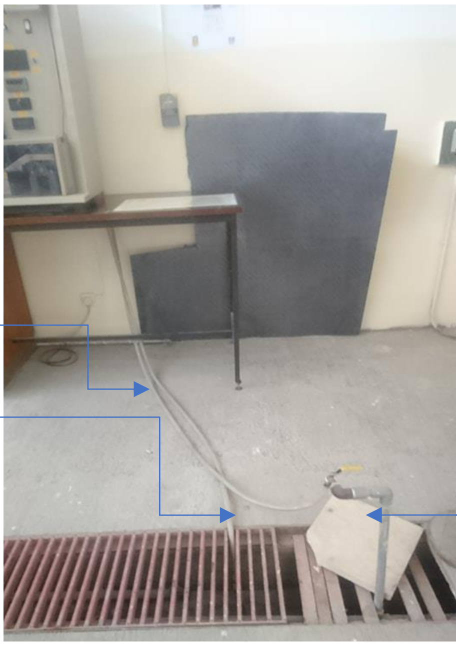
Objective

- To study the performance of a refrigeration cycle using both charts and actual data.

Experimental Setup

The experimental setup is shown in figure (1,a). The refrigeration laboratory unit consists mainly of four devices: a compressor, which is driven by an electric motor, a condenser, an expansion valve and an evaporator, which consists of two electric heating elements. The voltage across the heating elements is controlled by rotating the evaporator input control knob and hence the power consumed by the heating elements changes with changing the voltage. A dynamometer, that consists of a spring balance and arm torque, is used to measure the torque produced by the electric motor. There are two pressure gauges to measure the pressure of both condenser and evaporator. Furthermore, there are two flowmeters to measure the mass flow rate of the refrigerant and the water. Water is supplied and drained from the condenser through two tubes connected to the backside of the unit as shown in figure(1,b). The mass flow rate of water is controlled by revolving the needle valve.
Three screens are seen at front face of the unit. The first one is a wattmeter, which displays the power consumed by the motor when the switch to the left of it is switched up, while it displays the power consumed by the evaporator when the switch is switched down .The second one is a temperature indicator, which displays the temperature of the fluid (refrigerant or water) at specific states designated by the numbers 1 – 6, depending on the position of the selector switch . The last one is a tachometer, which displays the rotational speed of the compressor.



Start-up Procedure

1. Open the water supply valve to allow for water to flow through the coil of the condenser.
2. Turn on the main switch to operate the unit.
3. The experiment now is ready to carry on.

Experimental Procedure

1. Perform the start-up procedure.
2. Revolve the needle valve to set the value of mass flow rate of water to $\dot{m}_w = 40$ g/s.
3. Adjust the power consumed by the evaporator by rotating the evaporator input control knob.
4. Wait until readings reach steady state, and then start recording the temperatures (t_1, t_2, t_3, t_4, t_5, t_6), condenser and evaporator pressures, power consumed by the evaporator and the motor and the mass flow rate of the refrigerant.
5. Repeat the steps 2 – 4 with $\dot{m}_w = 20$ g/s.

Given Data

- Atmospheric Pressure P_{atm} = 90 kPa.
- Atmospheric Temperature T_{atm} = 21 ^oC.
- Arm torque R = 0.165 m
- Friction force F_f = 5 N.
- Constant pressure specific heat for water Cp = 4.18 kJ/kg.K

Data observed

Table (1) :Data Observed

Constant Condenser Pressure Test					
	No.	Parameter	1	2	Units
Refrigerant HFC 134a	1	Condenser Pressure, P_c (Abs)	1090	1090	kPa
	2	Evaporator Pressure, P_e (Abs)	400	310	kPa
	3	Compressor Suction Temp. (t_1)	9.7	2.7	^oC
	4	Compressor Outlet Temp. (t_2)	54.8	53.5	^oC
	5	Refrigerant Leaving the Cond.(t_3)	33.6	34.5	^oC
	6	Evaporator Inlet Temp. (t_4)	8.6	1	^oC
	7	R134a flow rate, $\dot{m}_r$	6.8	5	g/s
Water Condenser Cooling	8	Cooling water inlet Temp. (t_5)	23.8	23.5	^oC
	9	Cooling water outlet Temp. (t_6)	32	35	^oC
	10	Water flow rate, $\dot{m}_w$	40	20	g/s
	11	Evaporator Heat input, $\dot{Q}_e$	1130	760	Watt
	12	Motor Input, $\dot{W}_m$	530	500	Watt
	13	Spring Balance Force (F)	14.5	14	N
	14	Compressor Speed (n_c)	745	752	rpm
	15	Motor speed ($n_m = 1.98 \times n_c$)	1475	1489	rpm

Sample Calculations

Step(1): Calculate the performance parameters using P-H chart. Take column 1 from Table(1) as a sample for calculations.

Step(1-a): Find the values of enthalpy at states 1,2,3,4 using P-H chart

Compressor inlet (1) => h_1@(P= 4 bar , t_1= 9.7 ^oC)= 305 kJ/kg
Compressor Outlet(2) => h_2@(P= 10.9 bar , t_2= 54.8 ^oC)= 337 kJ/kg
Condenser Outlet(3) => h_3@(P= 10.9 bar , t_3= 33.6 ^oC)= 150 kJ/kg
Evaporator Inlet(4) => $h_4 = h_3$= 150 kJ/kg

These points are shown on the attached P-H chart.

Step(1-b): Find the values of performance parameters as follows

- Compressor power $\dot{W}_c = \dot{m}_r(h_2 - h_1)$ [1]

$$= \frac{6.8}{1000}(337 - 305) = 0.2176\ kW$$

- Evaporator heat absorbed $\dot{Q}_L = \dot{m}_r(h_1 - h_4)$ [1]

$$= \frac{6.8}{1000}(305 - 150) = 1.054\ kW$$

- Condenser heat rejected $\dot{Q}_H = \dot{m}_r(h_2 - h_3)$ [1]

$$= \frac{6.8}{1000}(337 - 150) = 1.272 kW$$

- Coefficient of Performance $(COP)_R = \frac{\dot{Q}_L}{\dot{W}_c}$ [1]

$$= \frac{1.054}{0.2176} = 4.84$$

Step(2): Calculate the performance parameters using the experimental data.

- Shaft motor power $\dot{W}_{m_s} = \tau \times \omega$ [1]

$$= 0.165 \times F \times 2\pi \times \frac{n_m}{60}$$

$$= 0.165 \times 14.5 \times 2\pi \times \frac{1475}{60} = 369.5\ W$$

Friction power $\dot{W}_f = 0.165 \times F_f \times 2\pi \times \frac{n_m}{60}$

$$= 0.165 \times 5 \times 2\pi \times \frac{1475}{60} = 127.4\ W$$

⇨ Compressor Power $\dot{W}_{c_i} = \dot{W}_{m_s} - \dot{W}_f = 369.5 - 127.4 = 242.1\ W$

The heat loss during compression process

$$\dot{Q}_{out} = |\dot{m}_r(h_2 - h_1) - \tau \times \omega| = |217.6 - 369.5| = 151.9\ W$$

- Heat absorbed by the evaporator $\dot{Q}_L = 1130\ W$

- Heat rejected by the condenser $\dot{Q}_H = \dot{m}_w \times C_{p_w} \times (t_6 - t_5)$ [1]

$$= \frac{40}{1000} \times 4.18 \times (32 - 23.8) = 1578\, W$$

- Coefficient of Performance $(COP)_R = \frac{\dot{Q}_L}{\dot{W}_c}$

$$= \frac{1130}{242.1} = 4.66$$

Step(3): Calculate the error in calculations assuming that the chart values are the true values.

$$\text{Error } \% = \frac{\text{Chart value} - \text{Experimental value}}{\text{Chart value}} \times 100\% \quad [2]$$

=> For compressor Error % $= \frac{217.6-242.1}{217.6} \times 100\% = -11.25\ \%$

=> For evaporator Error % $= \frac{1054-1130}{1054} \times 100\% = -7.21\ \%$

=> For condenser Error % $= \frac{1272-1578}{1272} \times 100\% = -24.06\ \%$

=> For COP Error % $= \frac{4.84-4.66}{4.84} \times 100\% = 3.72\%$

Table (2) :Data Calculated

S. No.	Performance Parameters	Calculated values using P-H chart		Calculated values using actual data		Error %	
		1	2	1	2	1	2
1	Compressor Power $\dot{W}_c$ (Watt)	217.6	160	242.1	231.4	-11.25%	-44.6%
2	Evaporator heat absorbed $\dot{Q}_L$ (Watt)	1054	750	1130	760	-7.21%	-1.33%
3	Condenser heat rejected $\dot{Q}_H$ (Watt)	1272	910	1578	1106	-24.06%	-21.5%
4	Coefficient of Performance $(COP)_R$	4.84	4.69	4.66	3.28	3.72%	30.06%

Uncertainty Analysis

- For a calculated quantity x that is dependent on another quantities $x_1, x_2, x_3, \dots, x_n$
$$x = f(x_1, x_2, x_3, \dots, x_n)$$

  The uncertainty of x (w_x) is given by :

$$w_x = \pm\sqrt{\left(\frac{\partial x}{\partial x_1} \times w_{x1}\right)^2 + \left(\frac{\partial x}{\partial x_2} \times w_{x2}\right)^2 + \left(\frac{\partial x}{\partial x_3} \times w_{x3}\right)^2 + \cdots + \left(\frac{\partial x}{\partial x_n} \times w_{xn}\right)^2} \quad [3]$$

- In this experiment, the calculated compressor $\dot{W}_c$ is dependent on F , R, n_m
  i.e
  $$k = f(F, R, n_m)$$

  The uncertainty of k is given by :

$$w_{\dot{W}_c} = \pm\sqrt{\left(\frac{\partial \dot{W}_c}{\partial F} \times w_F\right)^2 + \left(\frac{\partial \dot{W}_c}{\partial R} \times w_R\right)^2 + \left(\frac{\partial \dot{W}_c}{\partial n_m} \times w_{n_m}\right)^2}$$

- The uncertainty of an observed quantity measured using a device , is the value of one-half the smallest division of the device. [3] The uncertainties of F , R, n_m are as follows :
  $w_F = \pm 0.05\ N \quad w_{n_m} = \pm\ 0.5\ rpm \quad w_R = \pm 0.00165\ m$

- The following quantities are found by differentiating $\dot{W}_C = \tau \times \omega = R \times F \times 2\pi \times \frac{n_m}{60}$ partially :

  $\frac{\partial \dot{W}_C}{\partial F} = R \times 2\pi \times \frac{n_m}{60}$ $\qquad$ $\frac{\partial \dot{W}_C}{\partial R} = F \times 2\pi \times \frac{n_m}{60}$

  $\frac{\partial \dot{W}_C}{\partial n_m} = R \times F \times \frac{2\pi}{60}$

⇨ Take column 1 from Table(1) as a sample for calculations.

$$w_{\dot{W}_C} = \pm\sqrt{\left(0.165 \times 2\pi \times \frac{1475}{60} \times 0.05\right)^2 + \left(14.5 \times 2\pi \times \frac{1475}{60} \times 0.00165\right)^2 + \left(0.165 \times 14.5 \times \frac{2\pi}{60} \times 0.5\right)^2}$$

= ± 3.9 Watt

⇨ The value of uncertainty $\dot{W}_C$ for the second iteration in the experiment is

$w_{\dot{W}_C} = \pm$ 3.8 Watt

Results & Discussion

Refrigerators are devices that transfer heat from a low temperature region to a high temperature region. Since the objective of this experiment is to study the performance of a refrigeration cycle using both charts and actual data, the values of performance parameters obtained from both of them will be compared.

First, it is obvious that $\dot{W}_c$ calculated using the chart represents the rate of energy absorbed by the refrigerant $\dot{W}_c = \dot{m}_r(h_2 - h_1)$, while the corresponding value obtained from the actual data represents the power delivered to the compressor $\dot{W}_{c_i} = \dot{W}_{m_s} - \dot{W}_f$. It is seen that the value of $\dot{W}_c$ obtained using the chart is less than that obtained using the actual data. The reason beyond this difference is that some of the power delivered to the compressor is dissipated due to frictional and heat losses, which reduces the amount of energy absorbed by the refrigerant.

Furthermore, the value of $\dot{Q}_L$ calculated using the chart represents the rate of energy absorbed by the refrigerant $\dot{Q}_L = \dot{m}_r(h_1 - h_4)$. , while the corresponding value obtained from the actual data represents the rate of heat rejected by the evaporator. The value of $\dot{Q}_L$ absorbed by the refrigerant is less than that rejected by the evaporator due to heat losses. This also justifies the existence of the difference between the heat rejected by the refrigerant in the condenser($\dot{Q}_H$ calculated using the chart) and the heat absorbed by the water ($\dot{Q}_H$ obtained using the actual data).

Finally, it can be verified the following rule "The COP improves by 2 to 4 percent for each ^oC the evaporating temperature is raised" [1]. Regarding the first iteration in this experiment, P_e = 400 kPa ($T_{sat\ @\ p=400\ kPa}$ = 8.91 ^oC) , while for the second iteration P_e = 310 kPa ($T_{sat\ @\ p=310\ kPa}$ = 1.53 ^oC) . So, the change in the evaporating temperature $\Delta T \approx 7\ ^oC$.. Referring back to Table (2), the value of COP of the second iteration calculated using the actual data has increased by 4% for each ^oC the evaporating temperature is raised.

Sources of Error

Errors in this experiment are caused by several factors such as: using the P-H chart in finding the values of enthalpy, human error in recording the experimental values and computational errors due to approximation. Moreover, frictional and heat losses cause the performance parameters obtained using the chart to deviate from the corresponding values calculated using the actual data,

Summery & Conclusions

Overall, The experiment shows that performance of any refrigeration cycle is affected by frictional and heat losses. These kinds of irreversibilities cause a reduction in the coefficient of performance of the refrigeration cycle. Also, the experiment verifies the influence of changing the evaporating temperature in the coefficient of performance of the cycle under constant condenser pressure condition.

References

[1] Çengel, Y. A., & Boles, M. A. (2015). Thermodynamics: an engineering approach (8th ed.). New York: McGraw-Hill Education.

[2] Chapra, S. C., & Canale, R. P. (2010). Numerical Methods for Engineers (6th ed.). New York: McGraw-Hill Education.

[3] Holman J. P. (2012). Experimental Methods for Engineers (8th ed.). New York: McGraw-Hill Education.