THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,
Volume x, Number x/2024, pp. 000–000

EXERGY EFFICIENCY AND HEAT TRANSFER FROM THE CONDENSER IN HEAT PUMP SYSTEMS

Murat KAYA[1], Şükrü KAYA[2]

[1] Hitit University, Department of Mechanical Engineering, Çorum, Türkiye
[2] Keçiören Industrial Vocational School, Ankara, Türkiye
Corresponding author: Murat KAYA, e-mail: mrtkaya@hotmail.com

Abstract. In cooling systems, the thermal energy transfer capability of the condensers used for the condensation of the refrigerant is very important for the efficient operation of the systems. A heat pump assembly was installed and R134a was used as the fluid. During operation, the temperature of the refrigerant compressed in the condenser increases and reaches the superheated vapor phase. Heat is transferred from the surface of the condenser, whose temperature is increasing, to the environment with the help of a fan. The exergy efficiency of the condenser was determined based on the inlet and outlet temperature of the refrigerant to the condenser, the temperature of the air flow to and from the condenser surface, its masses and thermodynamic properties. It was observed that the exergy efficiency (ψ) increased and the irreversibility (İ) decreased with the increase of the air temperature difference (ΔT) passing over the condenser surface. In addition, it was determined that the exergy efficiency (ψ) and surface temperature of the condenser decreased with the increase in the amount of air passing through (m_a) the condenser surface.

Key words: heat pump, condenser, condensing, refrigerant R134a, exergy efficiency

Nomenclature

Symbol	Nomenclature	SI Units
$\dot{m}_R$	Refrigerant mass flow	kg/s
$\dot{m}_a$	Air mass flow rate	kg/s
h_R	Refrigerant specific enthalpy	kJ/kg
s_R	Refrigerant specific entropy	kJ/kg K
c_{pa}	Isobaric air thermal capacity per unit mass	kJ/kg K
P	Pressure	kPa
T_R	Refrigerant temperature	K
T_a	Airflow temperature	K
Q	Heat load	kJ
E	Exergy	kJ
$E^{\Delta P}$	Pressure component of exergy	kJ
$\dot{I}$	Irreversibility	kW
Ψ	Exergy efficiency	-
γ	Heat capacity ratio	-

Indices
0 : environment
face : surface
1 : input
2 : output
a : air
R : refrigerant

1. INTRODUCTION

Heat pump systems are used as air-conditioning devices as well as cooling and deep-freezing systems. Such systems are in the category of devices used in the first degree at the point of protecting human comfort, quality of life and human needs. Thermodynamically, these systems are designed to transfer heat energy to their surroundings or to extract heat energy from the environment. In both cases of these systems, the energy transfer is realized by the compressor working with electrical energy. Improvements to be made in the heat transfer of the evaporator or condenser will provide savings in electrical energy costs.

In heat pump systems, the refrigerant compressed by the compressor and sent to the condenser as superheated vapor is sent from the condenser to the throttling valve as a saturated liquid. In such systems, the condenser is considered as the heat exchanger that needs to be cooled. For this reason, it is important to dissipate the heat of the hot fluid in the condenser to the environment. In this respect, the manufacturing method of condenser devices determines the thermal performance of the condenser in terms of heat transfer. In addition, the performance of the condensers is closely related to the physical location, direction and arrangement of the device.

2. DESCRIPTION OF THE SYSTEM AND LITERATURE STUDIES

In air conditioning system, heat exchangers for heat pump condensers and evaporators are usually designed rated load conditions. In the refrigeration cycle, the heat is taken from one environment and transferred to another environment, It occurs with the heat transfer during the evaporation of the refrigerants used as intermediates from the liquid state to the gas state and their condensation from the gaseous state to the liquid state [1]. There are many studies on the operation of heat pump systems. When calculating the heat exchanger thermal design, a suitable correlation should be selected according to the condition of the refrigerant. Considering different manufacturing models, high heat transfer efficiency and low welding requirements, highly optimized heat exchanger design is widely used [2]. Reference [3] examined the effect of outdoor heat exchanger placement on performance in a three-heat exchanger system using R134a. The study determined that under heating situation, the placement method and the location of the refrigerant inlet have effects on performance. He also stated that the effect of fluid inlet in the superheated vapor phase would be better during the first process. In [4], the effect of outdoor heat exchanger placement on the performance of the heat pump was investigated. It has been determined that the heat exchange performance of a vertical heat exchanger is better than a horizontal heat exchanger and with the use of the vertical heat exchanger it is 12% higher at its COP. This is because the horizontal HX has longer flow paths and then higher pressure drop. However, considering the factor of frosting, the horizontal HX has better performance. On cooling conditions, horizontal external HX brings lower compressor power consumption, greater cooling capacity and higher COP. In [5], Heat and flow analyzes of the heat exchanger in a flat geometric design with parallel flow were made. The effect of flow on thermal performance is studied with varying design factors. It was found that the heat transfer rate of the optimized model increased by 6.0% and the pressure drop by 0.4% compared to the base model. In [6], the authors showed that the performance of a mobile air conditioning system operating normally with R134a in direct expansion mode can be significantly improved when the flash gas is switched to bypass mode. They observed that when operated at the same compressor speed, the system in the flash gas bypass mode produced approximately 13–18% more cooling capacity, with a 4%–7% higher COP than the direct expansion mode.

In their study, they investigated the difference between a design that considers the partial load condition and the rated load condition in the heat exchanger path design. The optimum number of paths for each load condition was chosen considering the thermal resistance ratio. The results show that the heat transfer rates of a condenser with optimum path number based on thermal resistance at 84%, 51% and 33% load conditions are 18.29%, 27.58% and 42.58% higher than the heat transfer rate of a condenser [7]. They work includes analysis, testing and performance verification for a 1-ton water-cooled vapor compression refrigeration system using a mist-based condenser. Small mist droplets that evaporated quickly spread over the hot surface of the condenser. In addition, the heat transfer area obtained for the fog-based system is 3.5 times higher than a water-cooled condenser for the same heat exchanger. They observed a COP increase of approximately 50% with the water-cooled condenser to cool 1 tonne of water compared to the air-cooled condenser. As a result, the coefficient of performance was 4.7, the energy efficiency ratio was 16, and the electricity consumption for water was 844 W/ton [8]. Bai et al. is a split ejector based cycle examiner with condenser outlet for high temperature heat pump in operation [9]. In their study, Zajacs et al. evaluated the theoretical feasibility of using low-temperature elevator heat pumps in the DH system to improve flue gas condenser efficiency [10]. In their study, ElSherbini et al. investigated the possibility of reducing electricity demand and saving energy by shading the condensers of air conditioning (A/C) equipment used for cooling in buildings. The theoretical increase in the coefficient of performance (COP) due to shading was determined to be within 2.5% [11].

3. HEAT PUMP SYSTEM

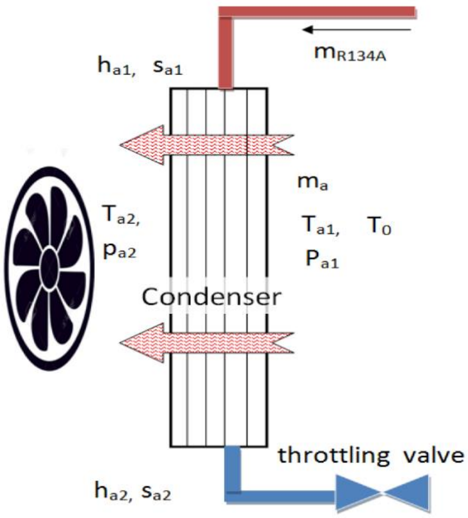

Fig. 1 – Heat pump operating principle diagram.

The working principle of the heat pump is that the refrigerant in the vapor phase is compressed into the condenser with the help of the compressor. The refrigerant is compressed up to the saturation pressure in the condenser by the heat pump, where the fluid condenses, and its temperature rises. It is made of materials with high thermal conductivity in order to discharge the heat load on the condenser to the environment. The surrounding air flow is provided by the help of a fan from the outer surface of the condenser made of finned pipes. While the temperature and pressure of the air flow provided by the fan are at ambient conditions, the temperature increases, and the pressure decreases slightly when leaving the condenser. Condensers used in the cooling system are evaluated in three parts. These are the sections where the superheat is taken, the cooling of the fluid, and the sub cooling.

As shown in Fig. 1, an experimental setup based on the principle of a heat pump system with a heat exchanger was set up and the performance of the heat exchanger was measured using the enthalpy difference method.

Many refrigerants are generally used in heat pump systems. In this study, only the thermodynamic properties of R134a (CH_2 FCF_3) refrigerant were used [12]. Some properties of R134a are boiling point (1 atm) –26.5 °C, melting point –101 °C, vapor pressure (25 °C) 6.65 bar, density, gaseous (air:1) 3.5 kg/m^3, specific weight (25 °C) 1.208, critical pressure 40.7 bar. [13]. In the study, depending on the condenser air fan speed, the air flow rate was taken between v = 3–10 m/s and the air mass flow rate was measured in the range of $\dot{m}_a$ = 2–4.5 kg/s. As a working principle, the superheat temperature of the R134a fluid in the condenser was kept at 319 K and the condenser outlet temperature was kept at 308 K. While the ambient air temperature was 288 K, the surface temperature of the condenser was measured as 310 K. Depending on the increase in the speed of the condenser fan, an increase in the amount of air mass was observed, and accordingly the condenser air outlet temperature was measured to vary between 295 K and 303 K. P_{a1} and P_{a2} pressures are the air flow pressures on the condenser surface. The ratio of c_{pa} specific heat capacity and heat capacity (γ) is taken as 1.4.

4. RELATED EQUATIONS

The thermal energy of the refrigerant passing through the condenser should, under ideal conditions, pass all of its thermal energy to the air flow passing through the outer surface of the condenser. This heat transfer principle is due to the temperature difference of the fluids. There may be thermal losses ($\dot{Q}_0$) in non-ideal heat transfers. If the energy equation is

$$\dot{m}_{\mathrm{R}}\left(h_{\mathrm{R2}}-h_{\mathrm{R1}}\right)=\dot{m}_{\mathrm{a}}c_{\mathrm{pa}}\left(T_{\mathrm{a2}}-T_{\mathrm{a1}}\right)+\dot{Q}_0 \quad (1)$$

It is determined from the equation. Heat exchangers that function as condensers form a specific thermal control zone in terms of thermodynamics. The irreversibility ratio ($\dot{I}$) of this formed region is determined by using Gouy-Stodola.

$$\dot{I}=\dot{m}_{\mathrm{a}}T_0\left(s_{\mathrm{a2}}-s_{\mathrm{a1}}\right)+\dot{m}_{\mathrm{R}}\left(h_{\mathrm{R2}}-h_{\mathrm{R1}}\right)-\dot{Q}_0 \quad (2)$$

It determines the entropy increase difference of the air flowing from the outer surfaces of the condenser from equation (2) ($s_{\mathrm{a2}}-s_{\mathrm{a1}}$). This entropy difference determines the pressure, temperature and thermal capacity of the incoming and outgoing air, respectively.

$$\left(s_{\mathrm{a2}}-s_{\mathrm{a1}}\right)=c_{\mathrm{pa}}\left[\ln\frac{T_{\mathrm{a2}}}{T_{\mathrm{a1}}}-\frac{\gamma-1}{\gamma}\ln\frac{P_{\mathrm{a2}}}{P_{\mathrm{a1}}}\right] \quad (3)$$

If air is considered an ideal gas irreversibility due to pressure loss.

$$\dot{I}_{\mathrm{a}}^{\Delta P}=\dot{m}_{\mathrm{a}}\frac{\gamma-1}{\gamma}c_{\mathrm{pa}}T_0\ln\frac{P_{\mathrm{a1}}}{P_{\mathrm{a2}}} \quad (4)$$

The refrigerant is compressed in the condenser by the heat pump. The temperature of the pressurized fluid rises up to the condensation temperature. In order to reduce the condenser temperature, air flow is given to its surface from the environment. The inlet temperature of the supplied cooling air should always be lower than the condenser temperature. In addition to the temperature difference of the air entering and leaving the condenser in flow, the surface temperature of the condenser is also important. This temperature difference causes heat loss and is calculated as exergy loss.

$$\dot{I}_{\mathrm{s}}^{Q}=\dot{Q}_0\ \frac{T_{\mathrm{face}}-T_0}{T_{\mathrm{face}}} \quad (5)$$

If a temperature difference occurs in a heat exchanger due to air flow, two irreversibility occur during the heat transfer process. ($\dot{I}^{\Delta T}$) Pressure loss occurs due to flow frictions between surfaces. Therefore, two irreversibility occur $\dot{I}_{\mathrm{a}}^{\Delta P}$ and $\dot{I}_{\mathrm{s}}^{Q}$, total irreversibility.

$$\dot{I}=\dot{I}^{\Delta T}+\dot{I}_{\mathrm{a}}^{\Delta P}+\dot{I}_{\mathrm{s}}^{Q} \quad (6)$$

Exergy analysis of systems determines where system efficiency can be improved; it is a way of determining the location, magnitude, and source of irreversibility. Ambient temperature and pressure are considered as dead states in calculations [14]. The exergy efficiency ratio of the condenser is

$$\psi=1-\frac{\dot{I}}{\Delta\dot{E}_{\mathrm{R}}^{\Delta T}\ +\ \Delta\dot{E}_{\mathrm{a}}^{\Delta P}} \quad (7)$$

There is no pressure drop during the refrigerant flow of the condenser, so the energy value ($\Delta\dot{E}_{\mathrm{a}}^{\Delta P}$) is the energy loss due to the viscous frictions that cause the pressure drop and ($\dot{I}_{\mathrm{a}}^{\Delta P}$) is equal. $\Delta\dot{E}_{\mathrm{a}}^{\Delta P}=\dot{I}_{\mathrm{a}}^{\Delta P}$, if $\Delta\dot{E}_{\mathrm{R}}^{\Delta T}$ is equal to $\Delta\dot{E}_{\mathrm{R}}$.

$$\Delta\dot{E}_{\mathrm{R}}=\Delta\dot{E}_{\mathrm{R}}^{\Delta T}=\left[\dot{m}_{\mathrm{R}}\left(h_{\mathrm{R2}}-h_{\mathrm{R1}}\right)-\dot{m}_{\mathrm{R}}T_0\left(s_{\mathrm{R1}}-s_{\mathrm{R2}}\right)\right] \quad (8)$$

The condenser refrigerant is determined by taking into account the entropy change.

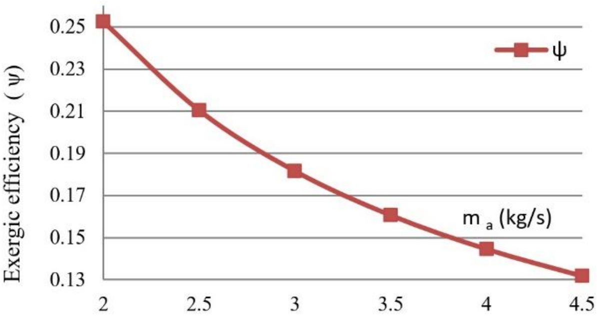

Fig. 2 – Exergy efficiency change of the amount of air passing through the condenser surface.

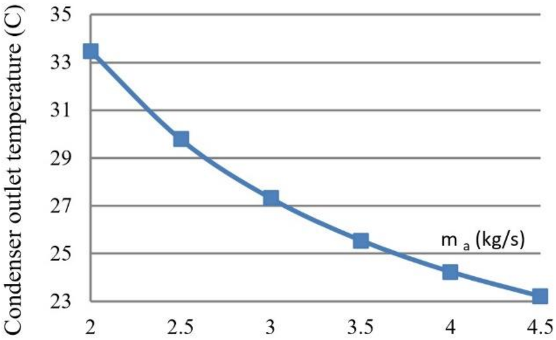

Fig. 3 – The air temperature value leaving the condenser for the change in the amount of air passing over the condenser surface.

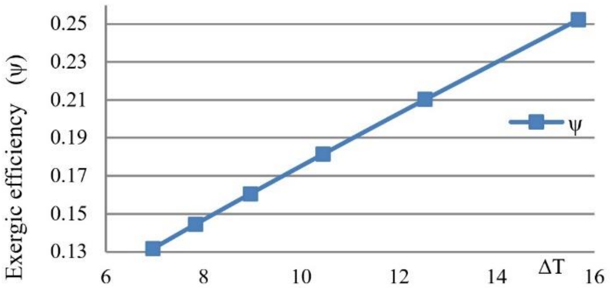

Fig. 4 – Exergy efficiency variation of the temperature difference of the air passing through the condenser surface.

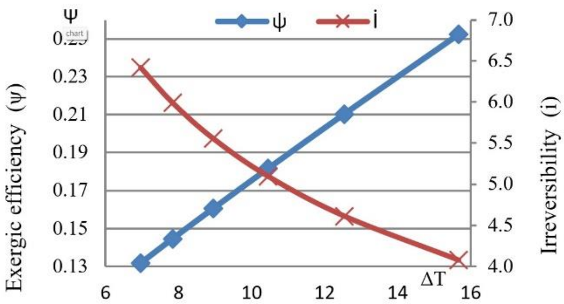

Fig. 5 – Irreversible and exergy efficiency variation of the temperature difference of the air passing over the condenser surface.

5. CONCLUSION

Inside the condensers used in air conditioning systems, there is a refrigerant whose temperature rises and condenses. Reducing the temperature of the refrigerant is the working principle of the system. Reducing the temperature of the refrigerant in the condensers occurs in three stages. The first is desuperheating from the refrigerant, the second is condensation, and the third is super cooling. Dissipating the heat of air-cooled condensers to the environment is also related to the design of the condenser. The efficiency of the condenser with a good surface air flow is high. A high efficiency condenser increases the efficiency of the heat pump. In the experimental study, the temperature of the refrigerant just above the saturation temperature of 48°C was measured. The exit temperature of the refrigerant from the condenser was measured at 35°C. The exergy efficiency ratio was calculated based on the thermodynamic properties of the refrigerant at this temperature. The condenser pressure is kept constant at 960 kPa, the amount of refrigerant $\dot{m}_R$ = 0.125 kg/s. In Fig. 2, as the amount of air passing through the condenser surface increases, the exergy efficiency (ψ) value decreases. In Fig. 3, the condenser air inlet temperature was taken as constant and it was observed that the condenser outlet temperature decreased depending on the increase in the amount of air coming out of the condenser surface. In Fig. 4, the exergy efficiency (ψ) increased with the increase of the air temperature difference (ΔT) passing over the condenser surface. In Fig. 5, while the temperature difference (ΔT) of the air passing over the condenser surface increases, the irreversibility ($\dot{I}$) of the condenser decreases and the exergy efficiency (ψ) increases.

REFERENCES

1. M. KAYA, A. ERIŞEN, *Soğutma Sistemlerinde Evaporatör, Kondensör ve Çevre Sıcaklıklarının Çeşitli Soğutucu Akışkan Özelliklerine Bağlı Olarak Değişimi*, Uluslar Arası Katılımlı Ulusal Isı Bilimi Ve Tekniği Kongresi, Gazi Üni., Ankara, Türkiye, September 6–8, 1995, vol. 2, pp. 861–874.
2. G.L. DING, *Recent developments in simulation techniques for vapour-compression refrigeration systems*, Int. J. Refrig., **30**, *7*, pp. 1119–1133, 2007.
3. J. BENOUALI, C. PETITJEAN, I. CITTI, R. BEAUVIS, L. DELAFORGE, *Evaporator-condenser improvement and impact on heat pump system performances for EVs*, SAE Technical Paper 2014-01-0708, 2014, DOI: 10.4271/2014-01-0708.
4. ZHANG, X., XUE, Q., ZOU, H., J. Liu, C. Tian, X. Zhang, *Influence of heat exchanger tube layout on performance of heat pump system for electric cars*, Energy Procedia, **105**, pp. 5085–5090. 2017.
5. K. CHUNG, K.S. LEE, W.S. KIM, *Optimization of the design factors for thermal performance of a parallel-flow heat exchanger*, Int. J. Heat Mass Transf., **45**, *24*, pp. 4773–4780, 2002.
6. H. TUO, P. HRNJAK, *Flash gas bypass in mobile air conditioning system with R134a*, Int. J. Refrig., **35**, *7*, pp. 1869–1877, 2012.
7. Y. KWAK, S. HWANG, J.H. JEONG, *Effect of part load operating conditions of an air conditioner on the number of refrigerant paths and heat transfer performance of a condenser*, Energy Conversion and Management, **203**, p. 112257, 2019, DOI: 10.1016/j.enconman.2019.112257.
8. S.H. SHAH, K.R. PAI, S.R. SHINDE, B.N. THORAT, *Analysis of a vapor compression refrigeration system using a fog-cooled condenser*, Applied Thermal Engineering, **196**, p. 117299, 2021, DOI: 10.1016/j.applthermaleng.2021.117299.
9. T. BAI, G. YAN, J. YU, *Thermodynamic assessment of a condenser outlet split ejector-based high temperature heat pump cycle using various low GWP refrigerants*, Energy, **179**, pp. 850–862, 2019, DOI: 10.1016/j.energy.2019.04.191.
10. A. ZAJACS, R. BOGDANOVICS, A. BORODINECS, *Analysis of low temperature lift heat pump application in a district heating system for flue gas condenser efficiency improvement*, Sustainable Cities and Society, **57**, p. 102130, 2020, DOI: 10.1016/j.scs.2020.102130.
11. A.I. ELSHERBINI, G.P.MAHESHWARI, *Impact of shading air-cooled condensers on the efficiency of air-conditioning systems*, Energy and Buildings, **42**, *10*, pp. 1948–1951, October 2010, DOI: 10.1016/j.enbuild.2010.05.031.
12. Y.A. ÇENGEL, M.A. BOLES, *Mühendislik Yaklaşımıyla Termodinamik*, Literatür yayınevi, 1996.
13. Y. AKTAŞ, *R-134a Soğutucu Akışkanlı Isı Pompası Sisteminin Sütün Pastörizasyonunda Kullanımının Deneysel İncelenmesi*, Atatürk University, Institute of Science and Technology, MSc Thesis, Department of Mechanical Engineering, 2008.
14. T.J. KOTAS, *The exergy method of thermal plant analysis*, Krieger Publishing Company, Malabar, Florida, 1985.

Received October 16, 2022