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The effect of condenser type and refrigerant type on the two-stage vapour compression refrigeration system: an experimental study

Kondenser türü ve soğutucu akışkan türünün iki kademeli buhar sıkıştırmalı bir soğutma sistemine etkisinin deneysel incelemesi

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The Effect of Condenser Type and Refrigerant Type on the Two-Stage Vapour Compression Refrigeration System: An Experimental Study

Highlights

- *An experimental investigation of micro channel condenser*
- *Presentation of variation between the coefficient of performance (COP) and refrigerants*
- *Showing the effect of condenser and evaporator temperature*
- *Analyzing energy consumption amounts*

Graphical abstract

COP values were obtained from the experiments for eight configurations.

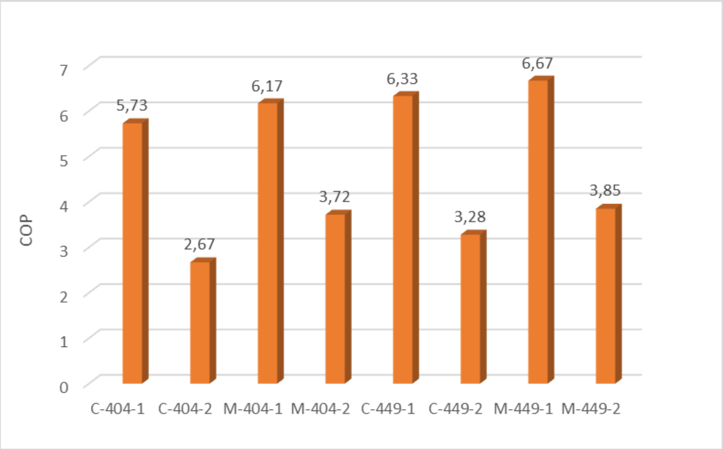

Figure. Variation of COP values with configurations

Aim

The aim of this study is to experimentally investigate the effect of condenser type, refrigerants, and number of compressors on the COP in a vapor compression refrigeration system.

Design and Methodology

A device was designed for this study, and there are three changeable elements used in the designed device: the number of compressors (one or two), type of condenser (copper tube condenser or microchannel condenser), and refrigerant (R-404A or R-449A).

Originality

In this study, the effects of different refrigerants were investigated in a two-stage refrigeration cycle using a micro-channel condenser. In addition, the amount of energy consumption was investigated experimentally by changing the number of compressors in the cycle.

Findings

The most important findings in this study are that configurations using micro-channel condensers have a higher COP value than configurations using copper tube condensers and configurations using R449A refrigerant have a higher COP value than configurations using R404A refrigerant.

Conclusion

The increase in the number of compressors also increases the cooling rate, and as a result of the analysis, it was seen that the most efficient design for the system is the one using the micro-channel condenser and working with R449A refrigerant.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

The Effect of Condenser Type and Refrigerant Type on the Two-Stage Vapour Compression Refrigeration System: An Experimental Study

Research Article / Araştırma Makalesi

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ABSTRACT

In this study, the effects of refrigerants and condenser type on the coefficient (COP) of performance value in a two-stage intercooled vapour compression refrigeration system have been investigated experimentally with the designed device. There is a total of eight configurations designed for experiments, and these are compared with each other. During the experiments, a copper tube condenser, a micro-channel condenser, and R404A and R449A refrigerants were used in the designed device. The main focus of this study is to investigate the effect of condenser type, refrigerants, and the number of compressors on the COP in a vapor compression refrigeration system. In this study, it was concluded that designs using a micro-channel condenser have a higher COP than designs using a copper tube condenser, and the most efficient design for the system is the one using the micro-channel condenser and working with R449A refrigerant.

Keywords: Micro-channel condenser, R449A, R449A, two-stage refrigeration.

Kondenser Türü ve Soğutucu Akışkan Türünün İki Kademeli Buhar Sıkıştırmalı Bir Soğutma Sistemine Etkisinin Deneysel İncelemesi

ÖZ

Bu çalışmada, iki kademeli, ara soğutmalı buhar sıkıştırmalı bir soğutma sisteminde soğutucu akışkan ve kondenser türünün performans katsayısı değerine etkisi tasarlanan cihaz ile deneysel olarak incelenmiştir. Deneyler için tasarlanmış toplam sekiz konfigürasyon vardır ve bunlar birbiriyle kıyaslanmıştır. Deney aşamasında bakır borulu kondenser, mikro kanallı kondenser, R404A ve R449A gazları tasarlanan cihazda kullanılmıştır. Bu çalışmanın ana odak noktası, kondenser tipinin, soğutucu gazların ve kompresör sayısının buhar sıkıştırmalı bir soğutma sisteminde performans katsayısı üzerindeki etkisini araştırmaktır. Bu çalışmada mikro kanallı kondenser kullanan tasarımların bakır boru kondenser kullanan tasarımlara göre daha yüksek performans katsayısı değerine sahip olduğu ve sistem için en verimli tasarımın mikro kanal kondenser kullanan ve R449A gazı ile çalışan tasarım olduğu sonucuna varılmıştır.

Anahtar kelimeler: Mikro kanallı kondenser, R449A, R404A, iki kademeli soğutma.

1. INTRODUCTION

In this study, the effects of refrigerants and condenser type on the coefficient of performance (COP) in a two-stage vapor compression refrigeration system have been investigated experimentally with the designed device. As with a single-stage vapor compression refrigeration cycle, the compressor, condenser, expansion valve, and evaporator are the basic components of a two-stage vapor compression refrigeration cycle. Different from the single-stage vapor compression refrigeration cycle, a heat exchanger and more than one compressor are used in the two-stage vapor compression refrigeration cycle.

The scheme of the designed device has been presented in Figure 1. The refrigerant is compressed in the first compressor and turned into superheated vapour, the temperature of the refrigerant leaving the first compressor is decreased in the heat exchanger, then compressing process is repeated in the second compressor. The refrigerant recompressed in the second compressor enters the condenser and condenses. The condensed refrigerant expands in the expansion valve and enters the evaporator after passing through the heat exchanger. As the refrigerant passes through the evaporator, it absorbs the heat of the environment and lowers its temperature, finally entering the compressor in the vapour phase [1]. There are three changeable elements used in the designed device which are the

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number of compressors (one or two), type of condenser (copper tube condenser or microchannel condenser), and refrigerant (R-404A or R-449A). These three elements were used to create eight different configurations.

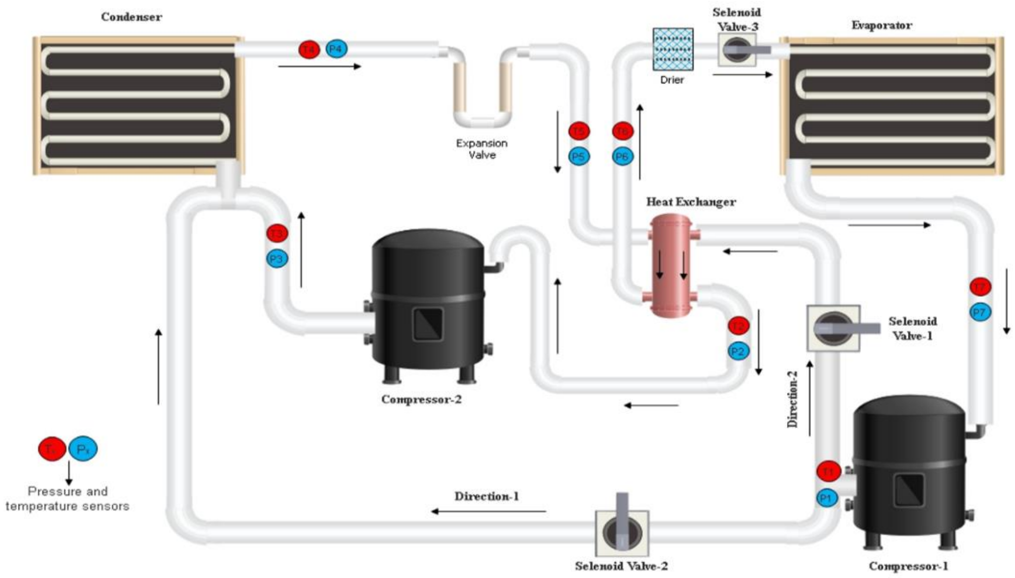

Figure 1. The scheme of the device

The reason for choosing R404A and R449A refrigerants in this study is that refrigerant R404A is one of the most preferred refrigerants on the market, the refrigerant R449A has a lower global warming potential value than the refrigerant R404A, and it is convenient to use the refrigerant R449A in systems designed for the refrigerant R404A refrigerant [2]. Micro-channel condensers provide a higher surface area/volume ratio than conventional copper tube condensers and have a high heat transfer coefficient [3]. In the study, the contact surface with the refrigerant was increased by using a micro-channel then results were compared with cycles that used a copper tube condenser, and the change in COP values has been investigated. Finally, the experiments were conducted with one and two compressors, and the effect of the number of compressors on the system has been examined. However, to prevent excessive temperature rises at the entrance to the second compressor, it is necessary to subject the refrigerant to intercooling; thus, a heat exchanger was added to the device.

In addition, the refrigerant and operating parameters that provide the highest COP value in the designed device have been determined. Many researchers have studied vapour compression refrigeration systems and some of these studies have been presented below.

Yildirim & Şencan Şahin have analyzed a two-stage vapour compression refrigeration system for different refrigerants. The authors have determined the refrigerant that gives the highest COP value by comparing different operating parameters. In the study, claimed that the refrigerant that gives the maximum COP value is R717, and for all refrigerants analyzed, the COP value rises with increasing evaporator temperature and falls with increasing condenser temperature [4]. Yılmaz et al. have investigated a two-stage vapour compression refrigeration system. The authors used R404A refrigerant for the high-temperature cycle. They concluded that raising the evaporation temperature in the heat exchanger improves system performance [5]. He et al. have conducted a theoretical study. They examined the performance of a two-stage vapour compression refrigeration system using a mixture of refrigerants. They compared the mixtures and investigated the optimum refrigerant ratio in terms of COP value. In the study, exergy analysis showed that the heat exchanger has the biggest proportion of the total exergy losses [6].

Heun and M.K. have conducted an analytical study to examine the thermal performance of micro-channel condensers. The authors stated that, compared to conventional condensers, microchannel condensers have higher heat transfer capacities and better pressure drop performances despite their small size. At the same time, it has been stated that the microchannel condensers have less internal volume, thus reducing the system charge [7].

Sivaraman et al. analyzed a refrigeration system in terms of the impact of expansion devices. The authors claimed that the thermostatic expansion valve, which is used as a throttling device in the present study too, provided the best performance for flow adjusting [8]. Hrnjak & Litch have conducted an experimental study and analyzed a refrigeration cycle using a micro-channel condenser. The authors have stated that the amount of refrigerant charged to the micro-channel condenser was less than an average of 53 percent compared to the conventional condenser. Similarly, in the presented study, the amount of loaded refrigerant decreased by 50 percent compared to the conventional condenser [9].

Kim & Bullard, have conducted an experimental study to analyze the vapour compression refrigeration cycle. Authors have concluded that by replacing a conventional condenser with a micro-channel condenser, the refrigerant charge amount can be reduced by 35 percent [10].

Nebot-Andrés et al. have conducted an experimental study to investigate the vapour compression refrigeration system using two compression stages, and to determine the optimal operating situations. The authors have concluded that there is a correlation between the COP value and the intermediate pressure, and if it decreases or increases, the COP value decreases [11].

Makhnatch et al. have studied a refrigeration system that operated with refrigerant R404A. In the study refrigerant R449A has been proposed to replace R404A. Because refrigerant R449A has a much lower GWP value than refrigerant R404A, the authors have claimed that replacing R449A with R404A would be a convenient decision given the problems with global warming [12].

Udroiu et al. have investigated cascade refrigeration cycles operating in ultra-low temperatures, and results obtained from simulations prepared for COP analysis were presented. In all, 42 alternative multistage refrigeration cycle designs were presented in the study. The authors have claimed that if the stage number increases, the system's COP value increases because the compressor power decreases [13]. Mohammadi & Ameri have studied a vapour compression refrigeration system numerically and conducted the energy and the exergy analysis. The authors have designed six different configurations. The authors have indicated that an increase in discharge pressure causes decreasing efficiency [14].

The findings of this study are expected to help academics and the private sector to analyze two-stage intercooled vapour compression refrigeration systems that use alternative refrigerants and micro-channel condenser.

2-MATERIAL AND METHOD

Experiments were conducted for a total of eight different designs. For the measurement of the system's cooling capacity, the evaporator was kept in an insulated room of 2.5*2.5*2 meters during the measurements and for each experiment, the device was operated between 100 and 150 minutes, the experiment time depends on the configurations. During the experiments, the insulated room's initial temperature was 14 °C.

The copper tube condenser was first placed in the cycle, and the experiments were carried out. Later, the micro-channel condenser was included in the system instead of the copper tube condenser.

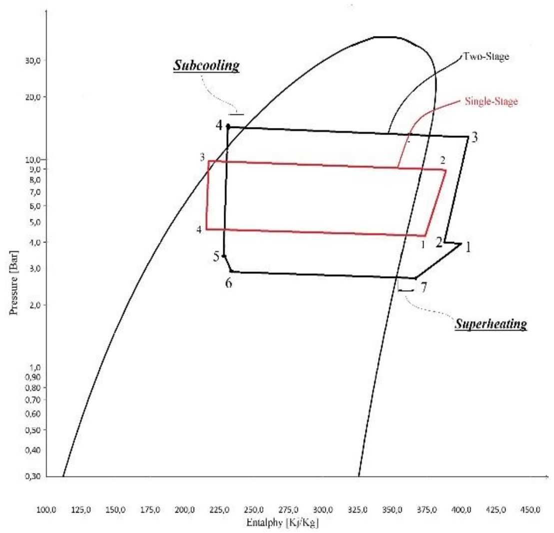

Figure 2. Pressure-enthalpy diagram of the cycle

R404A and R449A refrigerants were used in the experiments for both condensers. In addition, the experiments, in which a condenser and a refrigerant were selected in the experimental stage, were repeated for the cases where a single compressor and a double compressor were operating. Figure 2 shows the pressure and enthalpy diagram of the single-stage and double-stage cycles.

Pressure and temperature values were measured at the measurement points seen in the cycle diagram presented in Figure 1. The pressure-enthalpy diagram prepared with the data obtained as a result of the experiments for the single-stage and two-stage cooling cases is presented in Figure 2. It is seen that higher pressure is obtained in the two-stage cycle. In addition, subcooling and superheating are shown in the chart.

Table 1. Equipments used in the designed device.

Equipment	Description
Compressors/ 1 HP-Hermetic	Tecumseh-CAJ9510Z/
Micro-channel condenser	Sanhua Micro Channel Heat Exchanger SD-14/Bracket
0.42 m^2 Plate heat exchanger	MIT/MB-05-16
Thermostatic expansion valve	Danfoss/ 068Z3415 TES 2
Copper tube condenser	Thermoway/ KO4-27-140
Evaporator	Thermoway/ TEC-C-045-A11-J6-60
Temperature measurement device (-50…100 °C)	Emko/ 3710-N.5.18.0.1 Sensor: NTC-M5-L20-K1.5-S
Pressure measurement device	T-COLD/ TC-250-GFR
Ampere meter	Unit UT 200A AC Pensampermetre

The equipment used during the device's construction stage and measuring tools for the experiments were presented in Table 1.

Measured temperature and pressure values were used to obtain enthalpy values. With the help of the solenoid valves in the device, the fluid continues to move in the selected direction. High pressure is produced when two compressors operate simultaneously in the system. High pressures also increase the temperature. In this case, a heat exchanger was added to the cycle so that the high-pressure, high-temperature superheated vapor refrigerant coming out of the first compressor would not damage the second compressor and could be cooled by the relatively cold fluid coming out of the expansion valve. In this way, damage to the second compressor is prevented. The picture of the designed device is presented in Figure 3.

Figure 3. picture of the designed device

Two compressors are used in the device and connected in series in the two-stage design. There are two ways in which the cycle continues after the first compressor. The direction of the refrigerant is determined by controlling the solenoid valves. If direction 1 is selected, the cycle is single-stage, and the heat exchanger is dysfunctional because the refrigerant leaving the compressor will not be compressed in another compressor. If direction 2 is selected, the cycle becomes a two-stage cycle.

There are three changeable elements to analyze the designed device in the experiment phase, are the type of condenser (micro-channel condenser or copper tube condenser), the number of compressors running (one or two), or, in other words, whether the system is single-stage or two-stage, and the refrigerant (R404A or R449A).

A total of eight different cycles were designed for the device: three elements and two different alternatives for each element. To make it simpler to distinguish between the configurations, an abbreviation has been created for each configuration. In the abbreviations, "C" refers to the copper tube condenser used in that configuration "M" refers to the micro-channel condenser used in that configuration, "404" refers to R404A refrigerant and "449" refers to R449A refrigerant, "1" refers to single-stage compression and "2" refers to two-stage compression.

During the calculations, because there is a cycle difference, two different COP equations for single-stage refrigeration and two-stage refrigeration have been prepared. After the experiments were done, the following equations were used to calculate the COP values:

Equation 1a is used to calculate the evaporator cooling capacity for the two-stage vapour compression refrigeration cycle, the enthalpy of the refrigerant at the evaporator outlet is denoted by h_7, and the enthalpy of the refrigerant at the evaporator inlet is denoted by h_6. The Equation 1b is used to calculate the evaporator cooling capacity for the single-stage vapour compression refrigeration cycle, the enthalpy of the refrigerant at the evaporator outlet is denoted by h_1, and the enthalpy of the refrigerant at the evaporator inlet is denoted by h_4.

$$q_{evap2} = h_7 - h_6 \tag{1a}$$

$$q_{evap1} = h_1 - h_4 \tag{1b}$$

Condenser cooling capacity is calculated by using Equation 2a for the two-stage vapour compression refrigeration cycle, where h_3 is the enthalpy of the refrigerant at the condenser inlet and h_4 is the enthalpy of the refrigerant at the condenser outlet.

The Equation 2b is used to calculate evaporator cooling capacity for the single-stage vapour compression refrigeration cycle, where h_2 is the enthalpy of the refrigerant at the condenser inlet and h_3 is the enthalpy of the refrigerant at the condenser outlet.

$$q_{cond2} = h_4 - h_3 \tag{2a}$$

$$q_{cond1} = h_3 - h_2 \tag{2b}$$

Equation 3 is used to calculate the compressor energy consumption for two-stage compression, and Equation 4 for single-stage compression.

$$w_{comp2} = (h_1 - h_7 \ ) + (h_3 - h_2) \qquad (3)$$

$$w_{comp1} = h_2 - h_1 \qquad (4)$$

$$COP_1 = \frac{q_{evap}}{w_{comp1}} = \frac{h_1 - h_4}{h_2 - h_1} \qquad (5)$$

$$COP_2 = \frac{q_{evap}}{w_{comp2}} = \frac{h_7 - h_6}{(h_1 - h_7) + (h_3 - h_{2})} \qquad (6)$$

The COP value of the single-stage cycle is calculated using Equation 5, and the COP value of the two-stage cycle is calculated using Equation 6.

$$P(Watt) = I(Amper)xV(Volt) \qquad (7)$$

Equation 7 is used to calculate the energy consumption of the designed device. While calculating the energy consumption amounts,

the ampere value was measured with the help of an ampere meter for each configuration, and the volt value was assumed to be a constant 230 volts.

The physical properties of the refrigerants used in the experiment in the device are presented in Table 2 [15]. As can be seen in Table 2, neither refrigerant has any potential to deplete the ozone layer, and R-404A has a higher global warming potential than R-449A.

Table 2. Physical Properties of the used refrigerants

Physical Properties	Unit	R-449A	R-404 A
Molecular weight	(Gr/mol)	87,2	97,61
Boiling point (1,013 bar)	(°C)	-46	-46,45
Critical temperature	(°C)	81,5	72,07
Critical pressure	(Bar)	44,5	37,31
Vapour pressure (25 °C)	(Bar)	12,75	12,42
Liquid density (21,1 °C)	(Kg/m³)	1113,3	1048
Flammability (25°C)	-	None	None
Ozon Depletion potential (ODP)	-	0	0
Global warming potential (GWP)	-	1397	3922
Sliding point	K	4	0,7

While the amount of refrigerant loaded in the designs with the micro-channel condenser (M-404-1, M-404-2, M-449-1, and M-449-2) is 2000 grams, the amount of refrigerant loaded in the designs with the copper tube condenser is 4000 grams. The reason why the loaded refrigerant changes according to the condenser type is that the condensers have different internal volumes. The amount of loaded refrigerant was decided by looking at the pressures and the phase state of the refrigerant at the exit of the expansion valve.

3-RESULTS AND DISCUSSION

After the experiments were completed, the data obtained were analyzed. Figure 4 compares the COP values and energy consumption amounts of the eight configurations analyzed.

The design with the least energy consumption is the one using a micro-channel condenser with 1771 watts, operated with R449A refrigerant, and a single compressor.

The design with the highest energy consumption is the one using a copper tube condenser with 2668.3 watts, operated with R404A refrigerant, and two compressors.

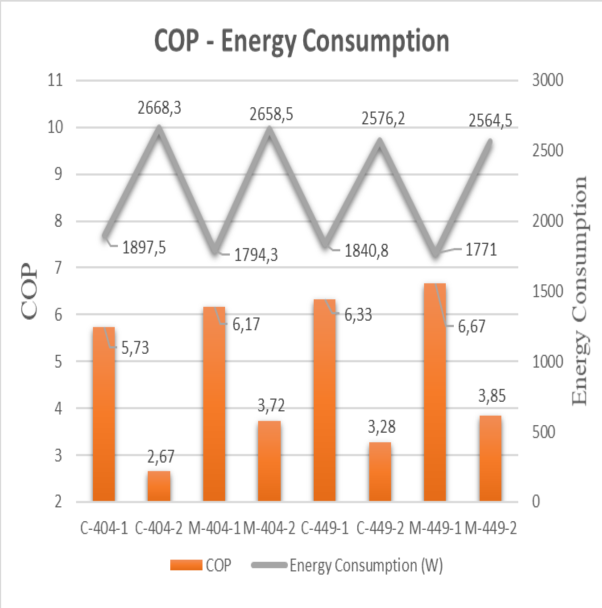

Figure 4. The COP values and energy consumptions

Configurations' COP values as a result of the analyses for eight different designs are presented in Figure 4. According to the graph, the design with the highest COP value of 6.67 is the single-stage design using R-449A refrigerant with a micro-channel condenser. The design with the lowest COP value of 2.67 is the two-stage design using R-404A refrigerant with a copper tube condenser.

As can be seen from Figure 4, cycles using refrigerant R449A have higher COP values and lower energy consumption, but the cost of R449A refrigerant is higher than the cost of R404A refrigerant.

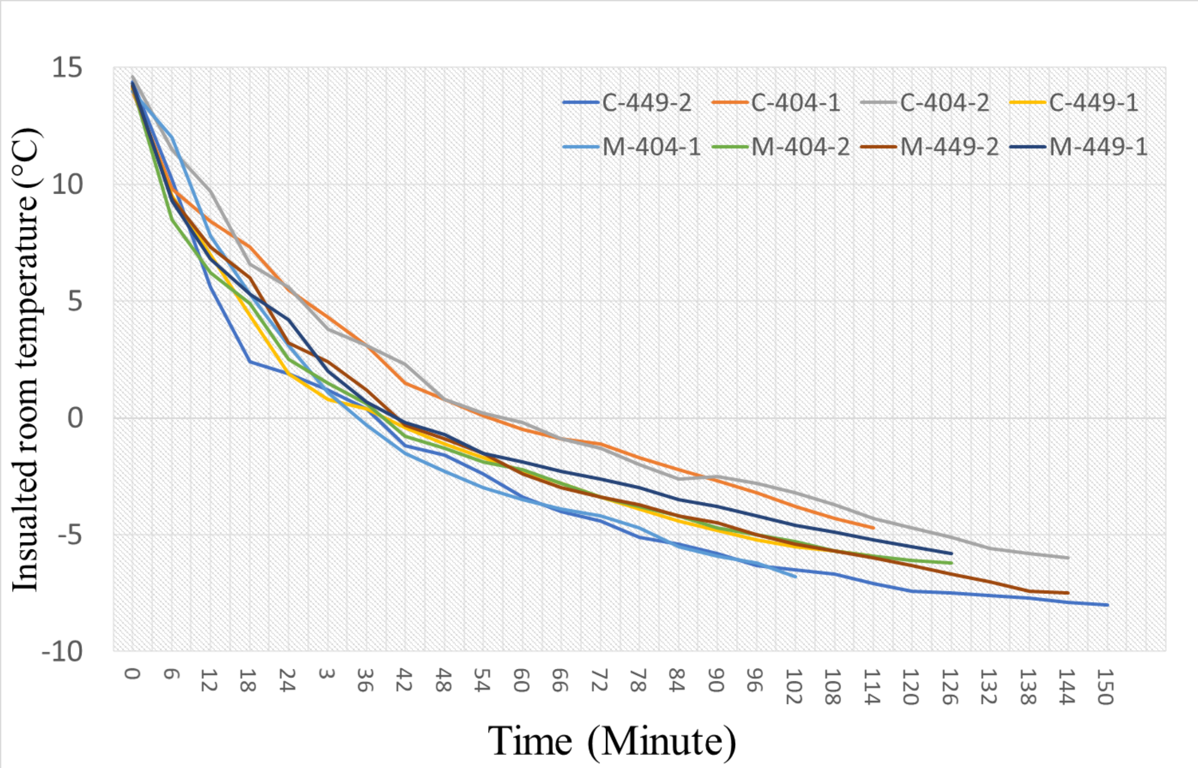

Figure 5. the variation of the insulated room temperature

However, refrigerant R449A has a much lower GWP value than refrigerant R404A, so it can be said that it would be more convenient to use R449A refrigerant instead of R404A refrigerant considering the energy saving and global warming problems that have become very critical today.

Figure 5 shows the variation of the insulated room temperature by time for eight different designs. While the insulated room temperature was 14 degrees Celsius at the beginning of the experiment, it decreased to -8 degrees Celsius at the end of the experiment. When the obtained data are examined, the M-449-2 design cools the insulated room in the shortest time and the C-404-1 design cools it in the longest time.

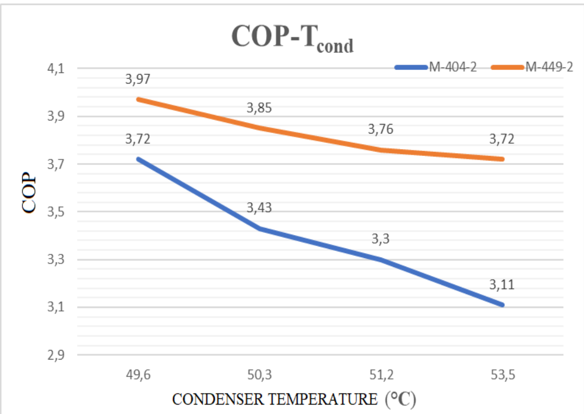

Figure 6. Condenser temperature and COP variation for two-stage refrigeration

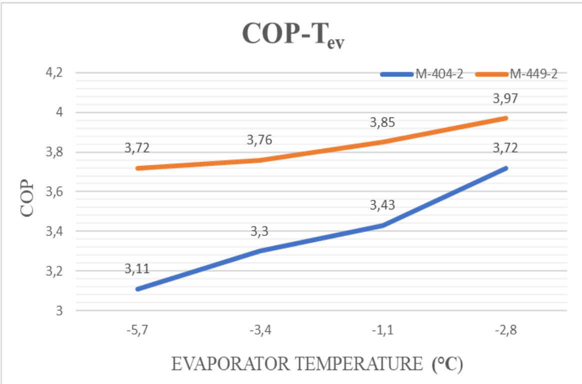

Figure 7. Evaporator temperature and COP variation for two-stage refrigeration

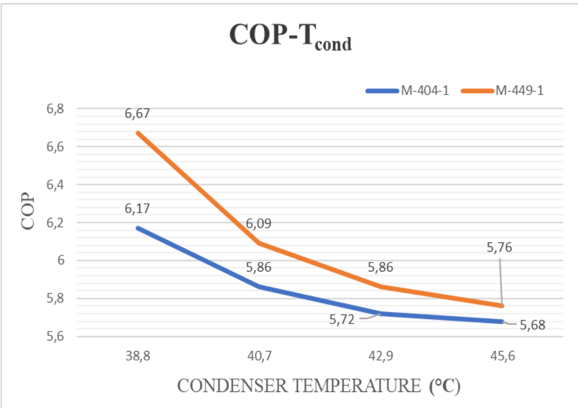

Figure 8. Condenser temperature and COP variation for single-stage refrigeration

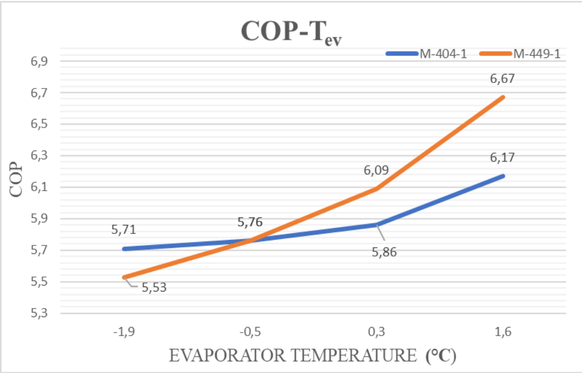

Figure 9. Evaporator temperature and COP variation for single-stage refrigeration

The alteration of the COP values on T_{ev} and T_{cond} is shown in Figures 6, 7, 8, and 9.

4-CONCLUSIONS

In this study, an experimental investigation of a vapor compression refrigeration cycle has been carried out. In the designed device, eight different cycles were made in total by changing three elements: condenser type, refrigerants, and the number of compressors. The data obtained as a result of the experiments for each cycle are presented in the previous sections.

The purpose of this study is to conduct an experimental investigation into how the type of condenser, refrigerants, and the number of compressors affect a vapor compression refrigeration system's performance. By using solenoid valves in the designed device, it was determined that the system would be single or two-stage so that the desired number of stages was obtained without the need to disassemble the system while choosing the number of compressors. As stated earlier, the number of compressors selected affects energy consumption. When the data obtained as a result of the experiments were analyzed, the following results were obtained:

- Compared to designs using copper tube condensers, designs using micro-channel condensers have a higher COP value.
- Compared to designs using R404A refrigerant, designs using R449A refrigerant have a higher COP value.
- Designs using one compressor have a higher COP value than designs using two compressors.
- The energy consumption of designs using two compressors is an average of 30,5 percent higher than designs using a single compressor.
- The design that cools the insulated room in the shortest time is M-449-2, and the design that cools it the longest is the C-404-1.
- Figures 6, 7, 8, and 9 demonstrate that as condenser temperature rises, the cycle's COP decreases, whereas as evaporator temperature rises, the cycle's COP rises.
- The cooling rate also rises as the number of compressors rises.
- As a result of the analysis, it was seen that the most efficient design for the system is the one using the micro-channel condenser and working with R449A refrigerant.

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS’ CONTRIBUTIONS

Mutlu Tarık Çakır: supervised the project, contributed to the design of the research and analysis of the results.

İsmail TUNÇİL: contributed to the design and implementation of the research, to the analysis of the results. He wrote the manuscript in consultation with Mutlu Tarık Çakır.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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