluded that the condenser is suitable for use in two refrigerants, and the cost can be reduced by reducing the condenser capacity by 21% and 57% for R404A and R290, respectively, with the area covered by the cooling system.

It was measured that the system operates at a maximum power of 150 W with R290 gas and 250 W with R404A, since it is mandatory to use different compressors in the system due to the different properties of refrigerants. The EMC 3121U model compressor used in the R290 fluid system for 24-hour power consumption measurements of R290 and R404A refrigerant systems under 220 V - 50 Hz operating conditions works in 4-minutes periods. Together with the defrosting times, the compressor worked for 12 hours and 13 minutes in a 24-hour period. In the R404A fluid system, the working period of the EMT 6165GK compressor was 3.5 minutes and the total working time was 11 hours and 32 minutes. The 24-hour power consumption values of the systems using R290 and R404A refrigerants were measured as 95 and 155 Watts, respectively. The system using R290 refrigerant has realized 63% less energy consumption in energy consumption.

4. CONCLUSION

In order to compare the cooling performances of the systems using R404A and R290 as refrigerants, the temperatures of the M-packages, the compressor pressure-suction line, the evaporator inlet-outlet pipes and the suction-blowing region of the condenser fan were measured in accordance with the TS EN ISO 23953-2 standard in this study and the energy consumption was compared. With the study conducted, the following results were found:
The R290 refrigerant system performs close to the M1 class specified in the standard, while the R404A refrigerant system is in the M2 Class.

There is a temperature difference of 1.57°C between the average product temperatures between the system used R290, and R404A. For this reason, the cooling efficiency of the R290 system in the cabinet is higher.

It has been determined that the region where sensor number 8 is located is less cooled than other regions. The reason for this is interpreted as the air circulation of the cabinet does not show a homogeneous distribution, and better cooling can be achieved in this region with a design change.

The condenser capacity of R404A refrigerant system is 33% larger than R290. For this reason, the same cooling efficiency can be achieved with a condenser with a capacity as small as 30% in the systems used R290.

When the heat dissipation performances of the same condenser are examined, the R290 refrigerant cycle performs 57% better.
The reason why the energy consumption of the R404A refrigerant system is higher is that the cooling capacity of the compressor of this system is 17% larger than that of the R290.

Since the condenser efficiency of the R290 refrigerant system is better, a decrease in the electrical energy used by reducing the rotation speed of the fan motor can be achieved by using a fan speed controller in the system. It will reduce the efficiency of the condenser by reducing the condenser fan speed. But this situation can provide customer satisfaction by making the cabinet work more noiselessly.

When the evaporation temperatures for both refrigerants are examined, they are -10.38°C and -8.73°C for R290 and R404, respectively. In other words, the cooling capacity provided by the R404A with less gas charge can be provided with the R290 refrigerant.

Since there will be less gas charge in systems with R290 refrigerant, smaller diameter pipes and smaller condensers can be used. With the reduction of the condenser, an increase in the internal area of the cabinet can be achieved.

Due to the different properties of the fluids used, the system with R290 is 63% more efficient in terms of energy consumption since different compressors are used in addition to the amount of fluid usage.

5. ACKNOWLEDGMENTS

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