THERMODYNAMIC ANALYSIS FOR INDUSTRIAL CABINET PROVIDING SIMULTANEOUS HEATING AND COOLING THAT CAN BE USED IN THE FOOD INDUSTRY

by

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In this study, a thermodynamic analysis of an industrial cabinet designed for industrial cabinet systems used in the food industry and providing simultaneous heating and cooling has been made. During the study, energy and exergy analyzes were carried out by using the engineering equation solver program to thermodynamic analysis of seven different refrigerants in the system designed by determining the mass-flow rate to obtain 10 kW heating power, which was selected by using the coolselector two program by using the refrigerant temperature values and operating pressure values. The condenser dew point temperature was kept at +30 °C and the evaporator dew point temperature was kept at –1 °C. Calculations were made under atmospheric conditions by keeping subcooling at –2 °C, superheating at +5 °C, and ambient temperature at 20 °C. The coefficients determining the system performance were obtained for the highest R22 refrigerant and the lowest for R513A refrigerant. The exergy heating efficiency was obtained in the highest R22 and lowest R407C refrigerants, respectively. The calculated exergy cooling efficiencies were observed to be the highest R407C and the lowest R513A, respectively. The results of the study are presented in graphics. It has been revealed that the most suitable fluid in the designed industrial cabinet system is the system using R22.

Key words: *energy analysis, exergy analysis, refrigeration cycle, refrigerant*

Introduction

Today, with the increase in environmental problems, depending on the development level of the countries, there has been a tendency towards sustainable and environmental resources. The amount of energy consumption per capita in a country is not only an economic indicator, but also determines the level of social development. Using a sustainable energy source increases energy efficiency, reduces environmental pollution and provides economic gains.

Particular attention is paid to the use of environmentally friendly fluids in air conditioning and cooling systems. The food industry is dependent on energy to maintain the safety and freshness of food. Refrigeration, freezing, heat treatment and drying are the most common techniques used for food preservation and are processes that require a significant amount of energy. In the food industry, 29% of the total energy is used for heating processes and 16% for cooling and freezing processes. Cooling and air-conditioning systems have been used for many years and studies have been carried out in these areas, primarily for the purpose of preserving food, healthier preservation and comfort of life. The 10-15% of the current electrical energy in the world is spent on cooling and air conditioning [1].

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Cooling describes the process of providing and maintaining the temperature below atmospheric temperature. In the normal cooling system, the heat dissipated in the condenser is wasted. However, we have the potential to use the heat discharged from the condenser. This potential can be exploited by simultaneous heating and cooling processes. The main advantage of simultaneous heating and cooling is that it can be accomplished with a single vapor compression cooling (VCC) system. The efficiency of the cooling system is determined by the coefficient of performance and depends on the refrigerant properties. However, the refrigerants GWP and ODP used in the world today are high. The use of environmentally friendly alternative refrigerants helps to reduce GWP and ODP [2].

In this context, it is important to design systems that can be used in the food industry, that can meet simultaneous heating and cooling at the same time, and that use environmentally friendly refrigerants. Industrial cabin systems that provide simultaneous heating and cooling. It is produced in places such as milk integrated facilities, packaged food products, chocolate factories, meat integrated facilities. The need for industrial facilities where heating and cooling is done simultaneously is increasing. In this study, the development of industrial cabin systems that provide more efficient simultaneous heating and cooling and the use of more environmentally friendly refrigerants are investigated.

Some studies, Austin [3], compared the performance of vapor compression refrigeration systems (VCRS) with various refrigerant mixtures such as R32, R152a, R290, R600a, R1270, and RE170 with VCRS using R134a, CFC22, CFC12, and R134a. The effects of important parameters such as refrigerant category, superheating and subcooling degree on cooling result, volumetric cooling capacity and coefficient of performance were investigated for different evaporation temperatures. The results showed better COP values for alternative refrigerants. Abdelaziz *et al*. [4] showed that suitable substitutes exist for both R22 and R410A at high ambient temperatures. Multiple alternatives to R22 performed well, and many R410A alternatives performed as well as and often better than R410A. Makhnatch *et al.* [5], showed that the refrigerant R449A can be used in this refrigeration system designed for R404A due to its favorable thermodynamic properties and maximum acceptable discharge temperature. Aized and Hamza [6], numerically investigated the thermodynamic analysis of various refrigerants on the basis of the vapor compression refrigeration cycle in order to find the alternative refrigerant of R134a numerically. The refrigerants studied are R134a, R152a, R404A, R410A, R407C, R507A, and R1234yf. The refrigeration capacity of R152a was found to be slightly lower than that of R134a, while its COP was found to be higher than that of R134a. Lee and Kim [7], conducted drop tests using R448A and R449A, which replaced R404A, to change the outside air and supply water temperatures. The power consumption of R404A is about 10% higher than that of R448A and R449A, while the COP obtained for R448A and R449A are similar, only 3.0% greater than that of R404A. Aricapa *et al*. [8], present the latest HC/HFC/HFO/R744 refrigerant mix options for an alternative to refrigerants and compare their energy and performance with the first developed mix prototypes. Babiloni and Makhnatch [9] describe a methodology for estimating the demand for refrigerants by 2030 for refrigeration, air conditioning and heat pumps available to EU customers. The results of this study are based on the refrigerant allocation model that predicts the replacement pattern for commonly used HFC refrigerants (R134a, R404A, R407C, and R410A). Velasco *et al.* [10] presented an experimental evaluation of the use of R513A refrigerant instead of R134a in a water chiller for air conditioning applications. A VCRS powered by a 0.92 kW piston type compressor with a mini-ducted air heat exchanger as the condenser was used to compare the performance of both refrigerants. In current practice, it has been found that the efficiency of the reciprocating compressor is sensitive to the mass-flow rate of the refrigerant. Babu *et al.* [2] made an analysis of the VCR system with R290 and R134a. They conducted experiments to determine the

COP and cooling capacity of the system with simultaneous heating and cooling and determined the amount of waste heat generated in the condenser using both refrigerants. The results found that the refrigeration of R134a COP was on average 16.43% lower than R290. They also determined that the heating value of R134a COP is 18.27% lower than R290.

In this study, some evaluations have been made in order to make simultaneous heating and cooling systems a more effective model, which is frequently encountered especially in the food sector – such as milk integrated facilities, packaged food products, chocolate factories, meat integrated facilities:
– determining the cooling COPc and heating COPh values of different fluids,
– determining for which systems is the total exergy destruction,
– exergy destruction effects of ambient temperature on system components and examination of exergy efficiencies,
– examining the effect of ambient temperature on cooling exergy efficiency and heating exergy efficiency, and
– investigation of the effect of superheat on COP and compressor power consumption.

System description

In this study, COP values and exergy efficiencies of the industrial cabin system providing simultaneous heating and cooling were determined with different fluids (R22, R134A, R404A, R407C, R410A, R449A, and R513A). The schematic view of the system and the *P-h* diagram are shown in fig. 1.

In the pressure/enthalpy diagram in fig. 1, the direction and processes of the refrigerant are determined: 1-2 – compression by the compressor, 2-4 – constant pressure heat removal process, 4-5 – supercooling, 5-6 – isenthalpic expansion, (expansion at constant enthalpy by throttling valve), 6-7 – constant pressure heat transfer process, (the heat is absorbed by the refrigerant in the evaporator), and 7-1 – superheating. Some properties of used refrigerants used for the designed cabin system are shown in tab. 1.

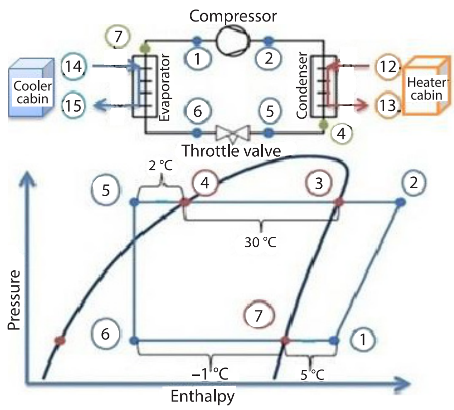

Figure 1. Schematic representation of the system

Table 1. Properties of used refrigerants [11-13]

Fluid	Composition of refrigrerants mixture	Critical pressure, *p* [MPa]	Critical temperature [°C]	Molar mass [kgkmol^{-1}]	Flammable/ toxic	ODP/ GWP
R22	CHCLF2	4.97	96.0	86.5	No/No	0/1700
R134A	C2H2F4	4.07	101.1	102.0	No/No	0/1300
R404A	R125/R143A/R134A (%44/%52/%4)	3.72	72.1	97.6	No/No	0/3800
R407C	R32/R125/R134A (%23/%25/%52)	4.63	86.4	86.2	No/No	0/1600
R410A	R32/R125 (%50/%50)	4.79	70.2	72.6	No/No	0/1900
R449A	R22/R125/R1234yf/R134A (%24,3/%24,7/%25,3/%25,7)	4.45	81.5	87.2	No/No	0/1400
R513A	R134A/R1234yf (%44/%56)	3.8	97	108.4	No/No	0/630

While performing the energy and exergy analysis of the concurrent industrial cabin system, some assumptions and fixed parameters have been taken. The engineering equation solver (EES) program was used for these analyses.

Assumptions and fixed parameters:

– All of the heat thrown from the condenser to the water and the heat taken from the water to the evaporator were transferred without loss.
– Mass-flow rate of the water circulating in the cabin is kept constant.
– Pressure losses in the compressor and on the pressure line in the system are neglected.
– Engine speed [N] 2900 rpm.
– Superheat 5 °C.
– Subcooling 2 °C.
– Condenser dew point temperature 30 °C
– Evaporating dew point temperature –1 °C
– Dead state 20 °C
– Power source 220-240 V
– Frequency 50 Hz

Thermodynamic analysis

Thermodynamic analysis for refrigeration system with simultaneous heating and cooling system components should be given for efficiently process design. The basis of a thermodynamic analysis is mass balance. In the steady-state condition, the mass balance equation can be given [14]:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{ex}} \tag{1}$$

where $\dot{m}$ is the mass-flow rate, the subscripts in and ex are the inlet and exit conditions, respectively. The energy balance is given [14]:

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \dot{m}\left(h + \frac{V^2}{2} + \text{g}z\right) = \dot{Q}_{\text{ex}} + \dot{W}_{\text{ex}} + \sum_{\text{ex}} \dot{m}\left(h + \frac{V^2}{2} + \text{g}z\right) \tag{2}$$

where $\dot{Q}$ is heat transfer rate, $\dot{W}$ – the power, h – the specific enthalpy, v – the velocity, z – the elevation, and g – the gravitational acceleration. The entropy balance equation for steady-state conditions is written:

$$\sum_{\text{in}} \dot{m}_{\text{in}} s_{\text{in}} + \sum_{k} \frac{\dot{Q}}{T_k} + \dot{S}_{\text{gen}} = \sum_{\text{ex}} \dot{m}_{\text{ex}} s_{\text{ex}} \tag{3}$$

where s is the specific entropy and $\dot{S}_{\text{gen}}$ – the entropy generation rate. The exergy balance equation can be written [15]:

$$\sum \dot{m}_{\text{in}} ex_{\text{in}} + \sum \dot{E}x_{Q,\text{in}} + \sum \dot{E}x_{W,\text{in}} = \sum \dot{m}_{\text{ex}} ex_{\text{ex}} + \sum \dot{E}x_{Q,\text{ex}} + \sum \dot{E}x_{W,\text{ex}} + \sum \dot{E}x_D \tag{4}$$

where $\dot{E}x_D$ is the exergy destruction rate, and can be defined:

$$\dot{E}x_D = T_0 \dot{S}_{\text{gen}} \tag{5}$$

where $\dot{E}x_W$ is the exergy rates releated with work, and is given:

$$\dot{E}x_W = \dot{W} \tag{6}$$

where $\dot{E}x_Q$ is the exergy rates releated with heat transfer, and is given:

$$\dot{E}x_Q = \left(1 - \frac{T_0}{T}\right)\dot{Q} \tag{7}$$

The specific flow exergy can be written [14, 15]:

$$ex = ex_{\mathrm{ph}} + ex_{\mathrm{ch}} + ex_{\mathrm{pt}} + ex_{\mathrm{kn}} \tag{8}$$

The kinetic and potential parts of exergy appear in the previous equation are assumed to be negligible. Also, chemical exergy is assumed to be negligible because there is no chemical reaction in the geothermal energy based integrated system. The physical or flow exergy, ex_{ph}, is defined:

$$ex_{\mathrm{ph}} = \left(h - h_0\right) - T_0\left(s - s_0\right) \tag{9}$$

where h and s are the specific enthalpy and entropy at the real case, respectively, also, h_0 and s_0 are the enthalpy and entropy at the reference environment states, respectively [15].

Compresor

The mass, energy, entropy and exergy balance for compressor can be defined:

– Mass balance

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_{\mathrm{ref}} \tag{10}$$

– Energy balance

$$\dot{W}_{\mathrm{comp}} = \dot{m}_{\mathrm{ref}}\left(h_2 - h_1\right) \tag{11}$$

– Entropy balance

$$\dot{S}_{\mathrm{gen,comp}} = \dot{m}_{\mathrm{ref}}\left(s_2 - s_1\right) \tag{12}$$

– Exergy balance

$$\dot{E}x_{D,\mathrm{comp}} = \dot{m}_{\mathrm{ref}}(ex_1 - ex_2) + \dot{W}_{\mathrm{comp}} \tag{13}$$

Condenser

The mass, energy, entropy and exergy balance are written for condenser:

– Mass balance

$$\dot{m}_2 = \dot{m}_5 = \dot{m}_{\mathrm{ref}}, \quad \dot{m}_{12} = \dot{m}_{13} = \dot{m}_{\mathrm{H_2O,con}} \tag{14}$$

– Energy balance

$$\dot{Q}_{\mathrm{con}} = \dot{m}_{\mathrm{ref}}\left(h_2 - h_5\right), \quad \dot{Q}_{\mathrm{con}} = \dot{m}_{\mathrm{H_2O}} c_{p_{\mathrm{H_2O}}}\left(T_{13} - T_{12}\right) \tag{15}$$

– Entropy balance:

$$\dot{\mathrm{S}}_{\mathrm{gen,con}} = \dot{m}_{\mathrm{H_2O}}\left(\mathrm{s}_{12} - \mathrm{s}_{13}\right) + \dot{m}_{\mathrm{ref}}\left(\mathrm{s}_2 - \mathrm{s}_5\right) \tag{16}$$

– Exergy balance:

$$\dot{E}x_{\mathrm{D,con}} = \dot{m}_{\mathrm{H_2O}}(ex_{13} - ex_{12}) + \dot{m}_{\mathrm{ref}}(ex_2 - ex_5) \tag{17}$$

Throttle valve

The mass, energy, entropy and exergy balance are written for throttle valve:

– Mass balance

$$\dot{m}_5 = \dot{m}_6 = \dot{m}_{\text{ref}} \tag{18}$$

– Energy balance

$$h_5 = h_6 \tag{19}$$

– Entropy balance

$$\dot{S}_{\text{gen},V} = \dot{m}_{\text{ref}}\left(s_6 - s_5\right) \tag{20}$$

– Exergy balance

$$\dot{E}x_{D,V} = \dot{m}_{\text{ref}}(ex_5 - ex_6) \tag{21}$$

Evaporator

The mass, energy, entropy and exergy balance are written for evaporator:

– Mass balance

$$\dot{m}_6 = \dot{m}_1 = \dot{m}_{\text{ref}}, \quad \dot{m}_{14} = \dot{m}_{15} = \dot{m}_{\text{H}_2\text{O,evap}} \tag{22}$$

– Energy balance

$$\dot{Q}_{\text{evap}} = \dot{m}_{\text{ref}}\left(h_6 - h_1\right), \quad \dot{Q}_{\text{evap}} = \dot{m}_{\text{H}_2\text{O}} c_{p,\text{H}_2\text{O}}\left(T_{14} - T_{15}\right) \tag{23}$$

– Entropy balance

$$\dot{S}_{\text{gen,evap}} = \dot{m}_{\text{ref}}\left(s_1 - s_6\right) + \dot{m}_{\text{H}_2\text{O}}\left(s_{15} - s_{14}\right) \tag{24}$$

– Exergy balance

$$\dot{E}x_{D,\text{evap}} = \dot{m}_{\text{ref}}(ex_6 - ex_1) + \dot{m}_{\text{H}_2\text{O}}(ex_{14} - ex_{15}) \tag{25}$$

Energy and exergy efficiency analyses

Energy efficiency, COP of a system can be described [14]:

$$COP = \frac{\sum \text{useful output energy}}{\sum \text{input energy}} \tag{26}$$

The simulteneous heating and cooling energy based integrated system efficiency can be calculated:

$$\begin{aligned} &\text{For heating system: } COP_{\text{h}} = \frac{\dot{Q}_{\text{heating}}}{\dot{W}_{\text{comp}}} \\ &\text{For cooling system: } COP_{\text{c}} = \frac{\dot{Q}_{\text{cooling}}}{\dot{W}_{\text{comp}}} \end{aligned} \tag{27}$$

The exergy efficiency, ψ, can be defined [14]:

$$\psi = \frac{\sum \text{useful output exergy}}{\sum \text{input exergy}} = 1 - \frac{\sum \text{exergy loss}}{\sum \text{input exergy}} \tag{28}$$

The simulteneous heating and cooling system efficiency can be calculated:

$$\text{Heating system efficiency} \quad \psi_c = \frac{\dot{E}x_{\text{cooling}}}{\dot{W}_{\text{comp}}}$$
$$\text{Cooling system efficiency} \quad \psi_h = \frac{\dot{E}x_{\text{heating}}}{\dot{W}_{\text{comp}}} \tag{29}$$

To investigate the inlet and outlet conditions for refrigeration system with simultaneous heating and cooling system components, the mass, energy, entropy and exergy balance equations can be written in subsections based on the steady-state conditions [16-18].

Results and discussion

The COP_h and COP_c values of refrigerants providing simultaneous heating and cooling are given in fig. 2.

When the *COP* values of the refrigerants used in heating and cooling processes are examined in fig. 2, it is seen that the best value is for the system using R22 fluids and the lowest *COP* value is for the system using R513A fluids. Between the fluid with the best *COP* and the fluid with the lowest *COP*, 10% higher for COP_h and 12% higher for COP_c.

The total exergy destructions for systems using different refrigerants are shown in fig. 3.

When fig. 3 is examined, the most destruction occurred in the system using R513A. The least exergy loss is seen in the system using R22. In this case, there was a 10% difference between the maximum and minimum difference in total exergy destruction throughout the systems. Reducing the total exergy destruction in a cycle will enable us to develop systems that operate more efficiently.

The exergy destruction of different refrigerants used in this system on each component is given in fig. 4.

In fig. 4, the exergy destruction of different refrigerants used in the system on each component is shown. While exergy destruction occurred in the compressor in R513A and R134A, the highest exergy loss occurred in the condenser in systems using other refrigerants. Higher exergy destruction in the compressor gives a lower *COP* value.

The exergy efficiencies of each component of the different refrigerants used in this system are given in fig. 5.

As seen in fig. 5, the highest exergy efficiency among the components was achieved in the throttling valve, followed by the condenser.

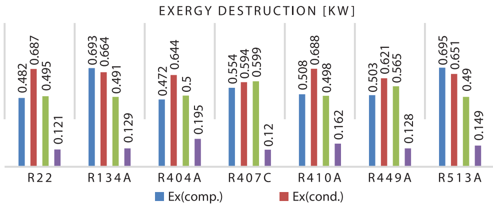

Figure 2. The COP values of refrigerants used in heating and cooling processes

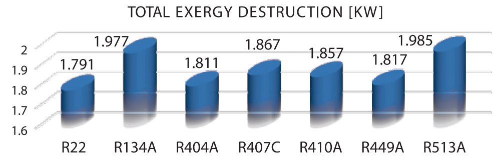

Figure 3. Total exergy destruction in systems working with different fluids

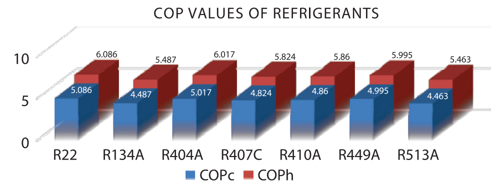

Figure 4. Exergy destruction of fluids on each component

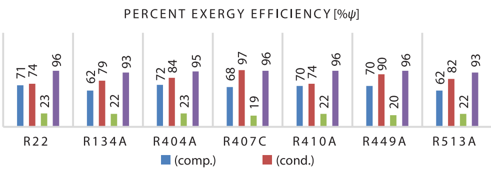

Figure 5. Exergy efficiencies of system components

The heating exergy efficiency depending on the ambient temperature is given in fig. 6.

Figure 6 shows that the heating exergy efficiency decreases with the increase in ambient temperature. The system using R22 refrigerant provides the best heating exergy efficiency.

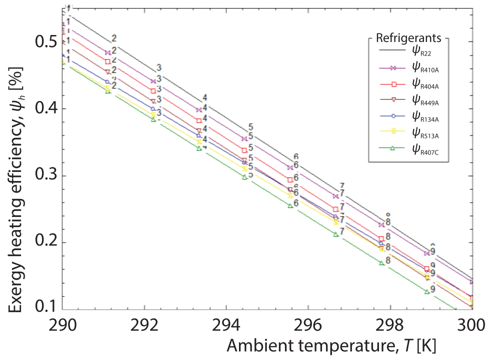

Figure 6. Heating exergy efficiency depending on ambient temperature

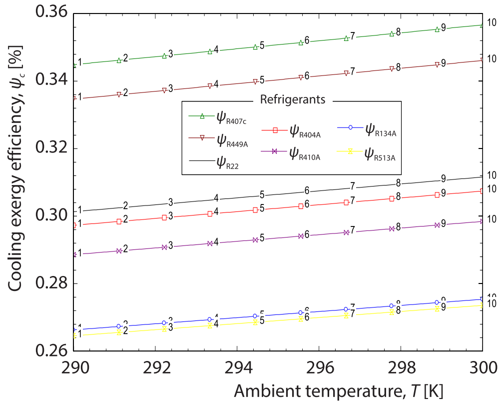

Figure 7. Cooling exergy efficiency depending on ambient temperature

The cooling exergy efficiency depending on the ambient temperature is given in fig. 7.

In fig. 7, it was observed that the cooling exergy efficiency increased with the increase in ambient temperature. The best cooling exergy efficiency was seen in the system using R407C fluid.

Total exergy loss due to ambient temperature is given in fig. 8.

Figure 8 shows how the total exergy destruction occurs with the increase in ambient temperature. In other words, the total exergy destruction decreased with increasing ambient temperature. Observation in the system using R513A fluid, which has the highest exergy loss depending on the ambient temperature among the refrigerants studied. This sequence did not change with the change in ambient temperature.

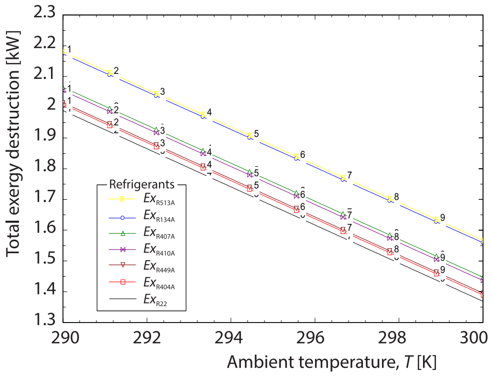

Figure 8. Total exergy loss due to ambient temperature

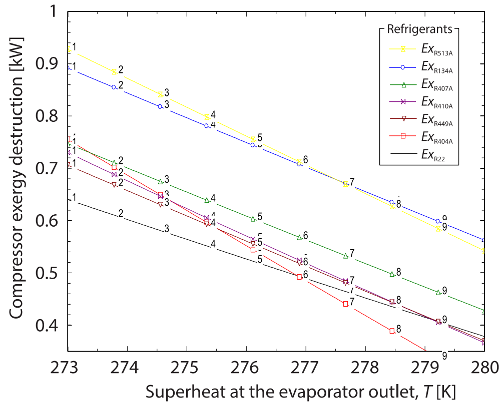

Figure 9. Variation of superheat in compressor exergy destruction

Compressor exergy destruction change of superheat at the evaporator outlet is shown in fig. 9.

Figure 9 shows the change in exergy destruction [kW] in the compressor with the increase and decrease of superheating at the evaporator outlet. It is seen that the refrigerant is

R404A, which minimizes the exergy loss in the compressor due to the increase in superheating temperature.

Since the evaporator outlet temperature affects the superheat in the system, fig. 10 shows how it affects the system COP_h value. Figure 10 shows the change in the system COP with the increase and decrease of the superheat temperature at the evaporator outlet temperature. The change in superheating was most observed in the refrigerant R404A.

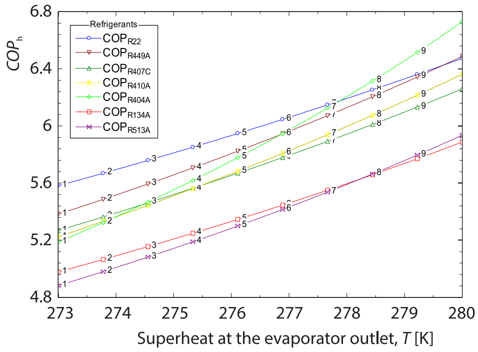

Figure 10. Effect of superheat on COP_h

Conclusions

In an industrial cabinet system that provides simultaneous heating and cooling; The avalanche point temperatures of the evaporator and condenser, providing 10 kW of condenser power, as well as superheating and subcooling temperatures were kept constant. It was determined using seven different fluid software programs during modelling. Working pressure and temperature values were taken from the program and calculations were made. In thermodynamic calculations, irreversibility depending on the change of ambient temperature and changes in system parameters due to superheating are emphasized.

- The best COP_h value was obtained in the system using R22 fluid (6.086). The lowest COP_h value was obtained in the system using R513A (5.463) refrigerant.
- The maximum total exergy destruction occurred in the system using R513A (1.985 kW) refrigerant.Total exergy destruction is seen in the system using at least R22 (1.791 kW) refrigerant.
- The most exergy destruction of each refrigerant on each component (for Ex_{DR513A} and Ex_{DR134A}) occurred in the compressor. In the other refrigerant systems, the highest exergy loss occurred in the condenser.
- Among the system components, the highest exergy efficiency occurs in the throttle valve, followed by the condenser.
- The best heating exergy efficiency (41.8%) was obtain with R22 refrigerant.
- Observation in the system using R513A fluid, which has the highest exergy loss depending on the ambient temperature among the working refrigerants. This order did not change with the change in ambient temperature.
- It is seen that the refrigerant is R404A, which minimizes the exergy loss in the compressor due to the increase in superheating temperature.
- The change in superheating is mostly observed in the refrigerant R404A.
- Determining the Irreversibility of different fluids on each component will result in less exergy loss on the components and less energy consumption. Therefore, this situation will contribute to the sustainable use of energy.

Nomenclature

c_p – specific heat [4.186 kJkg^{-1}K^{-1}]
Ex – exergy
ex – specific exergy, [kJkg^{-1}]
h – specific entalpy, [kJkg^{-1}]
$\dot{Q}$ – heat, [kW]
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
P – pressure, [MPa]
ph – physical exergy
T – temperature, [K]
$\dot{W}$ – power, [kW]

Greek symbol

ψ – exergy efficiency, [%]

Acronyms

EES – engineering equation solver
VCC – vapor compression cooling
VCRS – vapor compression refrigeration system

Subscripts

c – cooling
ch – chemical
comp – compressor
con – condenser
D – destruction
evap – evaporator
ex – exit
H_2O – water
h – heating
in – inlet
kn – kinetics
ph – physical of flow
pt – potential
Q – heat
ref – refrigerant
v – throttle valve
o – ambient tempreture
w – work

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