Objective

- To study the performance of a heat pump cycle using both P-H chart and actual data.

Experimental Setup

The experimental setup is shown in figure (1). The air & water heat pump unit consists mainly of four devices: a compressor, a condenser, which uses water to condense the refrigerant, an expansion valve and an evaporator, which uses either air or water to evaporate the refrigerant. An evaporator switch allows the user to direct the flow of the expanding refrigerant to either an air or water source evaporator. There are two pressure gauges to measure the pressure of both condenser and evaporator. Furthermore, there are three flowmeters to measure the mass flow rate of the refrigerant, the water flowing through the condenser and the water flowing through the evaporator. The mass flow rate of water is controlled by revolving the needle valve. Water is supplied and drained from the unit through two tubes connected to the backside of the unit. Two screens are seen at front face of the unit. The first one is a wattmeter, which displays the power consumed by compressor. 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 – 9, depending on the position of the selector switch.

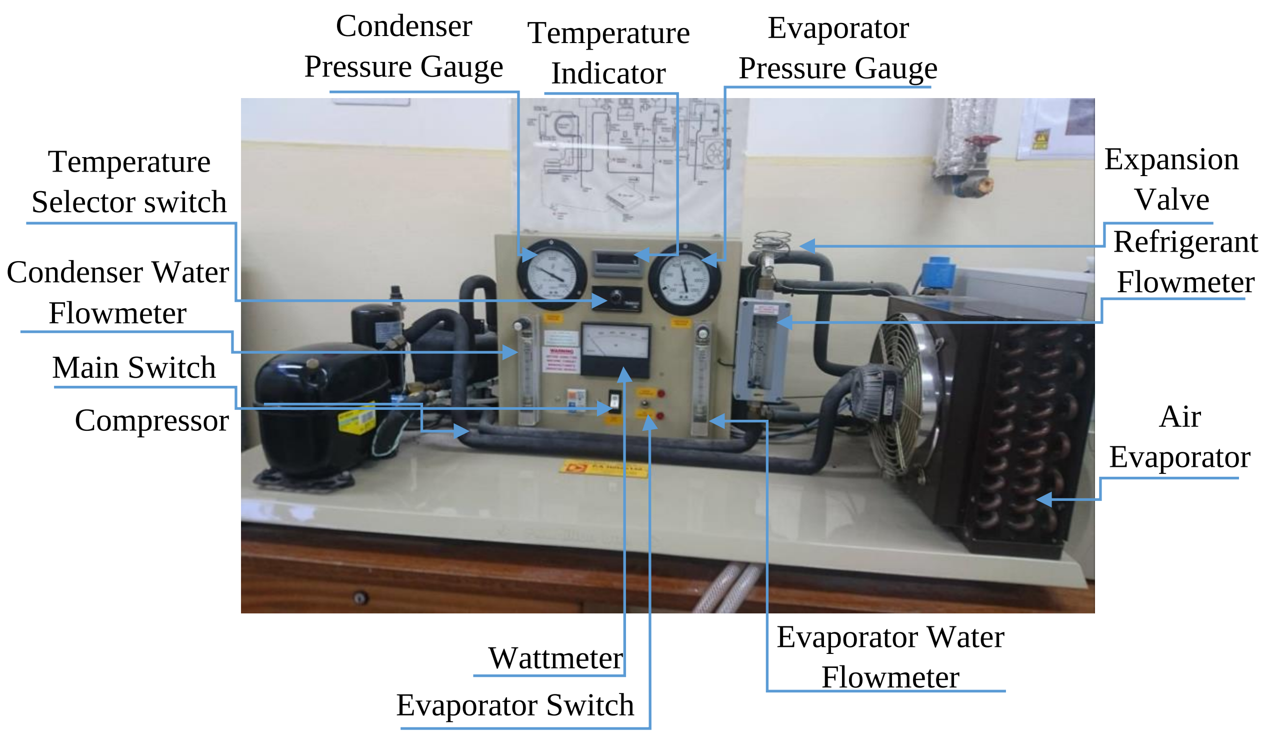


Figure (1): Air & water heat pump unit

Start-up Procedure

1. Open the water supply valve to allow water to flow through its own pipes.
2. Turn on the main switch to operate the unit.
3. Switch the evaporator switch to direct the flow of the refrigerant to the water source evaporator (In the experiment performed in the lab, only water source evaporator was used).
4. 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 in both the condenser and the evaporator to $\dot{m}_w = 30$ g/s.
3. Wait until readings reach steady state, and then start recording the temperatures (T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, T_9), condenser and evaporator pressures, power consumed by the compressor and the mass flow rate of the refrigerant.
4. Repeat the steps 2 – 3 with $\dot{m}_w = 50$ g/s.

Given Data

- Atmospheric Pressure P_{atm} = 89.75 kPa.
- Atmospheric Temperature T_{atm} = 22 ^oC.
- Constant pressure specific heat for water Cp = 4.18 kJ/kg.K [1].

Data observed

Table (1) :Data Observed

Series	Parameter	1	2	Units
Electrical	Compressor Electric Power	430	400	Watt
Refrigerant HFC134a	Mass flow rate ($\dot{m}_r$)	7	6.8	g/s
	Compressor Suction Pressure (P_1)	195	185	kPa (gauge)
	Condenser Pressure (P_2)	815	700	kPa (guage)
	Compressor Suction Temperature (T_1)	20.6	22	^oC
	Compressor Delivery Temperature (T_2)	69.4	72.2	^oC
	Condensed Liquid Temperature (T_3)	35.6	31.8	^oC
	Evaporator Inlet Temperature (T_4)	0.4	0.2	^oC
Water Compressor Cooling	Mass flow rate ($\dot{m}_c$)	30	50	g/s
	Inlet Temperature (T_5)	21.7	22.3	^oC
	Outlet Temperature (T_6)	22	22.5	^oC
Water Condenser Cooling	Mass flow rate ($\dot{m}_c$)	30	50	g/s
	Inlet Temperature (T_6)	22	22.5	^oC
	Outlet Temperature (T_7)	33.4	29.6	^oC
Water Source Evaporator	Mass flow rate ($\dot{m}_c$)	30	50	g/s
	Inlet Temperature (T_8)	21.7	22.1	^oC
	Outlet Temperature (T_9)	12.6	16.7	^oC

Sample Calculations

Step(1):Convert the values of pressure from gauge to absolute and from kPa to bar. Take column 2 from Table(1) as a sample for calculations.

$P_{abs} = P_{gauge} + P_{atm}$ [1]

1 bar ≈ 100 kPa [1]

$P_1 = 195 + 89.75 = 284.75$ kPa ≈ 2.85 bar

$P_2 = 815 + 89.75 = 904.75$ kPa ≈ 9 bar

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

Compressor inlet (1) => h_1@(P_1= 2.85 bar , T_1= 20.6 °C)=318 kJ/kg

Compressor Outlet(2) => h_2@(P_2 = 9 bar , T_2= 69.4 °C)= 355 kJ/kg

Condenser Outlet(3) => h_3@(P_2 = 9bar , T_3= 35.6 °C)= 150 kJ/kg

Evaporator Inlet(4) => $h_4 = h_3$= 150 kJ/kg

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

Step(3): Calculate the performance parameters as follows

- Evaporator heat absorbed :

=> Using experimental data

$$\dot{Q}_L = \dot{m}_c \times C_{p_w} \times (T_8 - T_9) \quad [1]$$

$$= \frac{30}{1000} \times 4.18 \times (21.7 - 12.6) \times 10^3 = 1141\ Watt$$

=> Using P-H chart

$$\dot{Q}_L = \dot{\mathrm{m}}_\mathrm{r} \times (\mathrm{h}_1 - \mathrm{h}_4) \quad [1]$$

$$= \frac{7}{1000}(318 - 150) \times 10^3 = 1176\ Watt$$

- Condenser heat rejected

=> Using experimental data

$$\dot{Q}_H = \dot{m}_c \times C_{p_w} \times (T_7 - T_6) \quad [1]$$

$$= \frac{30}{1000} \times 4.18 \times (33.4 - 22) \times 10^3 = 1430\ Watt$$

=> Using P-H chart

$$\dot{Q}_H = \dot{\mathrm{m}}_\mathrm{r} \times (\mathrm{h}_2 - \mathrm{h}_3) \quad [1]$$

$$= \frac{7}{1000}(355 - 150) \times 10^3 = 1435\ Watt$$

- Compressor power

=> Using experimental data

$$\dot{W}_c = 430 \text{ Watt}$$

=> Using P-H chart

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

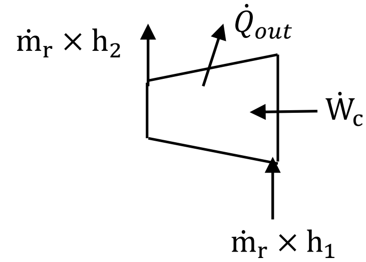
$$= \frac{7}{1000}(355 - 318) \times 10^3 = 259\ W\text{att}$$

=> Since the compressor is not adiabatic, the amount of heat transferred can be calculated using energy balance equation :

$$\dot{W}_c + \dot{m}_r \times h_1 = \dot{Q}_{out} + \dot{m}_r \times h_2$$

$$\dot{Q}_{out} = \dot{W}_c + \dot{m}_r \times (h_1 - h_2)$$

$$\dot{Q}_{out} = 430 - 259 = 171 \text{ Watt}$$



Step(4): Calculate the COP of the cycle using the following three methods

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

=> Using P-H chart

$$(COP)_{HP} = \frac{\dot{m}_r \times (h_2 - h_3)}{\dot{m}_r \times (h_2 - h_1)} = \frac{1435}{259} = 5.54$$

=> Using simple cycle analysis

$$(COP)_{HP} = \frac{\dot{m}_c \times C_{p_w} \times (T_7 - T_6)}{\dot{W}_c} = \frac{1430}{430} = 3.32$$

=> Using simple cycle analysis, taking into account heat lost from the compressor

$$(COP)_{HP} = \frac{\dot{m}_c \times C_{p_w} \times (T_7 - T_6) + \dot{Q}_{out}}{\dot{W}_c} = \frac{1430+171}{430} = 3.72$$

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 % $= \frac{259-430}{259} \times 100\% = -66.02\ \%$

=> For evaporator Error % $= \frac{1176-1141}{1176} \times 100\% = 2.97\ \%$

=> For condenser Error % $= \frac{1435-1430}{1435} \times 100\% = 0.34\ \%$

=> For COP Error % $= \frac{5.54-3.32}{5.54} \times 100\% = 40.07\%$

=> For COP Error % $= \frac{5.54-3.72}{5.54} \times 100\% = 32.8\%$ (For simple cycle analysis, taking into account heat lost from the compressor)

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)	259	272	430	400	-66.02%	-47.06%
2	Evaporator heat absorbed $\dot{Q}_L$ (Watt)	1176	1190	1141	1128.6	2.97%	5.16%
3	Condenser heat rejected $\dot{Q}_H$ (Watt)	1435	1462	1430	1483.9	0.34%	-1.49%
4	Coefficient of Performance $(COP)_R$	5.54	5.38	3.32	3.71	40.07%	31.04%
				3.72*	4.03*	32.8 %*	25.09%*

* These values are calculated, taking into consideration the heat lost from the compressor.

Uncertainty Analysis

- For a calculated quantity x that is dependent on another quantities $x_1, x_2, x_3, \ldots, x_n$

$$x = f(x_1, x_2, x_3, \ldots, x_n)$$

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 value $\dot{Q}_H$ is dependent on $\dot{m}_c, T_6, T_7$ i.e

$$\dot{Q}_H = f(\dot{m}_c, T_6, T_7)$$

The uncertainty of $\dot{Q}_H$ is given by

$$w_{\dot{Q}_H} = \pm\sqrt{\left(\frac{\partial \dot{Q}_H}{\partial \dot{m}_c} \times w_{\dot{m}_c}\right)^2 + \left(\frac{\partial \dot{Q}_H}{\partial T_6} \times w_{T_6}\right)^2 + \left(\frac{\partial \dot{Q}_H}{\partial T_7} \times w_{T_7}\right)^2}$$

- 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 $\dot{m}_c, T_6, T_7$ are as follows :
$w_{\dot{m}_c} = \pm 1\frac{g}{s}$ $\quad w_{T_6} = w_{T_7} = \pm 0.05\ ℃ = \pm 0.05\ K$

- The following quantities are found by differentiating $\dot{Q}_H = \dot{m}_c \times C_{p_w} \times (T_7 - T_6)$ partially :

  $\frac{\partial \dot{Q}_H}{\partial \dot{m}_c} = C_{p_w} \times (T_7 - T_6)$ $\frac{\partial \dot{Q}_H}{\partial T_6} = -\dot{m}_c \times C_{p_w}$

  $\frac{\partial \dot{Q}_H}{\partial T_7} = \dot{m}_c \times C_{p_w}$

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

$$w_{\dot{Q}_H} = \pm\sqrt{(4.18 \times (33.4 - 22) \times 1)^2 + (-30 \times 4.18 \times 0.05)^2 + (30 \times 4.18 \times 0.05)^2}$$

$= \pm$ 48.7 Watt = $\pm$ 3.4%

⇨ The value of uncertainty $w_{\dot{Q}_H}$ for the second iteration in the experiment is

$w_{\dot{Q}_H} = \pm 33.2$ Watt = $\pm 2.2\%$

Results & Discussion

Heat Pumps 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 heat pump cycle using both P-H chart and experimental 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 . 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 heat losses, which reduces the amount of energy absorbed by the refrigerant.

Second, 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 water source evaporator $\dot{Q}_L = \dot{m}_c \times C_{p_w} \times (T_8 - T_9)$. The value of $\dot{Q}_L$ absorbed by the refrigerant is greater than that rejected by the evaporator, which indicates that the refrigerant is flowing through tubes that are not well insulated. This causes heat to transfer from the ambient air to the refrigerant, which makes the rate of energy absorbed by the refrigerant greater.

Furthermore, it is noticeable that the heat rejected by the refrigerant in the condenser($\dot{Q}_H$ calculated using the chart) is greater than the heat absorbed by the water ($\dot{Q}_H$ obtained using the actual data), due to heat losses.

Regarding the coefficient of performance, it is obvious from both values of COP obtained from simple cycle analysis that heat losses causes a decrease in the COP. Thus, more power must be delivered to the compressor to achieve the desired output.

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 heat pump cycle is affected by frictional and heat losses. These kinds of irreversibilities cause a reduction in the coefficient of performance of the heat pump cycle. Hence, more power must be generated to feed the compressor to achieve the desired output.

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.