Brunel University
MSc Renewable Energy Engineering Programme

Energy Conversion Technologies – Assignment 2020/21

Performance Evaluation of Reciprocating Chiller System using DuPont™ Suva® 404A (HP62) Refrigerant

Author – Napassorn HONGHIRUN (Student ID: 2036078)

Introduction / Abstract / Summary

This report assesses the performance characteristics of a refrigeration system, which was tested under laboratory conditions. The system under test is a commercial reciprocating chiller system and its refrigerant is DuPont™ Suva® 404A (HP62), referred to as R404A.

Experimental method

In order to take the necessary measurements to evaluate the system's energy performance, the chiller system was set up in a test rig, which allows temperature and pressure readings to be logged at 8 different points along the system's operating cycle.

The system was run to steady state at three different condenser water leaving temperatures (30°C, 35°C and 40°C) with a range of evaporator leaving temperatures (at approximately 1 degree increments). Readings were taken at 4 second intervals and, in order to ameliorate flutuations in the readings, several readings were taken for each set of condenser/evaporator water leaving temperates and the results averaged.

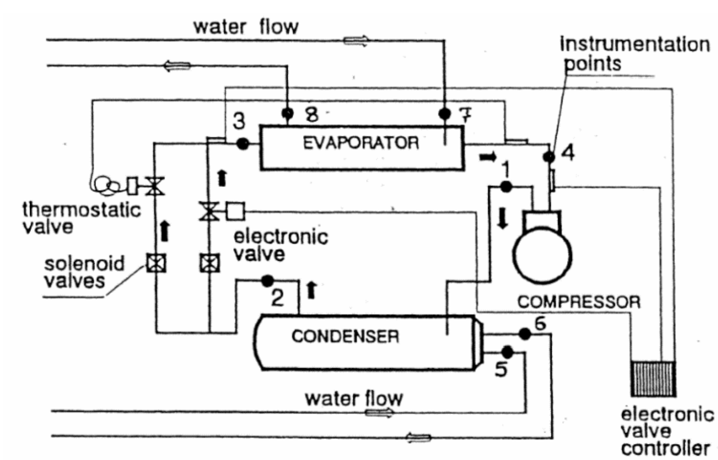


Figure i. Experimental test rig set up, where instrumentation points are numbered 1 to 8

Task 1 - Plot the performance characteristics (performance maps) of the refrigeration system as functions of the condenser water leaving and evaporator water leaving temperatures. These characteristics should include power consumption, cooling capacity and COP.

The experimental results were provided in Excel spreadsheet format. In order to account for the fluctuations in the readings, multiple readings were taken. The readings were averaged for **condenser water leaving temperatures (T6)** of 30°C, 35°C and 40°C. These data are provided in Appendix D.

The performance characteristics were derived by calculation from these results in the following way and are summarised in the tables below.

From the given experimental results spredsheet, we are told how to calculate the cooling capacity (Qc) and COP.

Qc = evaporator mass flow rate(EWFR) x CP of waterx(T7-T8)

COP = Qc/power consumption

Power consumption is one of the values provided in the experimental results.

i) Performance characteristics for **condenser water leaving temperature (T6)** of 30°C. **Evaporator water leaving temperatures (T8)** were varied from 5°C to 10°C, in increments of approximately 1°C.

T6(°C)	T8(°C)	POWER	Qc(kW)	COP
29.91375	5.015	10.27778	26.3207	2.560933
29.93417	5.98	10.32719	26.90278	2.605043
30.0358	7.1066	10.44444	28.08568	2.689054
29.98692	8.13	10.58889	29.07784	2.746071
30.02889	8.987778	10.67657	30.08742	2.818079
30.01273	10.1097	10.81111	31.21166	2.886998

Table i. Performance characteristics for the condenser water leaving temperature 30°C

ii) Performance characteristics for **condenser water leaving temperature (T6)** of 35°C. **Evaporator water leaving temperatures (T8)** were varied from 5°C to 10°C, in increments of approximately 1°C.

T6(°C)	T8(°C)	POWER	Qc(kW)	COP
34.90357	4.957857	11.46667	24.56516	2.14231
34.965	6.007647	11.58889	25.46554	2.19741
34.98091	7.081818	11.74444	26.59905	2.26482
35.06595	8.151081	11.98889	27.64637	2.305999
35.03302	9.123721	12.1	28.60659	2.364181
35.00636	10.04455	12.15556	29.5941	2.434615

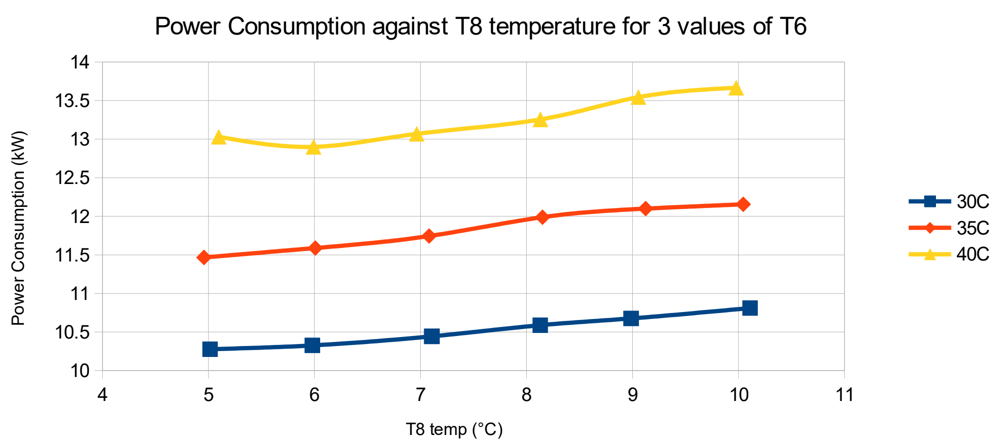
Table ii. Performance characteristics for the condenser water leaving temperature 35°C

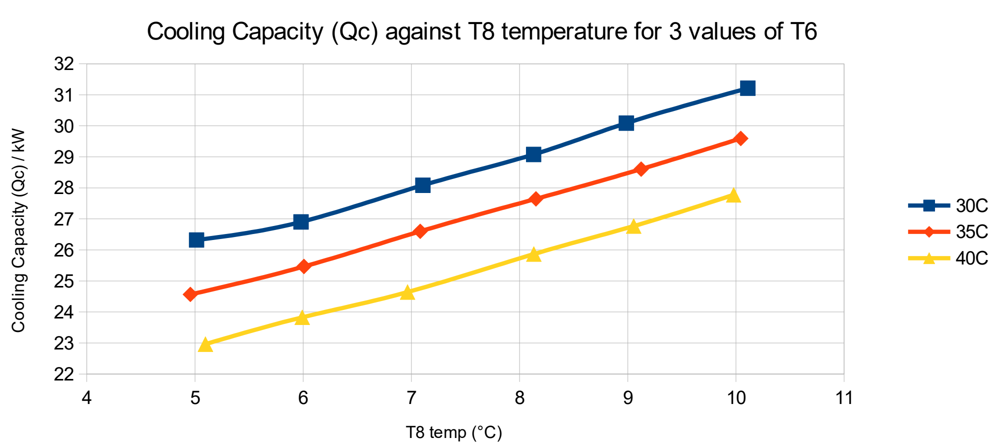
iii) Performance characteristics for **condenser water leaving temperature (T6)** of 40°C. **Evaporator water leaving temperatures (T8)** were varied from 5°C to 10°C, in increments of approximately 1°C.

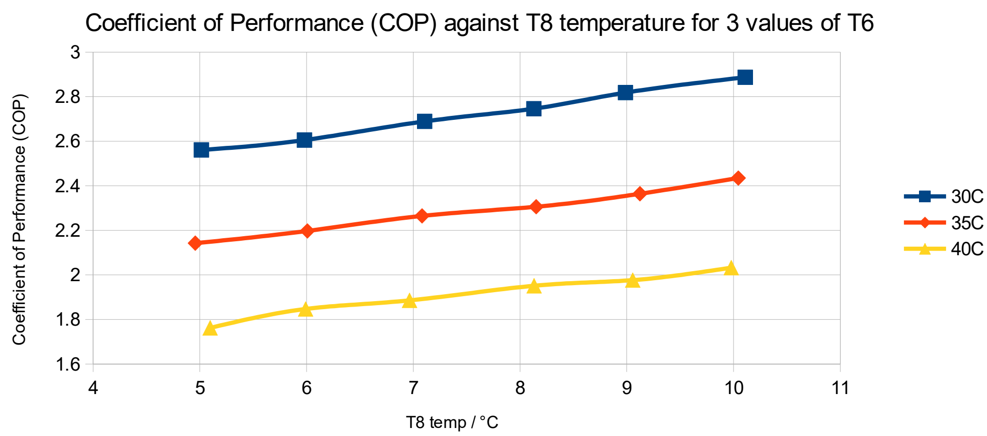
T6	T8	POWER	Qc	COP
40.02486	5.096757	13.03013	22.96212	1.762233
39.92267	5.991333	12.9	23.82688	1.847045
40.06333	6.965	13.06864	24.64129	1.885529
39.92529	8.131765	13.25556	25.86546	1.951292
40.12159	9.055682	13.54444	26.7697	1.976434
40.00429	9.978571	13.66667	27.77557	2.032358

Table iii. Performance characteristics for the condenser water leaving temperature 35°C

iv) The graphs below are plotted from the tables above.







We can see from the graphs above that increasing condenser and evaporator temperatures will yield a greater power consumption, cooling capacity and COP.

Task 2 – Calculate and plot other characteristics (efficiencies) that you may feel are relevant to your discussion and the performance evaluation of the system.

i) Volumetric efficiency (η_v)

One important characteristic we would like to know about our system under test is the compressor's **volumetric efficiency**. From the given notes [1], the volumetric efficiency can be calculated by rearranging the equation for the mass flow rate, which is:

$$\dot{m}_r = \eta_v \rho V_s N$$

Therefore

$$\eta_v = \frac{\dot{m}_r}{\rho V_s N}$$

Where

$\dot{m}_r$ = refrigerant mass flow rate

η_v = compressor volumetric efficiency

ρ = refrigerant vapour density at inlet to the compressor (kg/m^3)

V_s = compressor swept volume (m^3)

N = compressor speed (rev/s)

From the given appendix A, the 4-cylinder hermetic compressor designed for use with R404A and appropriate control has a compressor displacement of 45.07 m^3/hr when running at 1450 rpm (rev/min).

The compressor's swept volume (V_s) can be found thus:

$$V_s \text{ for 4 cylinders} = \frac{45.07(\frac{m^3}{hr})}{1450(\frac{rev}{min})\times(\frac{60\,min}{hr})} = 5.18\times10^{-4}\ m^3/rev$$

Therefore, V_s for 1 cylinder = **1.295×10^{-4} m^3/rev**

To calculate the volumetric efficiency, the refrigerant vapour density (ρ) was taken from the compressor inlet pressure and temperature (P4 and T4). The vapour densities in the **saturation properties table** (page 5) were used to determine the density volume for each T4 temperature, by interpolating between the two closest available values.

The compressor speed is 1450 rpm(rev/min) = 1450/60 (rev/s) = **24.167 rev/s**

Calculation of the refrigerant mass flow rate from the energy balance in the condenser.

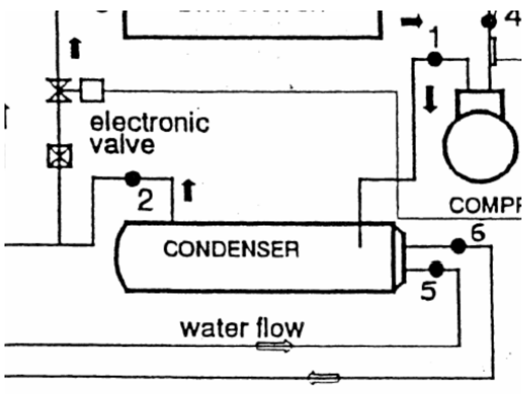


Figure 2.1 the condenser energy balance diagram

From the experimental test setup in Appendix A, the energy balance of the condenser can be expressed:

$$Q_{in} = Q_{out}$$

$$Q_1+Q_5 = Q_2+Q_6$$

$$\dot{m}_r h_1 + \dot{m}_{water} h_5 = \dot{m}_r h_2 + \dot{m}_{water} h_6$$

$$\dot{m}_r h_1 - \dot{m}_r h_2 = \dot{m}_{water} h_6 - \dot{m}_{water} h_5$$

$$\dot{m}_r (h_1 - h_2) = \dot{m}_{water} (h_6 - h_5)$$

$$\dot{m}_r = \frac{\dot{m}_{water}(h_6 - h_5)}{(h_1 - h_2)} = \frac{CWFR(h_6 - h_5)}{(h_1 - h_2)}$$

The condenser water mass flow rate (CWFR) is given in the experimental results. In order to calculate the refrigerant mass flow rate (ṁ), we need the enthalpy values. The temperatures and pressures from the data experimental results can be interpolated to find the enthalpy values. For h_1 and h_2, the R-404A properties table has been used for h_1 and h_2 interpolation. For h_5 and h_6, the saturated water-temperature table (attached in Appendix D) was used to obtain the enthalpy values for h_5 and h_6.

ii) The compressor's volumetric efficiency for condenser water leaving temperatures (T6) of 30°C, 35°C and 40°C for evaporator water leaving temperatures (T8) from 5°C to 10°C in steps of approximately 1°C.

For condenser water leaving temperatures(T6) 30°C

T6	T8	T4	p(kg/m3)	RMFR	Vs(m3)	N(rev/s)	efficiency	P1/P4
29.91375	5.015	12.2025	43.75554	0.209673	1.295×10^{-4}	24.167	1.53115	2.752014
29.93417	5.98	13.43472	45.41787	0.225438	1.295×10^{-4}	24.167	1.58602	2.706102
30.0358	7.1066	14.7138	47.20117	0.249221	1.295×10^{-4}	24.167	1.687094	2.645443
29.98692	8.13	15.75615	48.70142	0.280808	1.295×10^{-4}	24.167	1.842364	2.586098
30.02889	8.987778	16.67333	50.05827	0.31451	1.295×10^{-4}	24.167	2.007547	2.547244
30.01273	10.1097	17.63909	51.52345	0.362692	1.295×10^{-4}	24.167	2.249265	2.492825

Table 2.1 compressor volumetric efficiency at condenser temperature 30°C

For condenser water leaving temperatures(T6) 35°C

T6	T8	T4	p(kg/m3)	RMFR	Vs(m3)	N(rev/s)	efficiency	P1/P4
34.90357	4.957857	12.17464	43.71832	0.203946	1.295×10^{-4}	24.167	1.49059	3.053263
34.965	6.007647	13.43853	45.4231	0.221932	1.295×10^{-4}	24.167	1.561171	2.991733
34.98091	7.081818	14.63121	47.08464	0.244828	1.295×10^{-4}	24.167	1.66146	2.919745
35.06595	8.151081	15.7273	48.65958	0.275505	1.295×10^{-4}	24.167	1.809127	2.85523
35.03302	9.123721	16.76256	50.19121	0.305829	1.295×10^{-4}	24.167	1.946965	2.789045
35.00636	10.04455	17.5603	51.40282	0.344164	1.295×10^{-4}	24.167	2.139373	2.727458

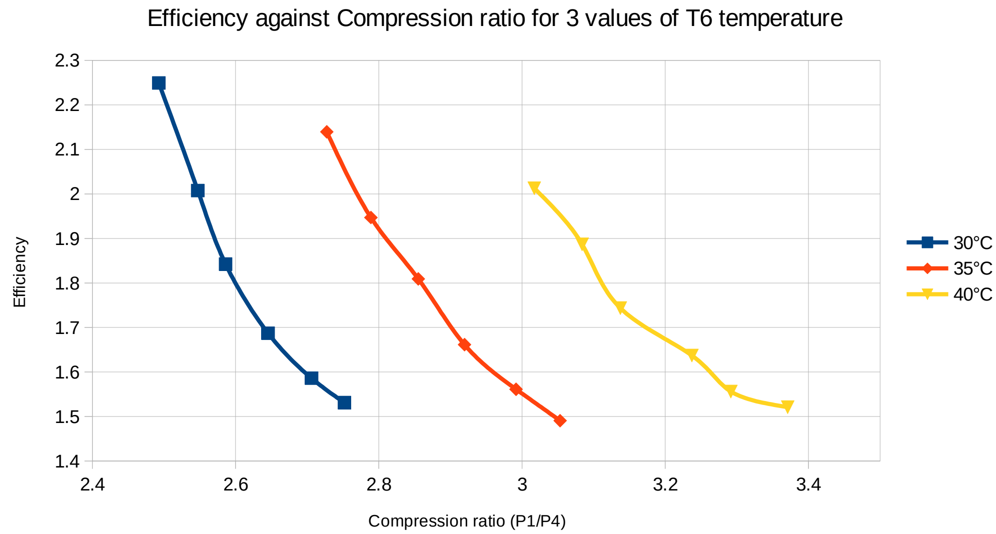
Table 2.2 compressor volumetric efficiency at condenser temperature 35°C

For condenser water leaving temperatures(T6) 40°C

Table 2.3 compressor volumetric efficiency at condenser temperature 40°C

T6	T8	T4	p(kg/m3)	RMFR	Vs(m3)	N(rev/s)	efficiency	P1/P4
40.02486	5.096757	12.12973	43.65832	0.207819	1.295×10^{-4}	24.167	1.520985	3.370991
39.92267	5.991333	13.16689	45.05014	0.21939	1.295×10^{-4}	24.167	1.556066	3.291723
40.06333	6.965	14.32	46.64552	0.238971	1.295×10^{-4}	24.167	1.63698	3.237248
39.92529	8.131765	15.66529	48.56968	0.265029	1.295×10^{-4}	24.167	1.743555	3.137348
40.12159	9.055682	16.7275	50.13898	0.296037	1.295×10^{-4}	24.167	1.88659	3.083992
40.00429	9.978571	17.76	51.70856	0.325729	1.295×10^{-4}	24.167	2.012806	3.01713

iii) Graphs, efficiency vs compression ratio (P1/P4)



As we can see from the graph above, in all cases, efficiency and compression ratio have an inversely proportional relationship. However, while higher T6 temperatures lead to increased compression ratios, generally better efficiencies are achieved when T6 temperature is 30°C.

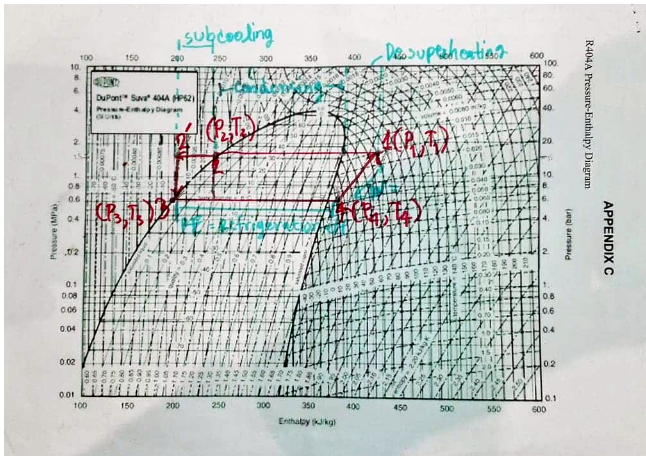
Task 3 – Calculate and Plot the Carnot COP and compare it with the actual COP of the system discussing the main reasons for the difference in the two values.

i) For Carnot COP

$$\text{Carnot COP} = \frac{evaporator\ temperature\,(^\circ K)}{condenser\ temperature\,(^\circ K) - evaporator\ temperature\,(^\circ K)}$$

ii) For actual COP

From the experimental test facility diagram in Appendix A, the refrigeration cycle on R404A P-h diagram is shown below



Actual COP = $\frac{refrigeration\,effect}{work \in put} = \frac{h_4 - h_3}{h_1 - h_4}$

From the experimental results, the data gives the temperatures and pressures of the refrigerant. From this we can determine the enthalpy values for h_1, h_3 and h_4 using the data in the R-404A properties table. Interpolation has been used to find the enthalpy for specific temperatures and pressures.

The calculation of the enthalpy values are given in Appendix D.

iii) The calculation of Carnot COP and actual COP for condenser water leaving temperatures (T6) 30°C, 35°C and 40°C for evaporator water leaving temperatures (T8) varied from 5°C to 10°C in steps of approximately 1°C.

For condenser water leaving temperatures(T6) 30°C

T6(°C)	T8(°C)	T6(°K)	T8(°K)	h1(kJ/kg)	h3(kJ/kg)	h4(kJ/kg)	COPcar	COPact
29.91375	5.015	303.0638	278.165	422.4805	199.7585	379.4398	11.17185	4.174684
29.93417	5.98	303.0842	279.13	420.5647	200.8155	380.3537	11.65267	4.4649
30.0358	7.1066	303.1858	280.2566	418.0339	202.3798	381.2217	12.22269	4.858226
29.98692	8.13	303.1369	281.28	415.0881	203.8542	381.9028	12.86915	5.365277
30.02889	8.987778	303.1789	282.1378	412.414	204.9627	382.5276	13.40888	5.941317
30.01273	10.1097	303.1627	283.2597	409.4288	206.5023	383.124	14.23199	6.714455

Table 3.1 Carnot COP and actual COP at condenser temperature 30°C

For condenser water leaving temperatures(T6) 35°C

T6(°C)	T8(°C)	T6(°K)	T8(°K)	h1(kJ/kg)	h3(kJ/kg)	h4(kJ/kg)	COPcar	COPact
34.90357	4.957857	308.0536	278.1079	429.027	199.465	379.4604	9.287067	3.631385
34.965	6.007647	308.115	279.1576	426.4854	200.777	380.3619	9.640303	3.893571
34.98091	7.081818	308.1309	280.2318	423.4611	202.3245	381.1529	10.04448	4.226806
35.06595	8.151081	308.2159	281.3011	420.3537	203.8709	381.8723	10.45151	4.625648
35.03302	9.123721	308.183	282.2737	417.4324	205.2566	382.5576	10.89469	5.083936
35.00636	10.04455	308.1564	283.1945	414.3186	206.7514	383.0375	11.34511	5.635553

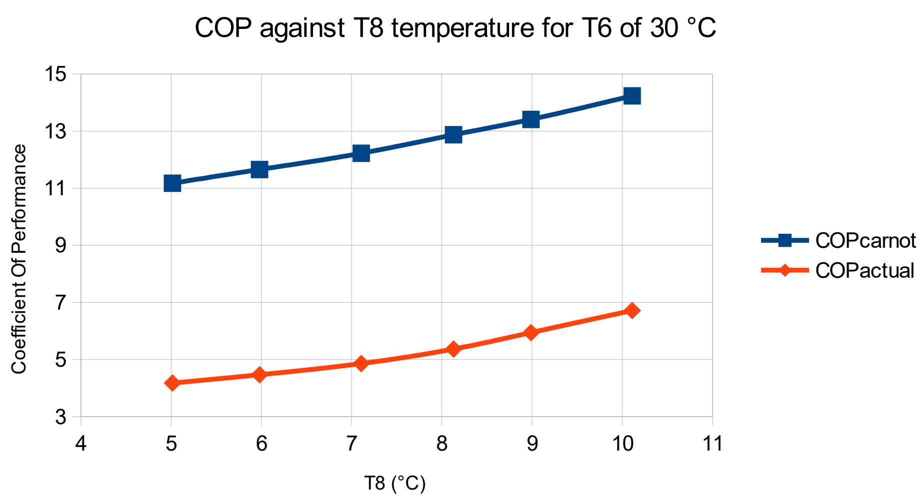
Table 3.2 Carnot COP and actual COP at condenser temperature 35°C

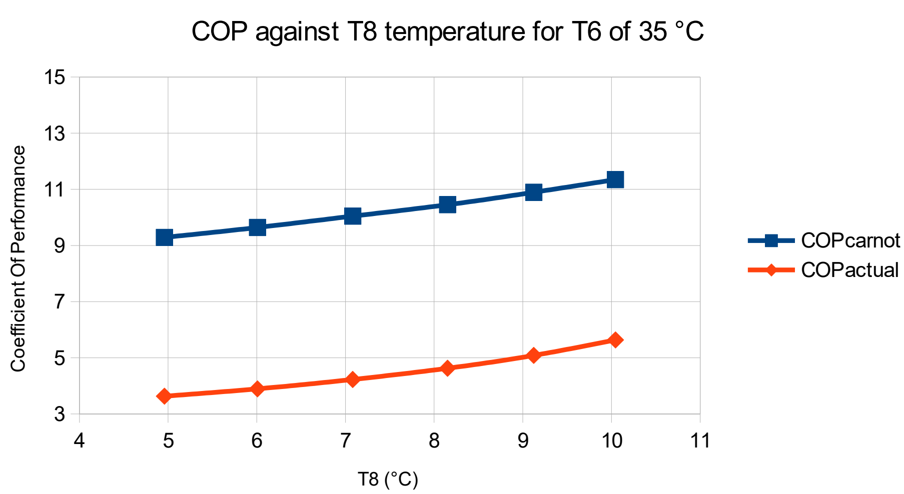
For condenser water leaving temperatures(T6) 40°C

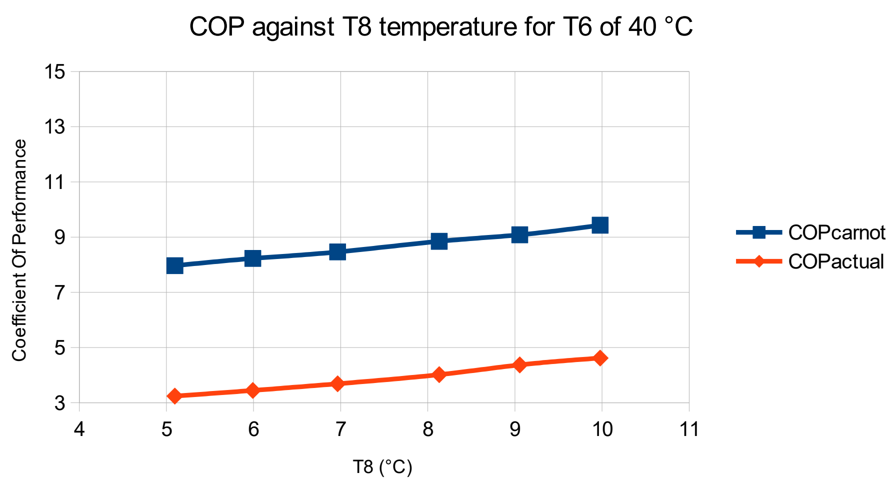
T6(°C)	T8(°C)	T6(°K)	T8(°K)	h1(kJ/kg)	h3(kJ/kg)	h4(kJ/kg)	COPcar	COPact
40.02486	5.096757	313.1749	278.2468	435.1525	199.1589	379.5095	7.96627	3.241209
39.92267	5.991333	313.0727	279.1413	432.3433	200.5021	380.2041	8.226654	3.446582
40.06333	6.965	313.2133	280.115	429.6377	201.7125	381.021	8.463115	3.688209
39.92529	8.131765	313.0753	281.2818	426.2812	203.6107	381.9093	8.847139	4.018273
40.12159	9.055682	313.2716	282.2057	423.2607	204.9889	382.6297	9.084095	4.372047
40.00429	9.978571	313.1543	283.1286	421.6275	206.3507	383.3191	9.429537	4.619575

Table 3.3 Carnot COP and actual COP at condenser temperature 40°C

iv) Carnot COP and actual COP graphs







From the graphs above, we can see that Carnot COP is greater than actual COP for each condenser temperature.

The carnot COP is the maximum COP for the refrigeration system, which only depends on two factors: condenser and evaporator temperatures. The actual COP depends on different factors including refrigeration effects and the work input into the compresser. In reality, they will not have ideal performance.

Task 4 - Discuss the performance characteristics of the system and their implications with respect to system design and optimal operation.

From task 2, the graphs show the relationship between the volumetric efficiency and the compression ratio. The efficiency is inversely propotional to the condenser temperature. The lower condenser temperature will have greatter efficiency.

Glossary of terms

Refrigerant – A substance, usually a fluid, used in a refrigeration system.

R404A – Shorthand name for the refrigerant used in the system under test in this report, DuPont™ Suva® 404A (HP62) [ASHRAE designation: R-404A (33/52/A)]. A non-ozone depleting blend of HFC-125, HFC-143a and HFC-134a.

Swept volume – The volume displaced by the movement of the piston in a cylinder.

References

1. Energy Conversion Technologies Lecture Notes (Part 1)