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Research Article

Thermo-Economic Analysis of Transcritical Carbon Dioxide Refrigeration Cycle

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Abstract

The use of refrigerants such as CFC and HCFC will have been completely finalized in 2030 because of the damage to the ozone layer by the international protocols. For this reason, CO2 refrigerant cooling cycles, which are considered to be an alternative refrigerant and give proper performance results, have begun to be used. In this study, thermo-economic analysis of transcritical carbon dioxide refrigeration cycle was examined. The necessary thermodynamic data for analysis were obtained by CoolPack program. The coefficient of performance (COP) and the annual cost analysis of the cycle in the different working conditions were examined. Energy consumption cost values required for the calculations were taken from Republic of Turkey Energy Market Regulatory Authority. The highest COP value of cycle for among all the working condition is found as 3.524 for 0 oC evaporator temperature, 30 oC gas cooler output temperature. The lowest annual cost values were found depending on the evaporator temperature change in transcritical carbon dioxide refrigeration cycle as 3269.376 Turkish Lira (TL). Obtained results were compared.

Keywords: Carbon dioxide, thermo-economic analysis, COP, refrigeration cycle.

1. Introduction

The most important characteristic of a refrigeration machine is coefficient of performance (COP). Studies are carried out to find environmentally friendly refrigerant solutions instead of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are used in cooling systems which negative impact on the environment, accelerator global warming, harmful to the ozone layer. Natural refrigerants that do not harm the ozone layer and no impact on global warming are the most important alternatives in this process. Carbon dioxide has emerged as an effective solution at this point. Carbon dioxide has been widely used in development stage of the refrigeration industry. But, halocarbon refrigerants were replaced to carbon dioxide. Because of decrease in the COP and the high operating pressure occurs cause heat transfer in the near or above of the critical point. Carbon dioxide has been used again as an alternative and natural refrigerant because of negative effects on the environment of halocarbon refrigerants. Transcritical carbon dioxide refrigeration cycle has reached a competitive level in terms of efficiency thanks to current machines, the heat exchanger technology and system components. Because of 31.06 °C low critical point temperature and 73.8 bar high critical point pressure, R744 (CO2) requires an additional technical requirement compared to conventional refrigerants. As can be seen from Table 1, CO2 has attractive thermo-physical properties and low viscosity, high volumetric capacity, high thermal conductivity and high vapor density compared to similar halocarbon refrigerants fluids.

Table 1. Thermo-physical Properties of Commonly Known Refrigerants

Fluid	**Critical Temperature [ºC]**	**Critical Pressure [bar]**	**Liquid Phase Density [kg/m^3]**	**Gas Phase Density [kg/m^3]**	**Thermal Capacity [kJ/kg]**	**Volumetric Capacity [kJ/m^3]**	**Heat Transfer Coefficient [W/mK]**	**Dynamic Viscosity [mPa.s]**
R22	96.2	49.9	1285.7	20.41	1.16	4205.28	0.09	0.22
R134a	101.1	40.6	1298.9	13.9	1.3	2773.75	0.09	0.27

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R407C	86.74	46.2	1240.8	18.86	1.4	3973.24	0.01	0.21
R507a	70.6	37.05	1161.1	30.98	1.37	5055.32	0.072	0.18
R744 (CO₂)	**31.06**	**73.7**	**934.26**	**94.148**	**2.5**	**22089**	**0.11**	**0.101**
R717	132.3	113.3	640.28	3.31	4.41	4192.51	0.56	0.172

Akdemir and Güngör have carried out thermodynamic analysis of CO_2 refrigeration cycle for different operating conditions. Performance variations were investigated and maximum performance values were determined in the study. The results of the study show that performance values can increase with optimum gas cooler pressures [2]. Llopi et al. have investigated energy performance of transcritical CO_2 refrigeration cycles. In the study has been shown that high evaporation levels were provided increasing the COP up to a maximum of 20% and the cooling capacity up to a maximum of 28.8%. The results show that this cycle is more appropriate for environment temperatures above 25 ºC [3]. Bai et al. have carried out thermodynamics analysis of transcritical CO_2 refrigeration cycle. The effects of some important variables on the performance of the cycle are numerically examined based on energy and exergy analyses. The results have been shown that maximum system coefficient of performance under the given operating conditions was reached 37.61% and 31.9% over those of the cycle [4]. Goodarzi and Gheibi have examined performance analysis of a modified transcritical CO_2 refrigeration cycle. The impact of gas cooler-evaporator temperatures and gas cooler pressures on the cycle performance was examined. The results have been shown that maximum COP was improvement 26.89% compared to the original cycle at particular operation conditions [5]. Paride et al. have investigated advanced exergy analysis of a R744 booster cooling system with parallel compression. The results of the study show that the exergy evaluation, the gas cooler-condenser, high stage compressor and medium temperature display cabinet exhibited maximum enhancement potential [6]. Haitao et al. have carried out energy analysis of an R744 ground source heat pump system. The results show that the investment and operation costs of the suggested R744 system are lower than that of the existing R134a system [7].

This study is one of the first articles on thermo-economic analysis of transcritical carbon dioxide refrigeration cycle in Turkey. In addition to the performance analysis of the cooling system, its usability is investigated economically. In this respect, it gains importance. This study is also important for the experimental studies planned in the future for author.

2. Thermodynamics Analysis

Transcritical carbon dioxide refrigeration cycle was modeled as theoretically with a computer program (CoolPack). P-h diagram for transcritical CO_2 refrigeration cycle is given Fig.1.

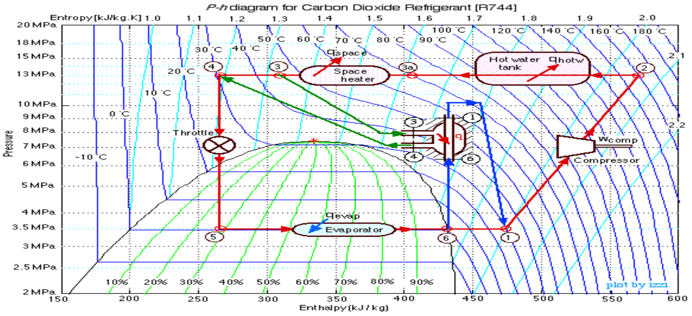

Fig.1. P-h diagram for transcritical carbon dioxide refrigeration cycle [8]

According to the first law of thermodynamics, the refrigeration capacity of the cycle can be calculated as follows:

$$\dot{Q}_E = \dot{m}\ (h_1 - h_5) \tag{1}$$

Compressor work load can be expressed as follows [10]:

$$\dot{W}_{Comp} = \dot{m}\ (h_2 - h_1) \tag{2}$$

Gas cooling heat load can be expressed as follows:

$$\dot{Q}_{GC} = \dot{m}\ (h_4 - h_2) \tag{3}$$

COP of the refrigeration cycle can be determineted as follows [11]:

$$COP = \frac{\dot{Q}_E}{\dot{W}_{Comp}} \tag{4}$$

The annual electricity cost of the cycle can be calculated as follows:

$$AEC = UEC\ W_{Comp} \tag{5}$$

where AEC is the annual electricity cost, UEC is the unit energy cost and W_{Comp} is compressor work load.

3. Results and Discussion

The coefficients of performance (COP) values were found depending on the evaporator temperature change in transcritical carbon dioxide refrigeration cycle and it was given in Fig. 2. Evaporator temperatures were changed and the gas cooler output temperature was kept constant at 30 oC in the cycle. It is observed that COP values have been decreased according to the reduction of evaporator temperature in the cycle. The highest COP value of cycle for among all the working condition is found as 3.524 for 0 oC evaporator temperature, 30 oC gas cooler output temperature.

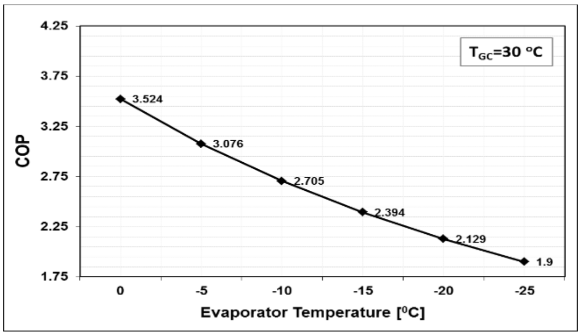

Fig.2. Variation of COP with evaporator temperature

The coefficients of performance (COP) values were found depending on the gas cooler temperature change in transcritical carbon dioxide refrigeration cycle and it was given in Fig.3. Gas cooler temperatures have been changed and the evaporator temperature was kept constant at -10 oC in the cycle. The gas cooler temperature is an important factor for carbon dioxide refrigeration cycle. The temperature of the CO2 outputted from the gas cooler directly affects the COP value. It is observed that COP values have been decreased according to the reduction of gas cooler temperature in the cycle. The highest COP value of cycle for among all the working condition is found as 2.705 for -10 oC evaporator temperature, 30 oC gas cooler output temperature.

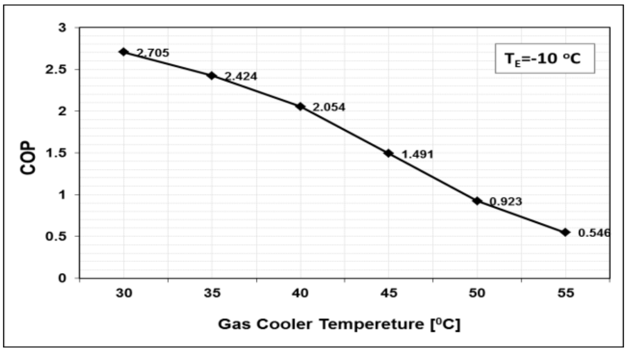

Fig.3. Variation of COP with gas cooler temperature

The coefficients of performance (COP) values were found depending on the gas cooler pressure change in transcritical CO2 refrigeration cycle and it is given in Figure 4. Gas cooler pressures have been changed, the evaporator temperatures and gas cooler output temperature have been kept constant at -10 oC and 30 oC in the cycle. It is observed that COP values have been decreased according to the increase of gas cooler pressure in the cycle. The highest COP value of cycle for among all the working condition is found as 2.409 for -10 oC evaporator temperature, 30 oC gas cooler output temperature and 12 MPa gas cooler pressure.

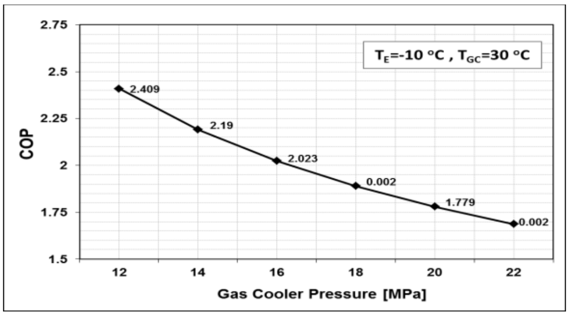

Fig.4. Variation of COP with gas cooler pressure

Analyses were made for three different working conditions in this study. For the economic calculations, annual amount of work hours 2920 h/years, unit energy costs 0.40 TL/kWh have been accepted. Unit energy costs are taken from Republic of Turkey Energy Market Regulatory Authority according to the latest data [9]. The annual cost values were found depending on the evaporator temperature change in transcritical carbon dioxide refrigeration cycle and it was given in Fig.5. It is observed that the annual cost values have been increased according to the reduction of evaporator temperature.

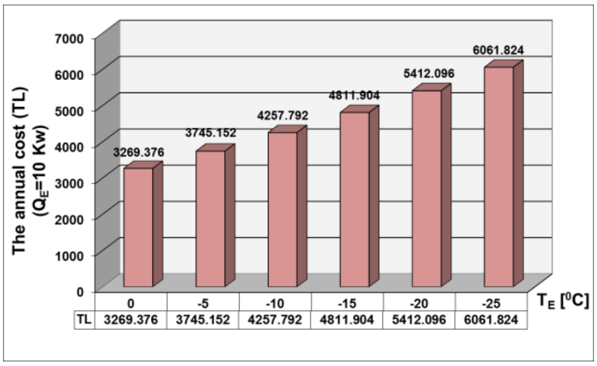

Fig.5. Variation of the annual cost with evaporator temperature

The annual cost values were found depending on the gas cooler temperature change in transcritical carbon dioxide refrigeration cycle and it was given in Fig.6. It is observed that the annual cost values have been increased according to the reduction of gas cooler temperature. Similarly, the annual cost values were found depending on the gas cooler pressure change in transcritical CO2 refrigeration cycle and it was given in Fig.7. It is observed that the annual cost values have been increased according to the reduction of gas cooler pressure.

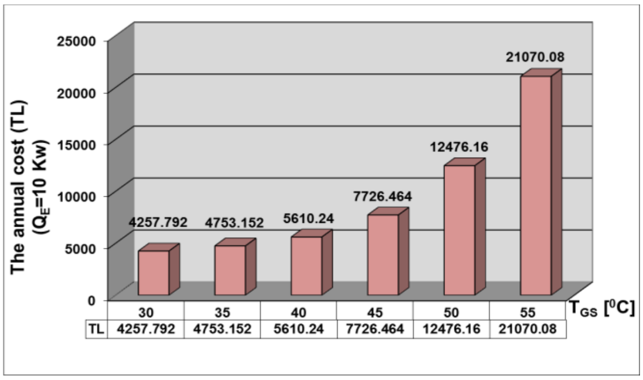

Fig.6. Variation of the annual cost with gas cooler output temperature

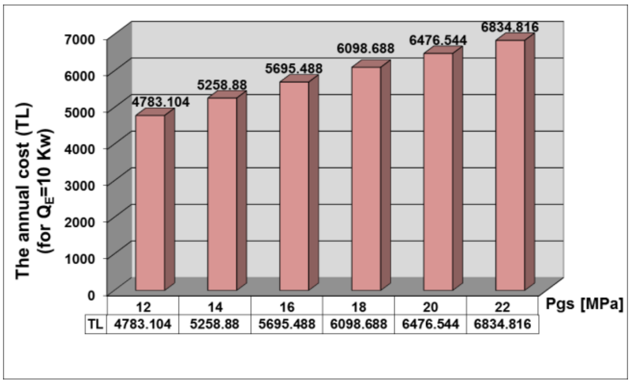

Fig.7 Variation of the annual cost with gas cooler pressure

The cost analyses showed that the change of gas cooler output temperature and pressure increases the annual cost. Hence, change of the evaporator temperature is more appropriate for minimum energy consumption in transcritical CO2 refrigeration cycle. As a result, the reduction of energy consumption which implies a reduction of the annual costs.

4. Conclusions

Widespread study is underway worldwide for the transcritical CO2 refrigeration cycle in many areas with promising results, refrigeration applications, heat pumps, water chillers. The thermo-physical properties of carbon dioxide are better than conventional refrigerants. In this study, thermo-economic analysis of transcritical CO2 refrigeration cycle was examined. The necessary thermodynamic data for analysis were obtained by CoolPack program. COP and the annual cost analysis of the cycle in the different operating conditions were examined. Energy consumption cost values required for the calculations were taken from Republic of Turkey Energy Market Regulatory Authority. Obtained results were compared. The highest COP value of cycle for among all the working condition is found as 3.524 for 0 oC evaporator temperature, 30 oC gas cooler output temperature. The lowest annual cost values were found depending on the evaporator temperature change in transcritical carbon dioxide refrigeration cycle as 3269.376 TL.

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Nomenclature

Symbols

$\dot{Q}$	heat rate [kW]
$\dot{W}$	work [kW]
T	temperature [oC]
$\dot{E}$	energy [kW]
$\dot{m}$	mass flow rate [kg/s]
h	specific enthalpy [kJ/kg]
$\dot{w}$	work [kW/kg]
$\dot{q}$	heat rate [Kw/kg]
cps	specific heat [kJ/(kg K)]
R	refrigerant
AEC	annual electricity cost [TL]
UEC	unit energy cost [TL/kWh]

TL	Turkish Lira

Subscripts

E	evaporator
Comp	compressor
GC	gas cooling
in	inlet
out	outlet
pump	pump