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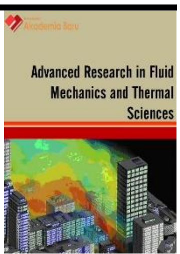
Akademia Baru

Journal of Advanced Research in Fluid
Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Experimental Study on The Performance of Trans-Critical Carbon Dioxide Refrigeration System Using Porous Evaporator

Mohammad Altarawneh[1,*]

[1] Department of Mechanical Engineering, The Hashemite University, Zarqa, Jordan

ARTICLE INFO

ABSTRACT

Article history:
Received 29 October 2019
Received in revised form 4 May 2020
Accepted 9 May 2020
Available online 15 August 2020

An experimental study on the performance of trans-critical carbon dioxide refrigeration system is conducted when using porous evaporator for different evaporation temperatures, ranging from (-2°C to 8°C), different gas cooler outlet temperatures ranging from (38°C to 49°C) and different porosities (empty tube (porosity = 100%)), 45%, 41% and 38% porous tube).Variations of refrigeration capacity with gas cooler outlet temperatures for different evaporator porosities were studied. Coefficient of performance as a function of gas cooler outlet temperature, gas cooler outlet pressure and evaporation temperature were investigated for different evaporator porosities. Pressure drop in porous evaporator as a function of evaporation temperature for different porosities is studied. Effects of evaporation temperature and evaporator porosity on power consumption per ton of refrigeration were also, studied. An average increase of about 40% and 64% in refrigeration capacity and COP were predicted, respectively, when decreasing gas cooler out let temperature from 49°C to 38°C and using evaporator with 38% porosity. Coefficient of performance of CO_2 trans-critical refrigeration system increases with increasing gas cooler pressure up to an optimum value and then it decreases at large values of gas cooler pressures. Power consumption per ton of refrigeration (PCTR) reached minimum values at low evaporation temperatures and low evaporator porosities with an average percentage decrease of about 38%. An increase of pressure drop was also, recorded during the evaporation process when evaporation temperature increased, and evaporator porosity decreased.

Keywords:
Carbon Dioxide; Refrigeration System; Trans-critical; Evaporation; Porous Media

1. Introduction

Carbon dioxide is one of environmentally friendly with zero ozone depletion potential refrigerants. The heat transfer coefficient of this natural refrigerant is considered to be low in comparison with other refrigerants. Inserting porous materials in the two-phase flow passages of this refrigerant during evaporation process as mean process in refrigeration system is suggested in this

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[*] *Corresponding author.*
E-mail address: Mohammad.Tarawneh@hu.edu.jo

https://doi.org/10.37934/arfmts.74.1.5767

research article to enhance heat transfer characteristics and coefficient of performance of a trans-critical refrigeration system using carbon dioxide as refrigerant. Many pieces of research are conducted during the last decade regarding the heat transfer behaviour of trans-critical carbon dioxide in refrigeration systems. Zhang *et al.,* [1] conducted a simulation study on the efficiencies of subcritical and trans-critical CO_2 inverse cycles with and without an internal heat exchanger. They concluded that, in using trans-critical CO_2 inverse cycles, the compressor discharge pressures and CO_2 gas cooler outlet temperatures both have significant impacts on system performance. Robinson *et al.,* [2] presented a comprehensive study and a detailed literature review on the use of carbon dioxide in trans-critical vapor compression refrigeration cycles. Numerical analysis of trans-critical carbon dioxide compression cycle was conducted by Keshtkar [3]. Yamasaki *et al.,* [4], presented an introduction of trans-critical refrigeration cycle utilizing CO_2 as working fluid. Tarawneh *et al.,* [5], conducted an experimental study on the effect of porous medium on the performance of a single tube heat exchanger using sub-critical CO_2 as a refrigerant. They concluded from this study that; the use of porous media could enhance the heat transfer performance of subcritical carbon dioxide refrigeration systems. Wang *et al.,* [6] performed an experimental and theoretical study on the cooling performance of a CO_2 mobile air conditioning system. Jiang *et al.,* [7] presented an experimental and numerical study on the convection heat transfer of CO_2 at supercritical pressures in vertical porous tubes. Experimental and numerical investigations of convection heat transfer of CO_2 at supercritical pressures in a vertical mini tube was conducted by Jiang *et al.,* [8]. Zhu *et al.,* [9] analysed, experimentally, the performance of a trans-critical CO_2 ejector-expansion refrigeration system. Dang *et al.,* [10] presented an experimental study on subcooling process of a trans-critical CO_2 air conditioning cycle working with microchannel evaporator. Bai *et al.,* [11] performed a thermodynamic analysis of a modified dual-evaporator CO_2 trans-critical refrigeration cycle with two-stage ejector. An advanced exergy analysis of an ejector expansion trans-critical CO_2 refrigeration system was conducted by Bai *et al.,* [12]. Dang *et al.,* [13] presented an experimental study on COP of CO_2 air conditioning system with mini-channel evaporator using subcooling process. Naveen *et al.,* [14] conducted an experimental investigation of a combined power refrigeration trans-critical CO_2 cycle. Many studies were carried out in last ten years on the thermodynamic behaviour of carbon dioxide trans-critical refrigeration systems [15-19]. Che Sidik *et al.,* [20] presented computational investigations on turbulent mixed convection heat transfer in concentric annulus using various Nano-refrigerants. Up to the in-hand references and up to the author's knowledge, there is no research reported in literature deals with using porous evaporators in trans-critical carbon dioxide refrigeration system. This research, comes to fill this gap in literature. The objective of this research is to conduct an experimental study on the performance of the modified trans-critical carbon dioxide refrigeration system using porous evaporator. The effect of gas cooling outlet temperature and the porosity of the evaporator on the refrigeration capacity, COP of refrigeration system was experimentally, investigated. The variations of COP, pressure drop and power consumption per ton of refrigeration with evaporation temperature during the two-phase flow of CO_2 in the used porous evaporator were investigated for different porosities. The properties of carbon dioxide compared with different refrigerants are shown in Table 1 [21]. It can be noticed that, CO_2 has low GWP and low ozone depletion potential when compared with other refrigerants. In the use of CO_2 as a refrigerant gas in refrigeration and heat pump systems we can find two applications in science; subcritical and transcritical. In the subcritical refrigeration or heat pump system, the refrigerant temperature of CO_2 in the heat rejection isothermal stage after the completion of the compression of the fluid is below the critical temperature, but in the transcritical systems, the temperature of CO_2 is greater than the critical temperature. The trans critical cycle can be used in certain periods of the year where the outside temperature is near or around the critical temperature of CO_2 (31.1°C). The transcritical cycle of CO_2 is preferred in the high-pressure industrial applications [22]. In the present work optimizations of the tanscritical cycle is done for, a selected range of evaporator temperature from -2°C to 8°C and gas cooler exit temperature range from 38°C to 49°C.

Table 1
Properties of Carbon dioxide (CO_2) compared with different refrigerants

Properties	CO_2 (R744)	R22	R134A	R410A
Critical pressure (MPa)	7.38	4.97	4.07	4.79
Critical temperature	31.1	96.0	101.1	70.2
Molar mass(kg/kmol)	44.0	86.5	102.0	72.6
Flammability/toxicity	N/N	N/N	N/N	N/N
ODP/GWP	0/1	0.05/1700	0/1300	0/1900

2. Experimental Setup

The schematic diagram of the refrigeration system used during this experimental work is shown in Figure 1. The test rig used to conduct the experiments consists of a porous evaporator, gas cooler, compressor, expansion valve and different measuring devices. The condenser consists of 19.05 mm diameter looped copper tube filled with metallic spheres with different porosities (38%, 41% and 45%). Forced convection gas cooler with 19.05mm looped copper tubes were used during the experiments. An automatic expansion valve is used to control the evaporation pressure. Semi-hermetic single stage CO_2 compressor with a nominal power of 1hp is used. K-type thermocouples with an accuracy of (±0.5°C) and pressure transducers (accuracy ±1% of range) were used to measure temperature and pressure, respectively. SCXI 1000, data acquisition system manufactured by National Instruments Company with 32channels was used during the experiments. LAB VIEW software is used for the processing of the thermocouple's temperature readings, pressure readings, and compressor power reading. A tube- in- tube aluminium internal heat exchanger (IHEX) is fitted between the condenser and the expansion valve in the trans-critical compression refrigeration system to protect the compressor from the probable liquid that may come from the evaporator. An accumulator of 400 ml is fitted between the evaporator and the IHEX. The trans-critical refrigeration system was operated for different evaporation temperatures (-2°C to 8°C), different gas cooling temperatures (38°C to 49°C), and different porosities of (38%, 41%, and 45%), while keeping constant value of degree of super heat at (8°C) and constant charge of refrigerant of 990 grams. The experiments were repeated for empty evaporator (no porous media is used). The refrigeration capacity, COP, power consumption per ton of refrigeration (PCTR), pressure drop, were predicted for different evaporation temperatures, different gas cooling pressures and different porosities. The pressure enthalpy (P-h) diagram of the refrigeration system is shown in Figure 2.

3. Porosity of The Metallic Spheres

Random samples of small metallic spheres, were chosen and used as porous inserts in the flow passages of the carbon dioxide refrigerant during its motion in the evaporator. Samples of the used spheres are shown in Figure 3. The porosity is often expressed as a percentage:

$$\varepsilon = \frac{V_V}{V_T} \tag{1}$$

where ε is the porosity, $\boldsymbol{V_V}$ is the void volume; $\boldsymbol{V_T}$ is the total volume of the sample. Three random different porosities were predicted. Cross sections of the used porous tubes in addition to the empty tube are shown in the schematic diagram in Figure 4.

The use of porous material in the evaporator results in a valuable increase in the average heat transfer coefficient of CO_2 and accordingly, the heat rate increases as the porosity decreases. This is due to the fact that as the porosity of the evaporator decreases the apparent thermal conductivity increases which means that, a large amount of heat is added in a short length of the porous evaporator. The decrease of the length of the evaporator, results in a decrease in the heat transfer surface area which leads to an increase in the average heat transfer coefficient of CO_2. As the average heat transfer coefficient of CO_2 increases the refrigeration capacity increases and the cycle coefficient of performance increases.

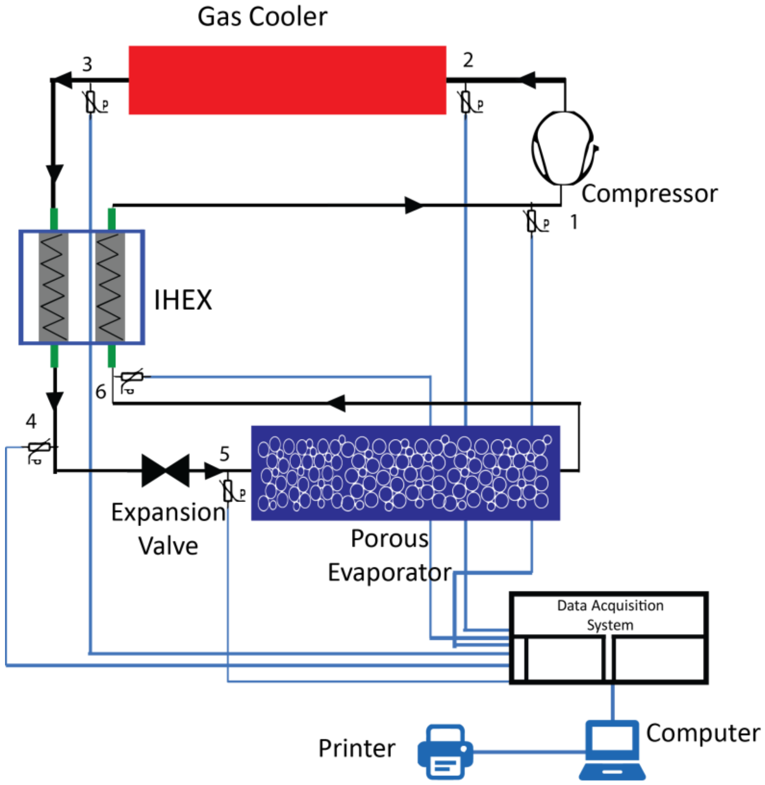


Fig. 1. Schematic Diagram of the Experimental Test Rig

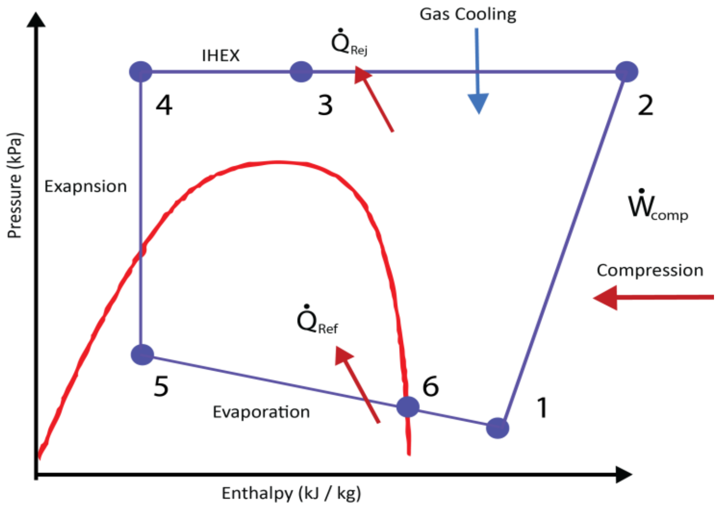
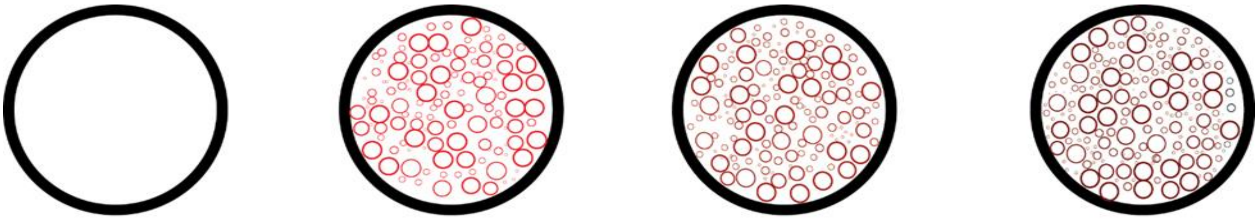


Fig. 2. P-h Diagram of the Refrigeration System

Fig. 3. Metallic Spheres Samples



Empty Tube $\varepsilon = 100\%$

Porous Tube $\varepsilon = 45\%$

Porous Tube $\varepsilon = 41\%$

Porous Tube $\varepsilon = 38\%$

Fig. 4. Schematic of Porous Tubes

4. Trans Critical Cycle Analysis

The effect of using porous evaporator and trans critical carbon dioxide on the performance of the refrigeration system is experimentally investigated during the evaporation process in porous media. Refrigeration capacity, coefficient of performance (COP), power consumption per ton of refrigeration, gas cooler outlet temperature, gas cooler outlet pressure, porosity, evaporation temperature and pressure drop were studied when using carbon dioxide as a refrigerant. P-h diagram of trans critical carbon dioxide refrigeration cycle is drawn in Figure 2. Carbon dioxide volumetric flow rates were measured by using high-pressure flow meter. This flow meter is installed between the gas cooler and the internal heat exchanger (IHEX). According to P-h diagram in Figure 2, the compressor power in (kW) can be found according to Eq. (2) below:

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

where,

$$\dot{m}_{ref} = \dot{V}/v \tag{3}$$

The refrigeration capacity$(\dot{Q}_{ref})$in (kW) is calculated according to Eq. (4):

$$\dot{Q}_{ref} = \dot{m}_{ref}(h_6 - h_5) \tag{4}$$

where: $\dot{m}_{ref}$ is mass flow rate of carbon dioxide in (kg/s).

h_1, h_2, h_5, and h_6 are enthalpies of carbon dioxide at states 1, 2, 5, and 6 respectively as show in Figure 2.

$\dot{V}$: is the volumetric flow rate in (m^3/s) and v is the specific volume of carbon dioxide in (m^3/kg).

The coefficient of performance (COP) of this trans critical cycle is calculated using the following equation:

$$\text{COP}=\frac{\dot{Q}_{ref}}{\dot{W}_{comp}} \tag{5}$$

The pressure-drop carbon dioxide in (kPa) in the evaporator is calculated according to the following relation:

$$\Delta P = P_5 - P_{\acute{6}} \tag{6}$$

where, P_5 and P_6 are the pressures of carbon dioxide in (kPa) at the inlet and exit of the evaporator.

The consumption of power per ton of refrigeration (PCPTR)in (kW/ ton of refrigeration) can be found as shown below in Eq. (7):

$$\text{PCPTR} = \frac{3.5\dot{W}_{comp}}{\dot{Q}_{ref}} \tag{7}$$

5. Results and Discussion

The performance of carbon dioxide trans-critical refrigeration system when using porous evaporator is studied for different evaporation temperatures, different gas cooling outlet temperatures and different evaporator porosities. The change of refrigeration capacity as a function of gas cooler outlet temperature for evaporation temperature of 4°C and different evaporator porosities is shown in Figure 3. It is very clear from this figure that, the refrigeration capacity and COP reached high values at low out let gas cooler temperature and low porosities. An average increase of about 40 % and 64% in refrigeration capacity and COP were predicted, when decreasing gas cooler out let temperature from 49°C to 38°C and using evaporator with 38% porosity as, it can be noticed from Figure 5 and Figure 6, respectively. An increase of about 50 % and 75% in refrigeration capacity and COP when changing the evaporator porosity from empty (no porous media is used) to the evaporator of 38% porosity is also detected from Figures 5 and Figure 6, respectively. The variation of COP as a function of gas cooler pressure for different evaporator porosities is plotted in Figure 7. It can be concluded from this figure that; the COP of CO_2 trans-critical refrigeration system increases with increasing gas cooler pressure up to an optimum value then it decreases at large values of gas cooler pressures.

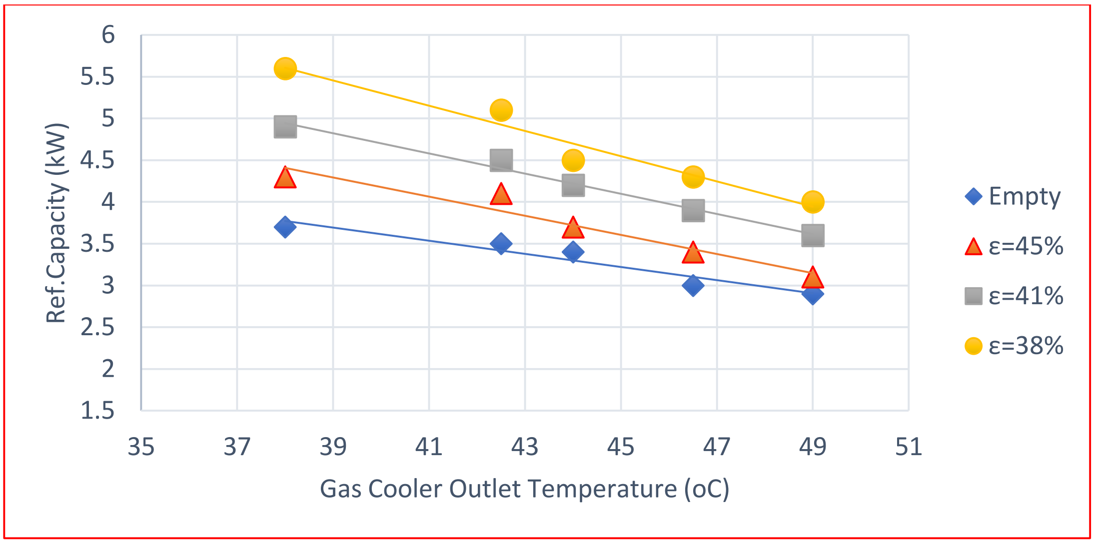


Fig. 5. Effect of gas cooler outlet temperature on Ref. Capacity of CO_2 cycle for Te = 4°C

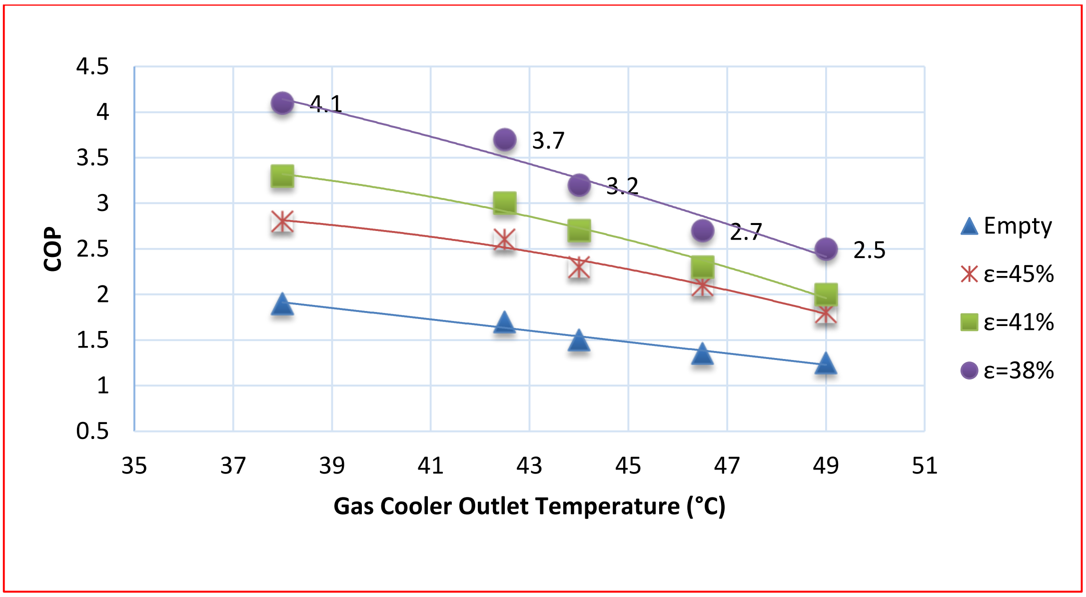


Fig. 6. Effect of gas cooler outlet temperature on COP of CO_2 cycle for Te = 4°C

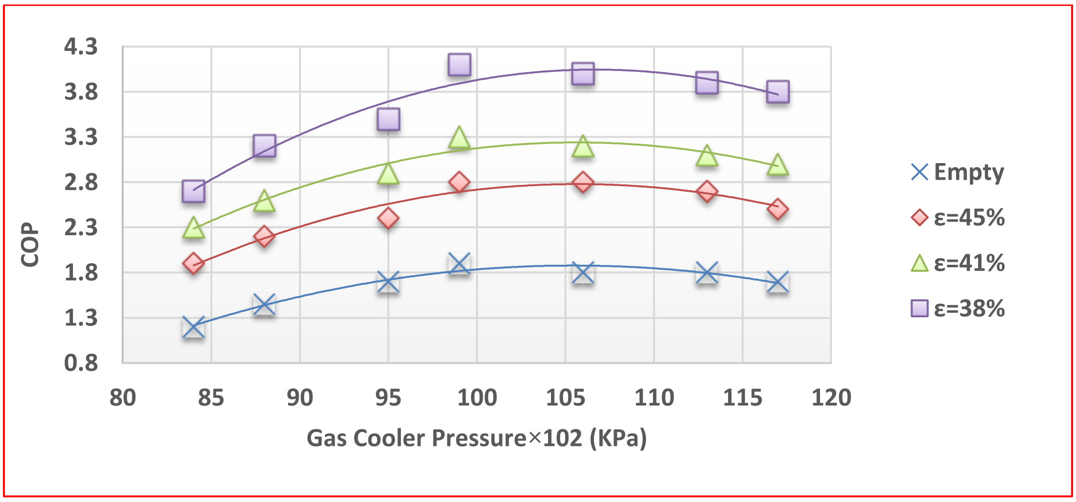


Fig. 7. Effect of gas cooler outlet pressure on COP of CO_2 cycle for Te = 4°C

The change of COP with evaporation temperature for different evaporator porosities is shown in Figure 8. It can be noticed from this figure that the COP can be increased by increasing evaporation temperature and by decreasing evaporator porosity at constant gas cooler pressure and gas cooler outlet temperature. The effect of evaporator porosity on COP of CO_2 cycle at constant evaporation temperature and different gas cooler outlet temperature is depicted in Figure 9. It is very clear from Figure 9 that the COP can be increased by decreasing evaporator porosity as well as by decreasing gas cooler outlet temperature. An average increase of the COP of about 80% is noticed when using 38% porous evaporator instead of the empty evaporator at a gas cooler outlet temperature of 38°C and evaporation temperature of 4°C.

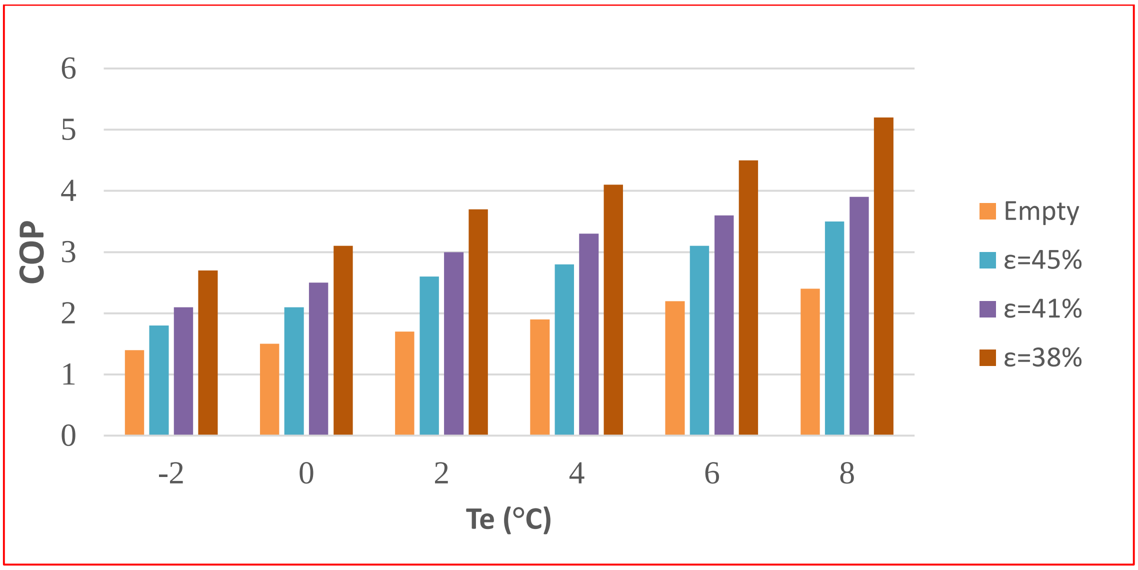


Fig. 8. Effect of evaporation temperature on COP of CO_2 cycle for Tgc = 38°C and Pgc = 99 bar

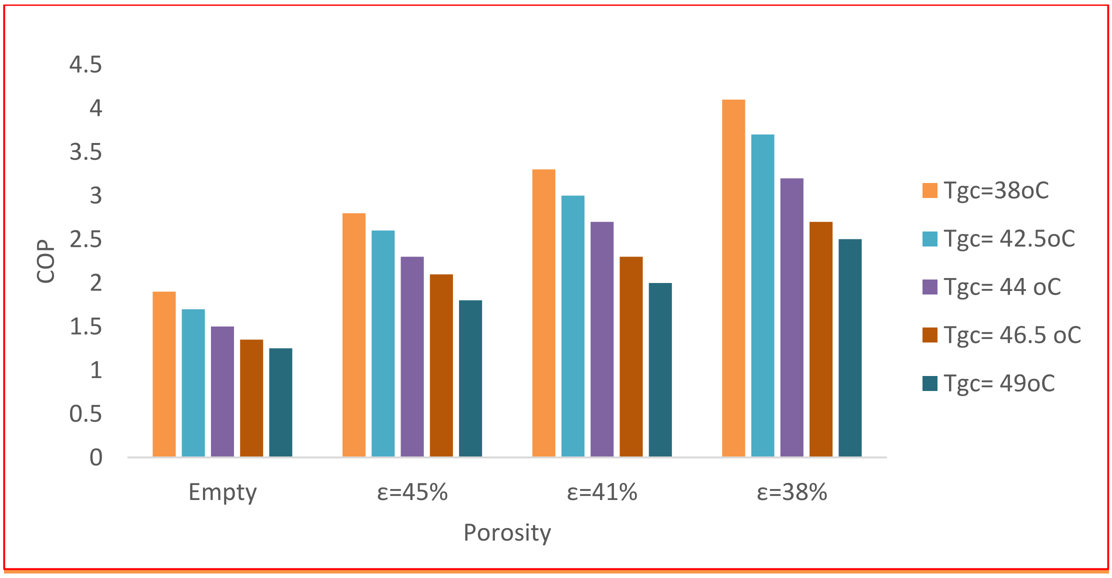


Fig. 9. Effect of evaporator porosity on COP of CO_2 cycle for Te = 4°C

The variation of PCTR with evaporation temperature for different porosities is plotted in Figure 10. It can be concluded from Figure 10 that, PCTR reached minimum values at low evaporation temperature and low evaporator porosity with an average percentage decrease of about 38%.

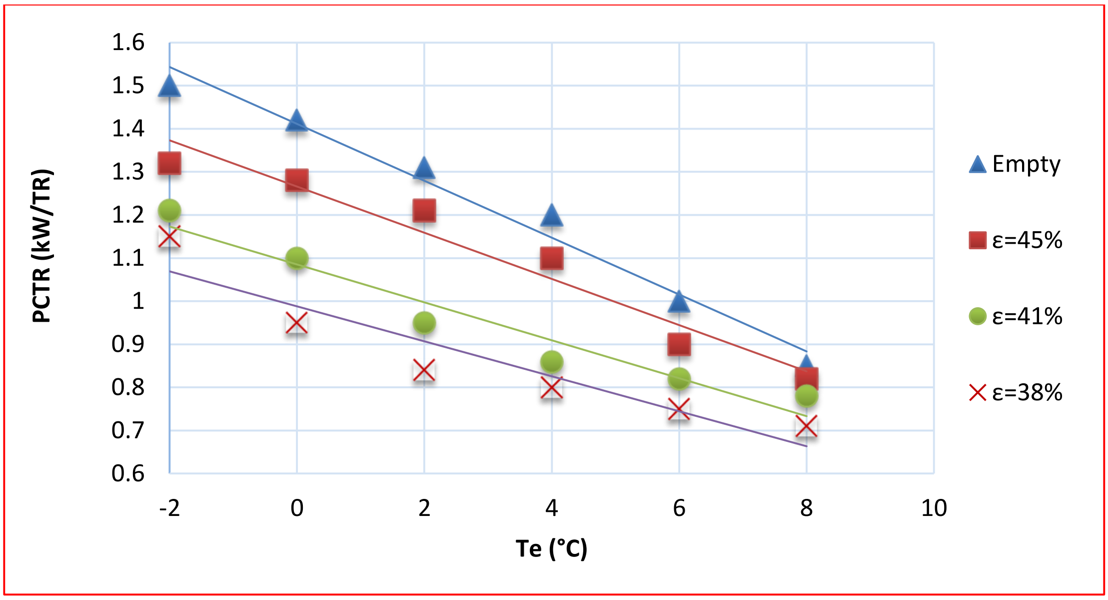


Fig. 10. Effect of evaporation temperature on PCTR of CO_2 cycle for Pgs = 9900 kPa and Tgc = 38°C

The pressure-drop of CO_2 during the evaporation process is plotted in Figure 11 against evaporation temperature for different porosities and constant gas-cooler pressure. Figure 11 shows that the pressure drop of CO_2 is increased by increasing evaporation temperature and by decreasing porosity. An average increase of pressure-drop of about 45% was recorded during the testes.

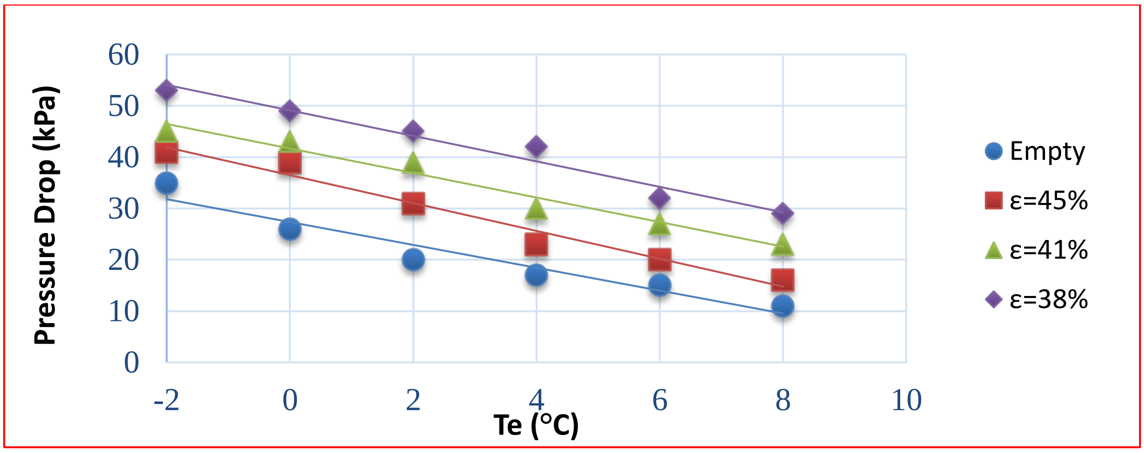


Fig. 11. Effect of evaporation temperature on the pressure of CO_2 cycle for Tgc = 38°C

6. Conclusions

One of the innovative techniques that can enhance the performance of trans-critical carbon dioxide refrigeration systems is the use of porous inserts in the flow passages of the refrigerant flowing in the evaporator.The use of porous evaporator increases the heat transfer rate and the coefficient of performance of the transcritical refrigeration cycle.It can be concluded from this experimental investigation that; the refrigeration capacity and COP of trans-critical carbon dioxide can be increased by decreasing gas cooler outlet temperature and decreasing porosity of evaporator. An average increase of about 40 % and 64% in refrigeration capacity and COP were predicted, when decreasing gas cooler outlet temperature from 49°C to 38°C and using evaporator with 38% porosity. It can also be concluded, that COP of trans-critical carbon dioxide is increased by increasing evaporation temperature and decreasing porosity of evaporator. An average increase of COP of about 80% is noticed when using 38% porous evaporator instead of the empty evaporator at gas cooler outlet temperature of 38°C and evaporation temperature of 4°C. PCTR is decreased by increasing evaporation temperature and by decreasing evaporator porosity. A Pressure drop of CO_2 during the evaporation process is increased by increasing evaporation temperature and by decreasing evaporator porosity. COP of trans-critical CO_2 is increased by increasing gas cooler pressure. An average increase of pressure-drop of about 45% was recorded during the tests. Carbon dioxide it expected to be a better alternative refrigerant when using porous evaporators in trans critical CO_2 systems.

The uncertainties in the measured and calculated performance parameters of this trans-critical refrigeration system were calculated and summarized as shown in Table 2.

Table 2
Uncertainty of measured and calculated parameters

Number	Measured/ calculated parameter	Uncertainty	Uncertainty Range
1	Pressure transducer reading(kPa)	±.0.8 bar	[-0.8 0.8]
2	Volumetric Flowrate (flow-meter reading) (m^3/s)	±0.45*10^{-3} (m^3/s)	[-0.45 0.45] *10^{-3}
3	Temperature (°C) (Thermocouple reading)	(±1°C)	[-0.1 0.1]
4	COP	±0.20	[-0.2 0.2]
5	Refrigeration capacity (kW)	±0.1 kW	[-0.1 0.1]
6	Compressor power((kW)	±0.05 kW	[-0.05 0.05]
7	PCPTR (kW/ton)	±0.35(kW/ton)	[-0.35 0.35]

Acknowledgements

Great thanks Engineering Geniuses Company-Jordan/Amman (www.egeniuses.net) for their assistance throughout all aspects of this experimental work.

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