GU J Sci, Part A, 7(3): 83-95 (2020)

Gazi University

Journal of Science

PART A: ENGINEERING AND INNOVATION

http://dergipark.gov.tr/gujsa

Performance Analyses of the Industrial Cooling System with Microchannel Condenser: An Experimental Study

Meltem KOŞAN[1,*], Süleyman ERTEN[2], Burak AKTEKELİ[1], Mustafa AKTAŞ[3]

[1]*Natural and Applied Science Institute, Gazi University, Ankara, Turkey*
[2]*Nurdil Technical Cooling, Ankara, Turkey*
[3]*Energy Systems Engineering, Technology Faculty, Gazi University, Ankara, Turkey*

Article Info

Received: 24/08/2020
Accepted: 05/10/2020

Keywords

Cooling,
Coefficient of performance,
Exergy,
Microchannel heat exchanger,
CO_2 emission

Abstract

Increasing the efficiency in equipment used in energy systems has a growing interest in the matter of energy efficiency and environmental effects. Microchannel heat exchangers, which will increase the efficiency of heat exchangers in cooling systems and reduce the amount of refrigerant charge, are of great importance. In this study, the theoretical and experimental results of classical and microchannel condensers used in a basic vapor compression cooling system were represented using R449a refrigerant. Two separate industrial systems with classical and microchannel condensers were designed, manufactured and tested under the same conditions. According to the test results performed for 24 hours, the average coefficient of performance, exergy efficiency and CO_2 emission values of the system with classical condenser and microchannel condenser were calculated as 2.086, 2.351; 23.950%, 25.564% and 16.357, 14.438 kg/hour, respectively. As a result, it has been seen that microchannel heat exchanger usage provides an advantage in terms of total energy consumption and total CO_2 emissions compared to the classical system at the rate of approximately 11% and using microchannel heat exchanger in industrial cooling systems has been recommended.

Nomenclature

α .... molar mass
e_x .... specific exergy (kJ/kg)
$\dot{E}_x$ .... exergy rate (kJ/s)
h .... enthalpy (kJ/kg)
$\dot{m}$ .... mass flow rate (kg/s)
P_r .... pressure ratio
$\dot{Q}_{con}$ .... condenser capacity (kW)
$\dot{Q}_e$ .... evaporator capacity (kW)
s .... specific entropy (kJ/kg K)
$\dot{W}_{comp}$ .... compressor capacity (kW)
W_R .... total uncertainty (%)
w_1, w_2, w_n .... uncertainties in the independent variables
T .... temperature (K)
T_0 .... dead state temperature (K)

Abbreviations

COP .... coefficient of performance
GWP .... global warming potential
NHV .... net heating value

*Corresponding author, e-mail: mltmkosan@gmail.com

Subscripts

c .... condensation
$comp$ .... compressor
$dest$ .... destroy
e .... evaporation
el .... electrical
mec................................. mechanical
0...................................... dead state
r .... refrigerant

1. INTRODUCTION

Heat exchangers that provide enhanced heat transfer are the most important equipment in energy systems. Condenser and evaporator, which are heat exchangers, are two basic equipments of basic vapor compression refrigeration cycles [1]. Both environmental and energy related problems of refrigeration cycles have motivated researchers to design more efficient evaporators, condensers, and utilize alternative refrigerants [2].

In recent years, microchannel heat exchangers are preferred as condenser and evaporator in cooling systems because of their advantages such as providing high heat transfer coefficients, being lightweight with their small dimensions, having low working fluid amount and being portable [3,4]. In the literature, there are a number of studies on which microchannel heat exchangers were used in cooling systems. Zhan et al. (2020) numerically investigated the performance of the vertical microchannel evaporator used in data center cooling systems using Icepack software. They found the maximum air side temperature difference as 9.5 ℃ and the vapor quality difference on the outlet side of the refrigerant to 0.15 in uneven conditions [5]. Tosun et al. (2019) 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 [6]. Xu et al. (2013) examined the frost and defrost performance of two types of microchannel heat exchangers in a heat pump system using a CCD camera. After four operating cycles, they observed that approximately 800 grams of water were retained in the microchannel heat exchanger, and as a result, the effective operating time was reduced by 40 minutes. The capacity of the system was decreased by 27% compared to the starting value [7]. Xu et al. (2016) experimentally and numerically analyzed 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% [8]. Zhou and Hrnjak (2015) presented the experimental results of the distribution of R410a and R134a refrigerants in a reversible outdoor microchannel heat exchanger. It was shown that the inertia of R410a was higher than that of R134a and the high-quality R410a distribution was worse than R134a [9].

Microchannel heat exchanger can sometimes be used both as the evaporator and condenser of the cooling system. Cremaschi and Yatim (2019) investigated the retention of oil in a microchannel condenser and evaporator of an R134a cooling system and evaporator 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 [10].

R448a and R449a refrigerants have been used as an alternative to R404a. Makhnatch et al. (2017) were 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 [11]. Vaitkus and Dagilis (2017) reported the reduction was 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 and therefore the performance criteria were the same [12].

In this study, two basic vapor compression industrial cooling systems, one with a classical (iron tube) condenser and the other with a microchannel condenser were designed and investigated experimentally. In both systems, all equipment was identical except for the condensers, and the refrigerant was R449a. The objective of this study is to analyze and compare energy, exergy and environmental aspects of classical and microchannel condensers. Another important purpose is to increase the cooling efficiency, to reduce energy consumption and to reduce carbon emissions for the industrial cooling system. The structure of this study is summarized in Fig. 1.

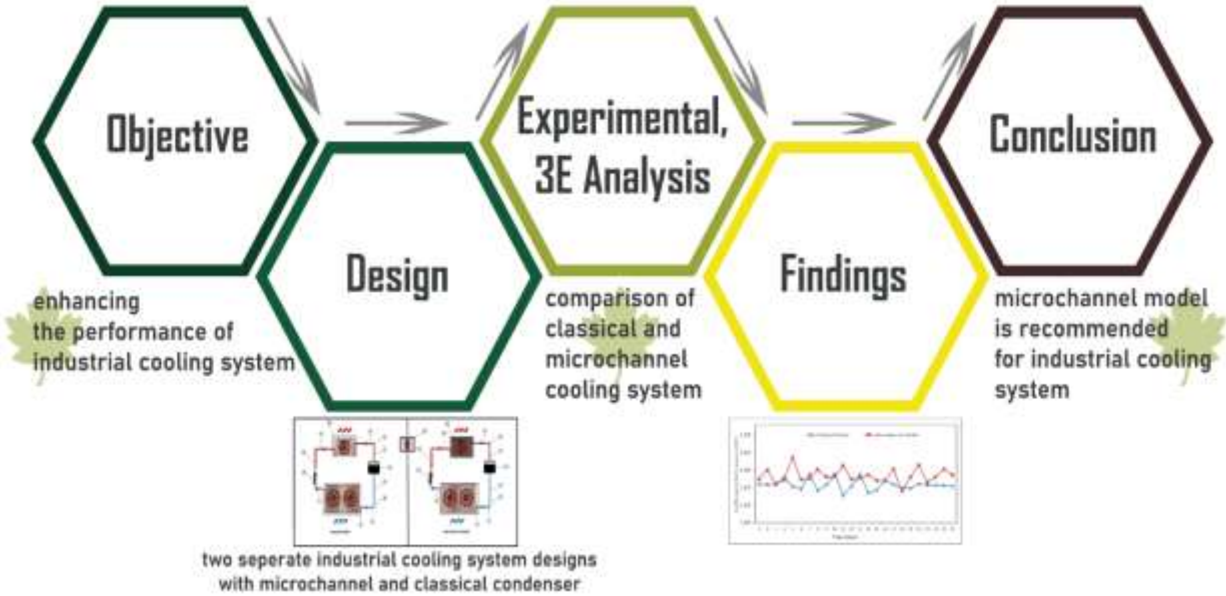
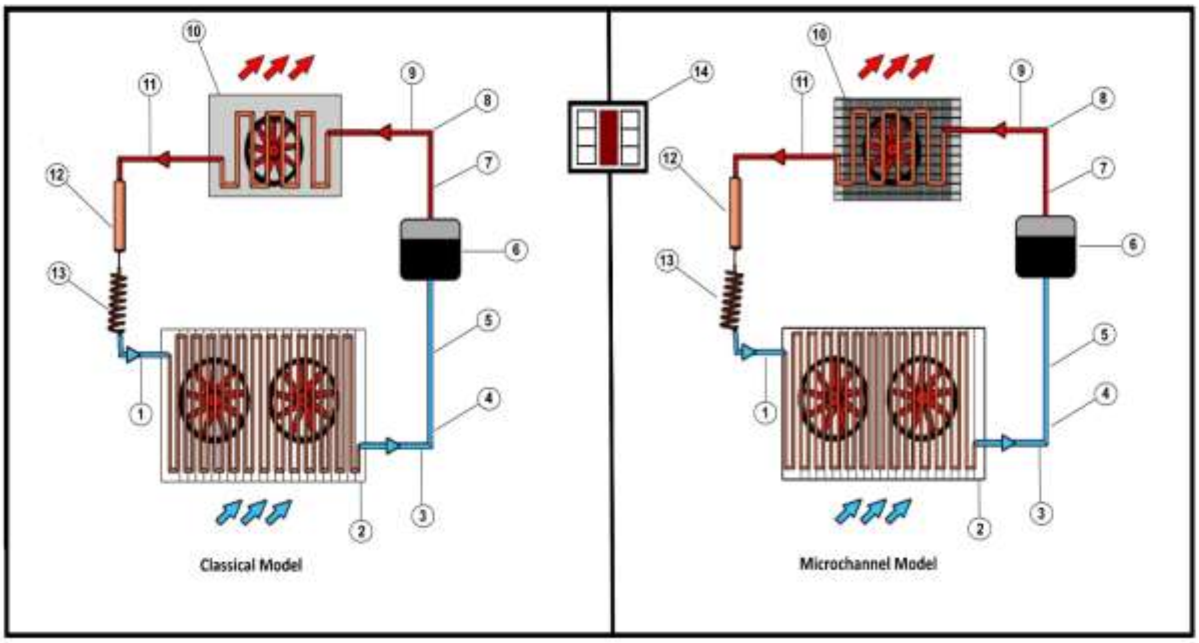


Figure 1. *Methodology of the current study*

2. MATERIALS AND METHOD

2.1. Experimental Procedure

The technical drawing of a basic vapor compression industrial cooling system is represented in Fig. 2. This system mainly included an evaporator, a compressor, a condenser, and a capillary tube. In this study, two cooling systems with classical and microchannel condensers were used and, R449a was used as a refrigerant in these systems. R449a was preferred because it was the main replacement gas with a global warming potential (GWP) value of 1397, and suitable for use in commercial and industrial applications at low and medium temperatures [13].



1- Evaporator Input	5- Compressor Suction Line	9- Condenser Inlet	13- Capillary Tube
2- Evaporator	6- Compressor	10- Condenser	14- Control Unit
3- Evaporator Output	7- Compressor Outlet Line	11- Condenser Outlet	
4- Low Pressure Line	8- High Pressure Line	12- Dryer	

Figure 2. *The schematic diagram of the cooling systems*

As shown in Fig. 2, the cooling system consisting of condenser iron tubes is called as the classical model, and the cooling system consisting of condenser microchannel is called as the microchannel model. The position of the measurements are the numbered Fig. 2 on both cooling systems. Temperature and pressure values were measured using the apparatus given in Table 1.

Table 1. *Technical specifications of the measurement devices*

Apparatus	Measurement Range	Accuracy
Thermometer	-40 / +150 °C	± % 0.02
Pressure transmitter	0-30 bar	± 0.1
Pressure transmitter	0.5-8 bar	± 0.01
Thermohygrometer	0-100 %RH 0 / +50 °C	± % 1.5 ± 0.03
Anemometer	0-2 m/s	± 0.01
Vacuum Pump	0,04-0,8 Pa	±0.02
Digital Gas Scales	0-100 kg	± % 0,05
Digital Manifold	-50 / +150 °C -1 / +60 bar	± 0.1 ± 0.01
Energy analyzer	95-240 V AC 0.001-7.4 A	± % 0.1 ± % 0.2
Flowmeter	0-1000 kg/h	± % 0.1

2.2. Energy, Exergy and Environmental (3E) Analyses

The performance analyses of cooling systems given in Fig. 2 were conducted by applying the first law and the second law of thermodynamics. With the development of technology and industry, gases emitted to the atmosphere create certain destructions in the ozone layer. Therefore, when evaluating energy systems, it is of great importance to calculate energy and exergy analysis of the system as well as CO_2 emission value.

2.2.1. Energy analysis of system

In the heat pump system, the evaporator capacity ($\dot{Q}_e$) is determined by the equation given below [14]:

$$\dot{Q}_e = \dot{m}_r(h_3 - h_1) \tag{1}$$

Here, $\dot{m}_r$, h_1, h_3 represent the mass flow rate of the refrigerant, the inlet enthalpy of refrigerant to the evaporator and the outlet enthalpy of refrigerant from the evaporator, respectively. The power of the compressor ($\dot{W}_{comp}$) is also proportional to the difference of enthalpy of the refrigerant entering (h_5) and exiting (h_7) the compressor as shown in Eq. (2) [15].

$$\dot{W}_{comp} = \dot{m}_r(h_7 - h_5) \tag{2}$$

The electrical power applied to the compressor is calculated by dividing the compressor power by electrical and mechanical efficiencies [16].

$$\dot{W}_{comp,el} = \frac{\dot{W}_{comp}}{\eta_{el}\eta_{mec}} \tag{3}$$

The energy balance in the classical and microchannel condensers can be calculated with the following equation [17]:

$$\dot{Q}_c = \dot{m}_r(h_9 - h_{11}) \tag{4}$$

where h_9 and h_{11} state the enthalpies of the refrigerant entering and leaving the condenser. Pressure ratio (P_r) can be defined as the ratio of the high pressure to the low pressure in a cooling system.

$$P_r = \frac{P_c}{P_e} \tag{5}$$

The coefficient of performance of the heat pump system is determined by the following equation [18]:

$$COP = \frac{\dot{Q}_e}{\dot{W}_{comp}} \tag{6}$$

2.2.2. Exergy analysis of system

The exergy is a measure of the potential of the flow or system that causes a change as a result of its stable balance compared to the reference environment. Therefore, it is necessary to analyze the second law of thermodynamics to the system to obtain accurate results. The general exergy balance for a continuous flow system is explained in Eq. (7) [18].

$$\sum \dot{E}_{x,dest} = \sum \dot{E}_{x,in} - \sum \dot{E}_{x,out} + \sum \left[\dot{Q}\left(1 - \frac{T_0}{T}\right)\right]_{in} - \sum \left[\dot{Q}\left(1 - \frac{T_0}{T}\right)\right]_{out} + \sum \dot{W}_{in} - \sum \dot{W}_{out} \tag{7}$$

Where $\dot{E}_{x,dest}$, $\dot{E}_{x,in}$ and $\dot{E}_{x,out}$ are exergy destroyed, inlet exergy and outlet exergy of the system, respectively. Also, T_0 represents the dead state temperature. The specific exergy (e_x) and total exergy rate ($\dot{E}_x$) can be expressed as in Eq. (8) and Eq. (9) [14]:

$$e_x = (h - h_0) - T_0(s - s_0) \tag{8}$$
$$\dot{E}_x = \dot{m}_r e_x \tag{9}$$

The exergy destruction equations for each equipment of the heat pump system are shown in the following equations [18]:

For the evaporator:

$$\dot{E}_{x,dest,e} = \dot{E}_{x,3} - \dot{E}_{x,1} + \left[\dot{Q}_e(1 - \frac{T_0}{T_e})\right] \tag{10}$$

For the compressor:

$$\dot{E}_{x,dest,comp} = \dot{E}_{x,7} - \dot{E}_{x,5} + \dot{W}_{comp,el} \tag{11}$$

For the condenser:

$$\dot{E}_{x,dest,\mathrm{c}} = \dot{E}_{x,9} - \dot{E}_{x,11} + \left[\dot{Q}_c(1 - \frac{T_0}{T_c})\right] \tag{12}$$

For the expansion valve:

$$\dot{E}_{x,dest,ex} = \dot{E}_{x,1} - \dot{E}_{x,11} = \dot{m}_r T_o(s_1 - s_{11}) \tag{13}$$

The second law efficiency of the heat pump system is given below [18]:

$$\eta_{ıı} = \frac{\dot{E}_{x,3} - \dot{E}_{x,1}}{\dot{W}_{comp,el}} \tag{14}$$

2.2.3. Environmental analysis of system

Since electrical energy is used in the vapor compression industrial cooling systems, the environmental impact of the production source of electrical energy is important. The quantity of CO_2 emitted needs to be reduced for preventing greenhouse gases released into the atmosphere. CO_2 emissions rate in kg/hour can be calculated using the model of Smith and Delaby [19].

$$CO_2 emission = \frac{Q_{fuel}}{NHV} \times \frac{C\%}{100} \alpha \tag{15}$$

here, NHV means the net heating value, $C\%$ is the carbon content depending on the type of fuel and α symbolizes the molar masses and is equal to 3.67.

2.2.4. Uncertainty analysis

When measuring a value for uncertainty analysis, the total error calculation can be made according to the equation given in Eq. (16), taking into account the errors caused by fixed, random and some errors [20].

$$\mathrm{W_R} = \left[\left(\frac{\delta \mathrm{R}}{\partial \mathrm{x_1}} \mathrm{w_1}\right)^2 + \left(\frac{\delta \mathrm{R}}{\partial \mathrm{x_2}} \mathrm{w_2}\right)^2 + \cdots + \left(\frac{\delta \mathrm{R}}{\partial \mathrm{x_n}} \mathrm{w_n}\right)^2\right]^{1/2} \tag{16}$$

3. RESULTS AND DISCUSSIONS

In this study, energy, exergy and environmental analyses of two cooling systems with classical and microchannel condensers used in an industrial cooling system were carried out. R449a was used as the refrigerant in both systems. The values obtained as a result of 24-hour analysis are presented in the graphics.

Fig. 3 and Fig. 4 show the operating pressure ranges of classical and microchannel model, respectively. While classic model operated in the range of high pressure 17-20, low pressure 2.9-5 bar, microchannel model also operated in the range of high pressure 13.5-15.6, low pressure 2.7-5 bar. The average low and high pressure values were as 3.821 and 18.741 bar for the classical model and 3.704 and 14.689 bar for the microchannel. In this case, it was observed that the high-pressure value was 4.052 bar lower at the microchannel condenser. Since the heat transfer was better in microchannel condenser, heat extraction occurred better at lower pressure.

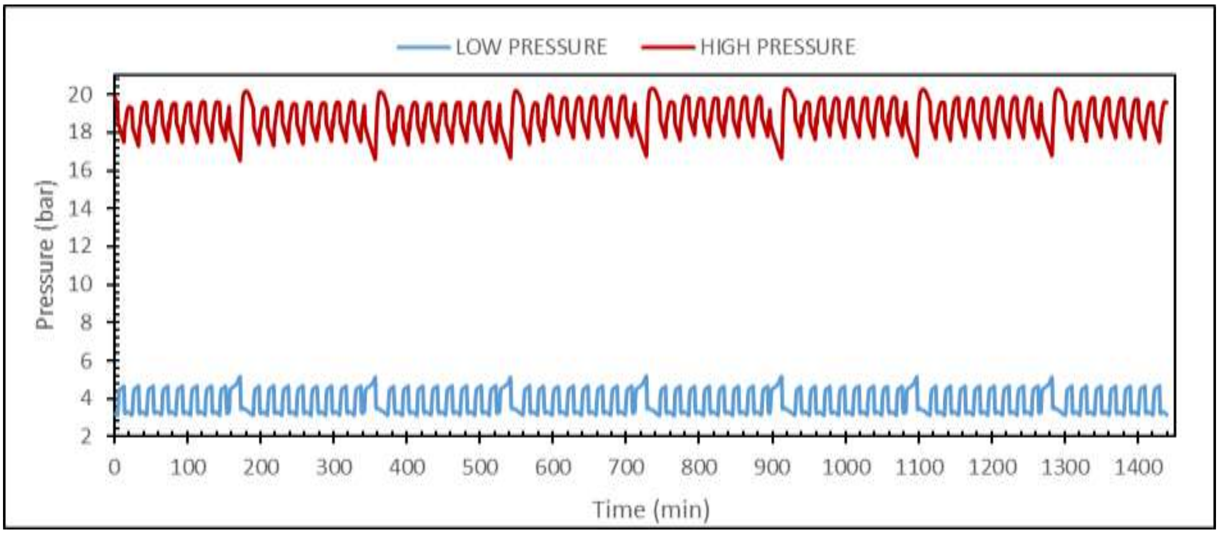


Figure 3. *Time-dependent high and low pressure values of classical model*

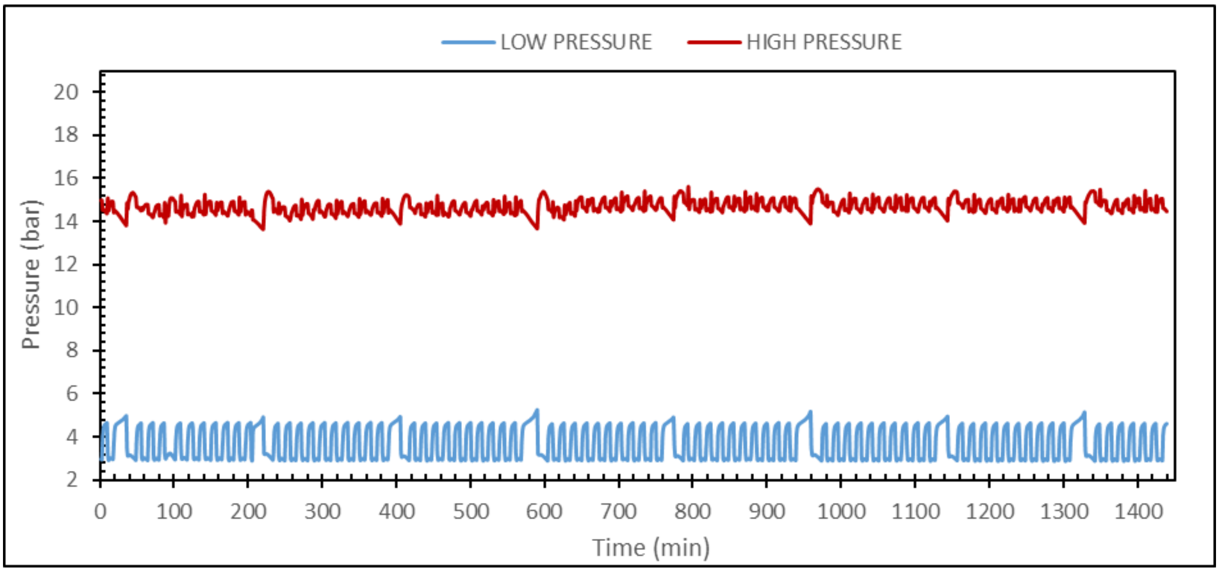


Figure 4. *Time-dependent high and low pressure values of microchannel model*

The time-dependent energy consumed by compressors and fans in classical and microchannel model cooling systems is given in Fig. 5. The compressor in classical model consumed more energy over time. The highest energy consumption was observed as 0.791 kWh at the 11th hour in the classical model and as 0.662 kWh at the 18th hour in the microchannel model. The average energy consumption value of classical model was 0.675 kWh and that of microchannel model was 0.595 kWh. In the microchannel model, the compressor consumed less electricity because the condenser pressure operates at lower values. In addition, the higher efficiency of the microchannel condenser was enabled the compressor to work more efficiently. Thus, it was observed that there was less energy consumption in the microchannel model. Energy consumption has a significant impact on the industrial cooling system. Thus, it is seen that the use of microchannel condenser in cooling systems will provide a great advantage in the long run.

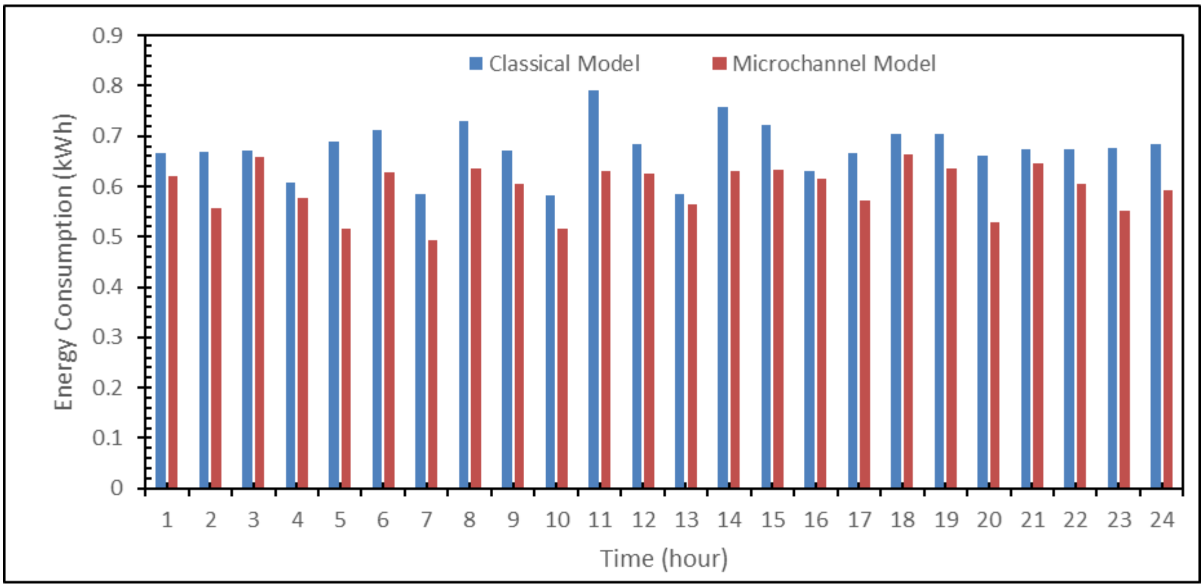


Figure 5. *Energy consumption graph of the cooling system*

Fig. 6 shows the time-dependent cooling COP classical and microchannel model cooling systems. The cooling COP of classical and microchannel models was calculated according to Eq. (6). While the highest COP value was seen as 2.872 in microchannel model at the 5th hour, the highest COP value was seen as 2.402 in classical model at the 10th hour. The average cooling COP value of classical and microchannel model was 2.086 and 2.351, respectively. It is known that in heat pump systems, when the heat transfer in the condenser is better or when the condenser efficiency is increased, the system increases the cooling performance. As the condenser efficiency increased when microchannel condenser was used, it was seen that COP also increased. Pawar et al. (2017) found the average COP of the cooling system which has a microchannel condenser system as 2.64 using R134a refrigerant [21]. Park and Hrnjak (2008) calculated the average COP of the cooling system using refrigerant R410a as 3.40 [3].

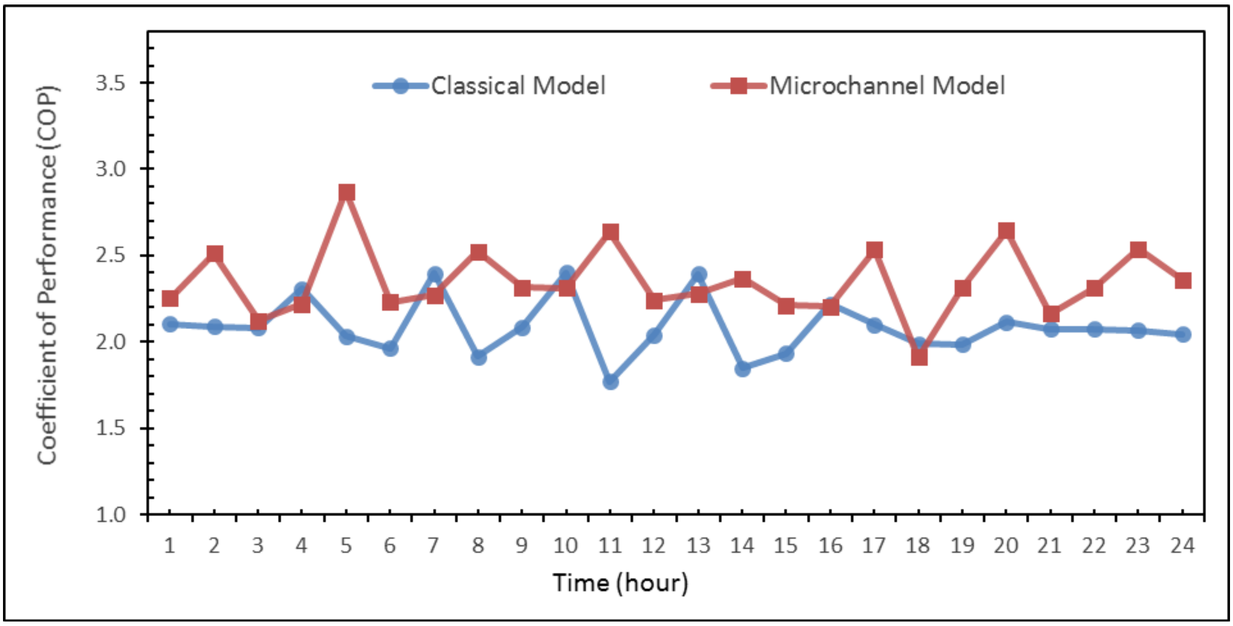


Figure 6. *The cooling COP graph of the cooling system*

Evaporator inlet and outlet temperatures for both cooling system models are given in Fig. 7. The average inlet and outlet temperatures of the evaporators in the classical and microchannel model cooling systems are -4.753℃, -5.638℃ and 1.588℃, 1.011℃, respectively. As can be understood, it is seen that the use of microchannel condenser in the cooling system improves the evaporator capacity. It also means that the higher the cooling capacity, the lower the evaporator inlet temperature and the better its performance.

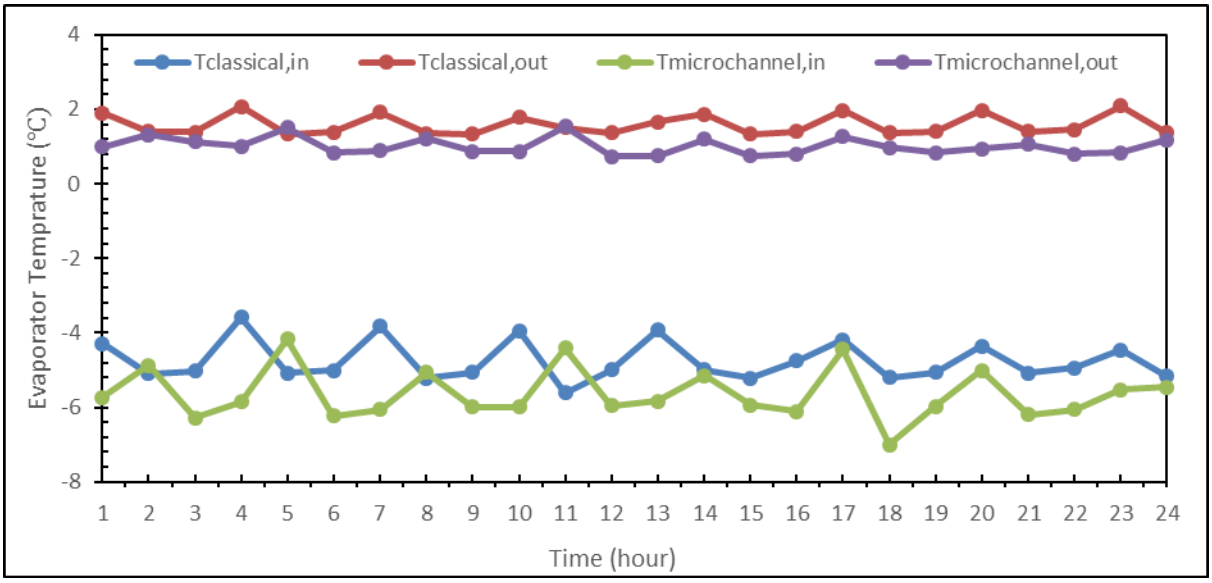


Figure 7. *Evaporator inlet and outlet temperature values of the cooling system*

Exergy analysis is a method for realistically and meaningfully evaluating and comparing energy systems and process changes. Exergy analysis for classical and microchannel models, it has an important place in terms of assessing their cooling performance. Exergy efficiency of cooling systems was calculated using Eq. (14). Exergy efficiencies of the cooling systems reached their maximum value at the1st hour. Then, it gradually decreased and balanced. The highest exergy efficiency for classical and microchannel models was calculated as 30.872% and 37.571%, respectively. The average exergy efficiency values were found as 23.950 % and 25.564 % for classical and microchannel models, respectively.

Fig. 8 shows CO_2 emission values per hour for classical and microchannel cooling systems. The CO_2 emission value was determined using Eq. (15). These values change in proportion to the energy consumed by the compressor. While the CO_2 emission value of the classical model was at most 19.158 kg/hour, and at least 14.122 kg/hour, the microchannel model was 16.052 kg/hour and 11.923 kg/hour. Average CO_2 emission values of classical and microchannel models were 16.357 kg/hour and 14.438 kg/hour, respectively.

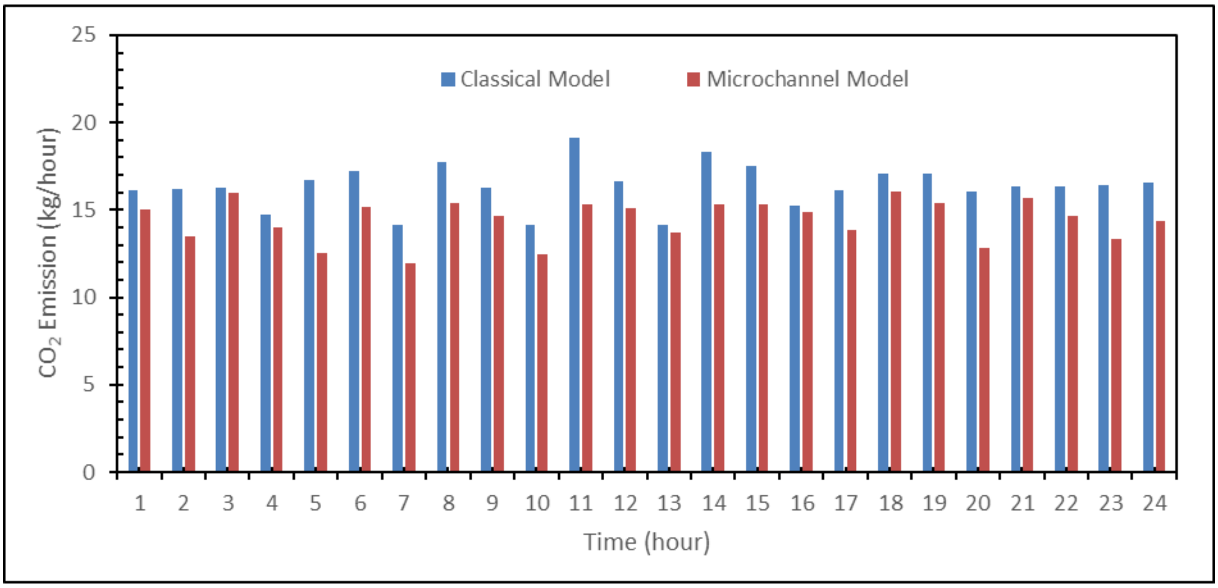


Figure 8. *CO_2 emission graph of the cooling system*

According to Eq. (16), the uncertainties of the cooling COP and exergy efficiencies were calculated by taking into account the experimental measurements. The cooling COP and exergy uncertainty in classical model were calculated as ± 0.0712 and ± 0.2862 %, respectively. The cooling COP and exergy uncertainty in microchannel model were found as ± 0.0524 and ± 0.1973%, respectively.

Table 2. *Summary of the results of this study*

	Microchannel Model	Classical Model
Refrigerant quantity	R449a, 1150 g	R449a, 1450 g
Average pressure ratio*	3.952	4.961
Volumetric air flowrate	600 m^3/h	780 m^3/h
The average current value	3.066 A	3.463 A
Total energy consumption	14.409 kWh	16.202 kWh
The average cooling COP	2.351	2.086
The average exergy efficiency	25.564 %	23.950 %
Total CO_2 emission value	346.524 kg/day	392.575 kg/day

* The ratio of average condensation pressure to evaporation pressure throughout the experiment
** The average current value of the compressor throughout the experiment

According to Table 2, the usage of microchannel condenser was seen to be more effective than classical condensers in large denominators such as pressure, temperature, thermal capacity and efficiency, which was also observed in literature reviews. Besides, the refrigerant charge amount in the microchannel model is 20.689% less than in the classical model. It was also determined that when the microchannel condenser was used in the cooling system, there was less carbon dioxide emission.

On the other hand, the microchannel condenser is lighter and smaller in size than the classical condensers, resulting in a decrease in the total amount of refrigerant in the system and thus a reduction in overall copper pipe length and diameter. Thanks to its high efficiency, the system allows the main equipment to be used at a lower capacity and the last of all, the cost of the cooling system also reduces.

4. CONCLUSIONS

The performances of two industrial cooling systems using classical and microchannel condensers were experimentally investigated and energy, exergy, and environmental (3E) analyses were performed. According to these analyses, the following outcomes can be listed:

- The average amount of energy consumed by the microchannel model is 11.852% less than classical model. Thus, the importance of using microchannel condenser in the cooling system has been further understood.
- The cooling COP determines how effectively the cooling system is used. The average COP of the microchannel model was found as 2.351, and the average COP of the classical model as 2.086.
- The average exergy efficiency value of classical and microchannel model was calculated as 23.950 % and 25.564 %, respectively. These values indicate that the use of microchannel condenser in the cooling system offers increased efficiency.
- The CO_2 emissions of the average classical and microchannel models were determined as 16.357 kg/hour and 14.438 kg/hour. These values show that the proposed system can be an eco-friendly alternative considering the problems related to global warming.
- It is recommended to use the microchannel heat exchanger in the industrial cooling system with regard to energy consumption, COP, exergy efficiency, and CO_2 emission values

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

REFERENCES

[1] Mohanraj M, Belyayev Y, Jayaraj S, Kaltayev A. “Research and developments on solar assisted compression heat pump systems—a comprehensive review (Part A: modeling and modifi-cations)”, *Renew Sustain Energy Rev.* 83: 90–123, (2018).

[2] Gürel AE. Ağbulut Ü. Ergün A. Ceylan İ. "Environmental and economic assessment of a low energy consumption household refrigerator", *Engineering Science and Technology*. 23(2): 365-372, (2020).

[3] Park CY, Hrnjak P. “Experimental and numerical study on microchannel and round-tube condensers in a R410A residential air-conditioning system”, *Int. J. Refrigeration*. 31: 822-31, (2008).

[4] Moallem E, Cremaschi L, Fisher DE, Hong T. “Effects of frost growth on louvered folded fins of microchannel heat exchangers on the time-dependent air side convective heat transfer coefficient”, *Exp Thermal and Fluid Science*. 88: 326-35, (2017).

[5] Zhan B, Shao S, Zang H, Tian C. "Simulation on vertical microchannel evaporator for rack-backdoor cooling of data center", *Applied Thermal Engineering*. 164-114550, (2020).

[6] Tosun M, Doğan B, Öztürk MM, Erbay LB. "Integration of a mini-channel condenser into a household refrigerator with regard to accurate capillary tube length and refrigerant amount", *Int. J. Refrigeration*. 98: 428-35, (2019).

[7] Xu B, Han Q, Chen J, Li F, Wang N, Li D, Pan X "Experimental investigation of frost and defrost performance of microchannel heat exchangers for heat pump systems", *Applied Energy*. 103: 180-8, (2013).

[8] Xu B, Wang Y, Chen J, Li F, Li D, Pan X. "Investigation of domestic air conditioner with a novel low charge microchannel condenser suitable for hydrocarbon refrigerant", *Measurement*. 90: 338-48, (2016).

[9] Zou Y, Hrnjak P. "Comparison and generalization of R410A and R134a distribution in the microchannel heat exchanger with the vertical header", *Science and Technology for the Built Environment*, 21: 555-63, (2015).

[10] Cremaschi L, Yatim AS. "Oil retention in microchannel heat exchangers of an R134a refrigeration system and effects on their energy performance and system COP", *Science and Technology for the Built Environment*. 25(3): 272-81, (2019).

[11] Makhnatch P. Mota-Babiloni A. Rogstam J. Khodabandeh R. "Retrofit of lower GWP alternative R449A into an existing R404A indirect supermarket refrigeration system". *Int. J. Refrigeration.* 76: 184–192, (2017).

[12] Vaitkus L. Dagilis V. "Analysis of alternatives to high gwp refrigerants for eutectic refrigerating systems", *Int. J. Refrigeration*. 76: 160–169, (2017).

[13] Makhnatch P, Mota-Babiloni A, Rogstam J, Khodabandeh R. "Retrofit of lower GWP alternative R449A into an existing R404A indirect supermarket refrigeration system", *Int. J. Refrigeration*. 76: 184-92, (2017).

[14] Aktaş M, Koşan M, Arslan E, Tuncer AD. "Designing a novel solar-assisted heat pump system with modification of a thermal energy storage unit", *Proc IMechE Part A: J Power and Energy*. 233(5): 588-603, (2019).

[15] Fernando P, Palm B, Lundqvist P, Granryd E. "Performance of a Single-Family Heat Pump at Different Working Conditions Using Small Quantity of Propane as Refrigerant", *Experimental Heat Transfer*. 20(1): 57-71, (2007).

[16] Ergün A. Gürel AE, Ceylan İ. "Ticari Soğutma Sistemlerinde R22 Akişkaninin Alternatifi Olarak R438a Ve R417a Akişkanlarinin Performansinin İncelenmesi", *Gazi Üniversitesi Fen Bilimleri Dergisi Part C: Tasarım ve Teknoloji*. 6(4): 824-833, (2018).

[17] Fang Z, Feng X, Zheng Z, Zhou X, Li L, Huang Y, Wang H, Liu F, "Experimental study on performance optimization of air source heat pump using DOE method", *Experimental Heat Transfer*. 32(3): 267-83, (2019).

[18] Dincer I, Rosen MA. *Exergy*, second ed. Elsevier. Oxford, UK. 2013.

[19] Smith R, Delaby O. Targeting flue gas emissions. *Trans IChemE*. 1991;69:492-505.

[20] Koşan M, Demirtaş M, Aktaş M, Dişli E. "Performance analyses of sustainable PV/T assisted heat pump drying system", *Sol. Ener.* 199: 657-72, (2020).

[21] Pawar T, Kulkarni A, Kulkarni G, Patil S, Yadav J, Shikalgar V. "Performance comparison of conventional and microchannel condenser in vapour compression refrigeration system", *International Journal of Innovative Research in Science, Engineering and Technology,* 6(4),(2017).