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Investigate the Performance Characteristic of A Commercial Reciprocating Chiller That Utilises Vapour Compression Cycle at Several Operating Conditions

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ABSTRACT
The objective of this report is to investigate the performance characteristic of a commercial reciprocating chiller that utilises vapour compression cycle at several operating conditions. The specific objectives that are accomplished in terms of performance characteristics of the refrigeration system are: the determination of the power consumption of compressor, the cooling capacity of the evaporator, the COP of cooling, the isentropic efficiency of compression process, the volumetric efficiency of compressor, the overall combine compressor efficiency of compressor and Carnot COP for the given cycle.
The experiment was conducted with a refrigeration rig that employs R404A refrigerant. R404A is a near-azeotropic mixture of HFC-125/143a/134a, 44/52/4% by weight, which is a non-ozone depleting compound. The experimental steady state results are averaged into 3 sets of 6 results, as the condenser water leaving temperatures were set at 30℃, 35℃ and 40℃ and at each condenser water leaving temperature, the evaporator water leaving temperature varied from 5℃ to 10℃, with even increments of 1℃, where refrigerant evaporating temperature was kept constant at each test.
Results have shown that cooling capacity and the cooling COP of the refrigeration system, the heat (energy) transfer across the evaporator and efficiency of the cycle are improved greatly when reducing the temperature difference between water leaving temperatures of the condenser and the evaporator, providing an increment in cooling capacity of 8.3 when the temperature difference is reduced from maximum value of 34.9℃ to minimum value of 19.8℃. The cooling COP is also increased by 2.9. Furthermore, the isentropic efficiency resulted in increased values when increasing the temperature difference between the condenser and evaporator leaving temperatures. Similarly, volumetric efficiency is also increased by a small margin of 4.7% as the temperature difference is increased by 6℃. Finally, the highest overall efficiency of 43.7% is given at a temperature difference of 21.01℃ and the lowest efficiency of 40.9% at a temperature difference of 34℃. An increment on pressure ratio leaded to a sharp decrement of isentropic, volumetric and overall efficiencies.

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GLOSSARY OF TERMS

T1 & P1	Compressor discharge / Condenser Inlet Temperature and pressure °C and bar
T2 & P2	Condenser Outlet /Expansion valve Inlet Temperature and pressure °C and bar
T3 & P3	Expansion Outlet / Evaporator Inlet Temperature and pressure °C and bar
T4 & P4	Evaporator Outlet /Compressor Inlet Temperature and pressure °C and bar
T5	Condenser Inlet Water Temperature °C

T6	Condenser Outlet Water Temperature °C
T7	Evaporator Inlet Water Temperature °C
T8	Evaporator Outlet Water Temperature °C
CWFR	Condenser Water Flow Rate (kg/s)
EWFR	Evaporator Water Flow Rate (kg/s)
TAMB	Ambient Temperature °C
ṁ ref, ṁr	Refrigerant Mass Flow Rate (kg/s)
ηυ	Volumetric Efficiency
ηis	Isentropic Efficiency
ηcs	Combined (Overall) Efficiency
Wc	Actual Work in KW
Wis	Work Required By Isentropic Compression in KW
We	Electrical Work Input for Motor in KW
COP	Coefficient of performance
Cp (water)	The specific heat capacities of water in (kJ/kg·k)
V	Volume of superheated vapor in (m3/kg)
h	Enthalpy KJ/Kg
h1`	Isentropic enthalpy (KJ/kg)
S	Entropy in (KJ/(kgk)

I. Introduction

The definition of the chiller is a machine that removes heat from a liquid via a vapor compression or absorption refrigeration cycle. [3] This liquid can be circulated through a heat exchanger to cool equipment, or another process stream (such as air or process water). Since the liquid or water is fluid and has specific heat value, it makes an excellent secondary refrigerant. Water is also inexpensive, nontoxic and largely non-corrosive. Some commonly used secondary refrigerants are calcium chloride, ethylene and glycols and others[4]. The compressors which used in vapor compression chillers are Reciprocating compression, scroll compression, screw-driven compression, and centrifugal compression. They produce their cooling effect via the "Reverse-Rankine" cycle, also known as 'vapor-compression'.

Important specifications to consider when searching for commercial chillers include the total life cycle cost, the power source, condenser material, condenser capacity, evaporator capacity, chiller cooling capacity, evaporator material, evaporator type, chiller IP rating, ambient temperature, motor fan type, noise level, internal piping materials, number of compressors, type of compressor, number of fridge circuits, coolant requirements, fluid discharge temperature, and COP.

Experiment test facility and method:

The chiller under consideration is equipped with shell and tube heat exchangers, an externally equalised thermostatic expansion valve, a 4-cylinder hermetic compressor designed for use with R404A and appropriate controls. The compressor displacement is 45.07 m3/hr at 1450 rpm and provides a nominal cooling capacity of 25KW.

Three sets of experimental tests were carried out for condenser water leaving temperatures of 30°C, 35°C and 40°C. The condenser water leaving temperature approximately corresponds to a constant refrigerant condensing temperature (saturated vapour). For each condenser water leaving temperature the evaporator water leaving temperature which approximately corresponds to a constant refrigerant evaporating temperature (saturated vapour) was varied from 5°C to 10°C in steps of approximately 1°C. In experimental investigations it is very difficult to ensure that conditions are kept constant at exactly the required value and you will see from the results (temperature T8) that the evaporator water leaving temperature fluctuates between +/- 0.25°C about the set point. Please refer to Appendix (A) for further details.

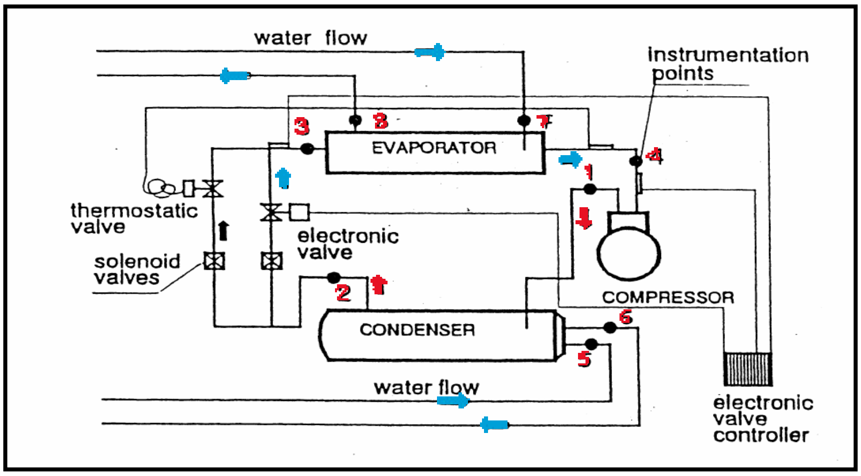

Figure1: the experimental test facility (test rig)

The reading for the refrigerant mass flow was disregarded. Calculation of the refrigerant mass flow rate was based on an energy balance between the refrigerant and the water across the condenser.

Experiment 1:

1.1 Power consumption of compressor:

The purpose of compressor is to compress the refrigerant leaving the evaporator to a higher pressure and temperature, however the compressor does not transfer heat in or out. Since the cooling capacity is the rate of heat transfer per unit mass, the mass flow rate can be determine as shown:

$$Mass\ flow\ rate,\ \dot{m}_r = \frac{Q_H}{h_1 - h_2} = \frac{CWFR * Cpwater * (T6 - T5)}{h_1 - h_2}$$

- Calculate the mass flow rate, ($\dot{m}_r$) from the **condenser side** that is to make sure it is liquid.

The enthalpies for every set point in the cycle (h1,h2=h3 and h4) have been determined then the refrigerant mass flow rate (ṁr) for every set point has been determined based on an energy balance between the refrigerant and the water across the condenser. Calculations for power consumption for compressor (Wc), Cooling Capacity and COP cooling have been carried out. (Sample of calculations please refer to Task1 in **appendix).**

Thus, the power consumption of compressor is given as:

$$Power\ consumption\ of\ compressor, W_c = \dot{m}_r(h_1 - h_4)$$

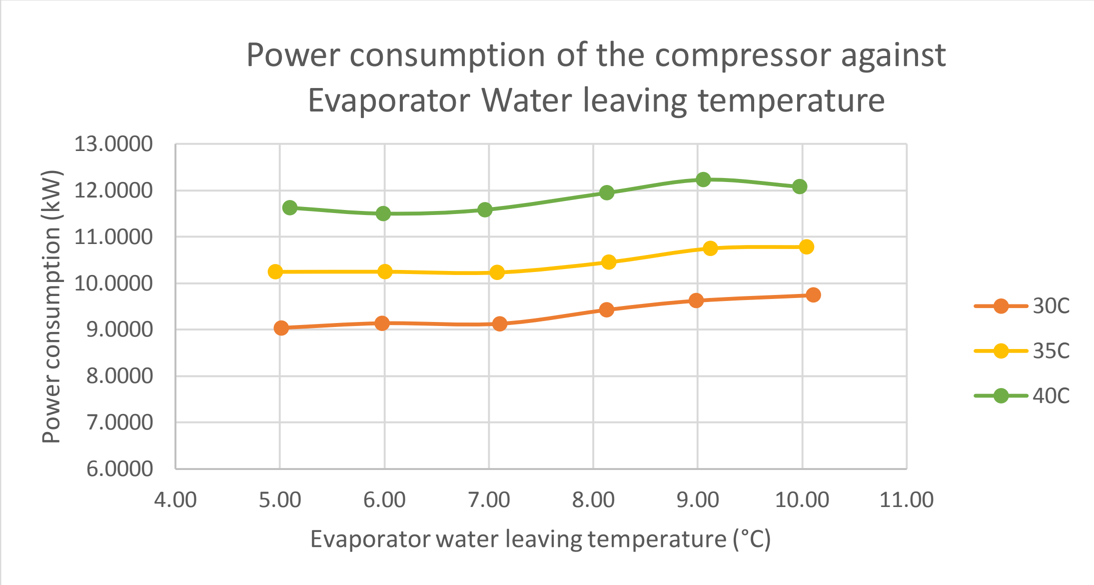

Figure1: Power consumption of the compressor against Evaporator water leaving temperature

The power consumption of the compressor against evaporator water leaving temperature graph in figure 1 show that the behaviour of curves for all three-condenser water leaving temperature which are shows an effect on the performances of characteristics when the temperature of the evaporator and condenser water leaving is changed. Results show similar trend with slightly higher power consumption after evaporator water leaving temperature at 7℃. The increment in evaporator leaving temperature results in an approximately same of power consumption, however at higher condensing temperature still consumes more power at any set evaporator water leaving temperature.

1.2 Cooling capacity of refrigeration:

The heat is transferred is absorbed from the refrigerated space as the refrigerant passes through the evaporator, which causes the refrigerant to vaporise. Since the cooling capacity is the product of mass flow rate and the change in enthalpy across the evaporator, we can obtain the rate of heat (energy) extraction from the refrigerated space.
It can be said that the rate of energy transfer of the refrigerant per unit of mass and the rate of energy transfer of the water per unit mass across the evaporator can be assumed to be the same. Please refer to sample of calculations in Task1 in **appendix).**
Thus the cooling capacity of the refrigeration is given by:

$$\text{Cooling capacity } (C_{cap}),\ Q_c = EWFR \times Cp_{water} \times (T7\text{-}T8)$$

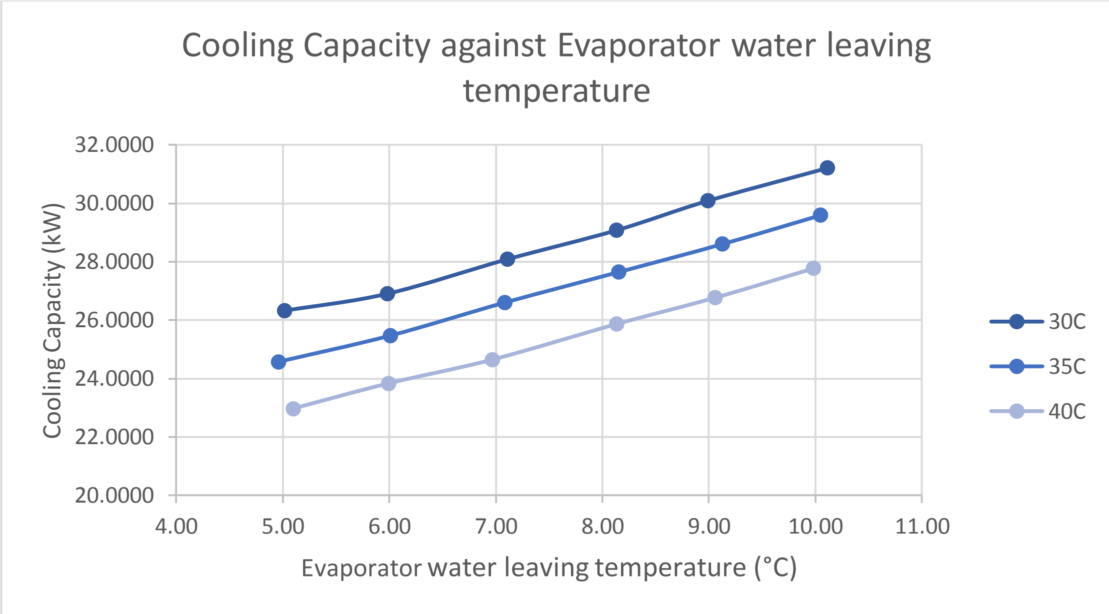

Figure 2: Cooling Capacity against Condenser water leaving temperature graph

The Cooling Capacity against Condenser water leaving temperature graph in figure 2 shows that cooling capacities at each set condenser temperature of 30, 35 and 40℃ are increasing at an average rate of about 0.96 per condenser water leaving temperature. Hence, all three curves are showing similar trend. Furthermore, the increase in temperature difference between the condenser and evaporator leaving temperature is directly proportional to the cooling capacity of the refrigeration system. In addition, results show that higher condenser water temperature delivers higher cooling capacity at each varying evaporator water leaving temperature.

1.3 Cooing Coefficient of Performance:

Since the purpose of a refrigeration system is to keep the refrigerated space temperature below that of the temperature of environment, thus it is important to minimise the power input, while transferring heat from the refrigerated region. (See sample of calculations Task1 in **appendix)**

Therefore, the efficiency measurement of cooling can be expressed as:

$$Cooling\ Coefficient\ of\ Performance, COP = \frac{Cooling\ capacity\ of\ refrigeration, Q_c}{Power\ consumption}$$

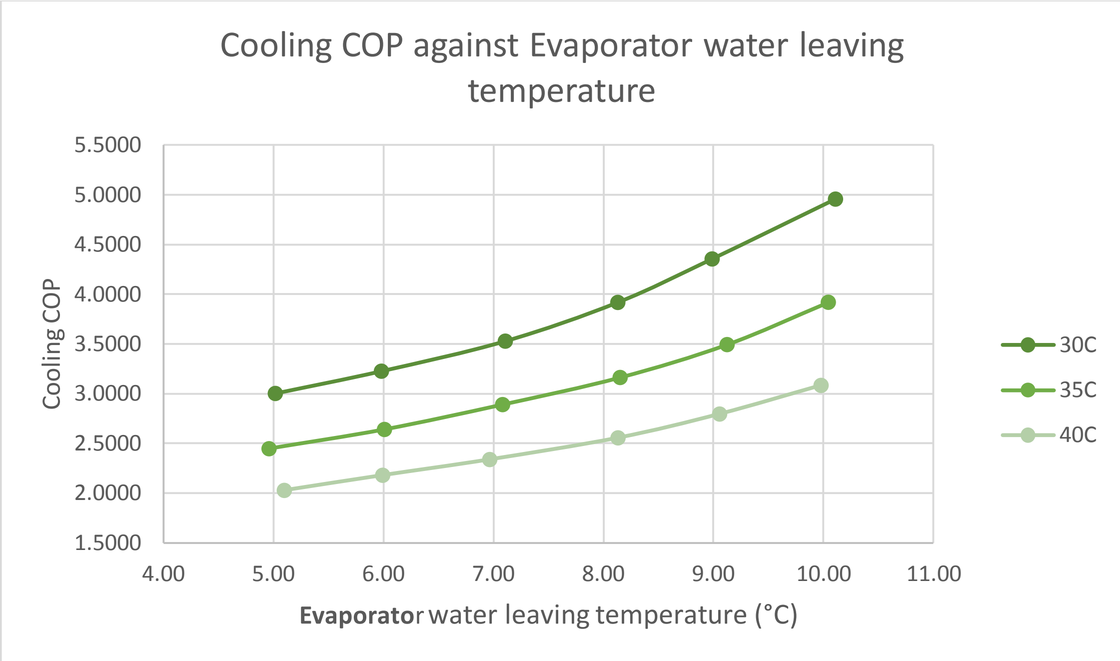

Figure 3: Cooling COP against Condenser water leaving temperature

Figure 3 shows that the cooling COP at each set condenser temperature of 30, 35 and 40℃ is increasing at an average rate of 0.0465 per condenser water leaving temperature, while the trend of all three curves are showing similar behaviour. Even though, there are slight fluctuations for all three curves, however the increase in temperature difference between the condenser and evaporator leaving temperatures are almost directly proportional to the COP of the refrigeration system, and in extension, higher condenser water leaving temperatures represented higher COPs at each varying evaporator water leaving temperature.

Experiment 2:

There are many factors that directly affect the performance of a compressor, as it is the heart of the refrigeration cycle. The operation of the compressor can be characterized by three main parametric efficiencies: The Volumetric Efficiency (ηv), the Isentropic Efficiency (ηis) and the Overall Efficiency (ηcs). All of these efficiencies have an influence on the performance of the compressor and these factors have been calculated and plotted below. A high volumetric efficiency represents a good mechanical design while isentropic efficiency represents the friction during compression and fluid flow losses. Moreover, the overall efficiency provides a holistic overview of the compressor performance.

2.1 Isentropic Efficiency

Isentropic efficiency is the ratio of work done for isentropic compression to that of the actual work done. Isentropic compression is the ideal compression process, however for actual compression process, the entropy increase across compressor, which is mainly due to frictional energy during compression process and heat exchange between vapour and cylinder wall. Therefore it can be said that it is a ratio between rates of energy (Power) of two quantities. Hence, isentropic efficiency is given as: (Please refer to Sample of calculations Task 2 in **appendix)**

$$Isentropic\ efficiency, \eta_{is} = \frac{\dot{m}_r(h'_1 - h_4)}{\dot{m}_r(h_1 - h_4)}$$

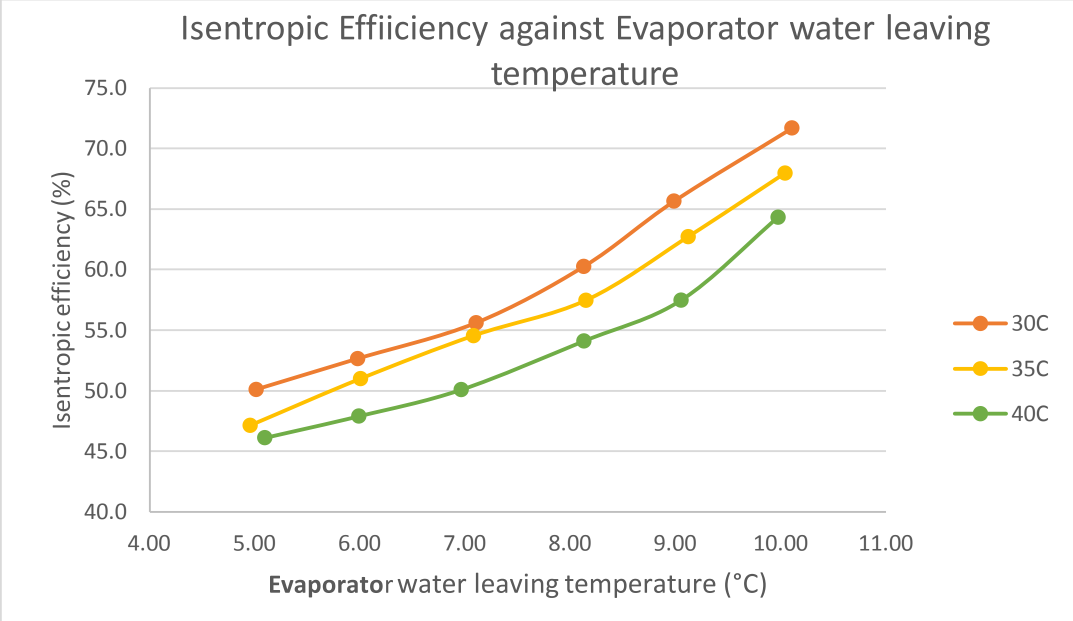

Figure 4: Isentropic Efficiency against Condenser water leaving temperature

Figure 4 suggests that the isentropic efficiency for each set condenser temperature of 30, 35 and 40℃ increases with condenser water leaving temperature. All three curves are displaying a positive gradient, and at about 8.2℃ of evaporator water leaving temperature, rate of change in isentropic efficiency start to increase with evaporator temperature. All curves are behaving in a similar manner, however there is a slight fluctuation on each curve. Furthermore, the graph suggests that higher condenser water temperatures represented greater isentropic efficiency at each varying evaporator water leaving temperature.

2.2 Volumetric Efficiency

The purpose of volumetric efficiency is to measure the compressor's performance in terms its capability to compress vapour. However, it does not have any effect on the isentropic efficiency of the compressor. In terms of mechanical design, the volumetric efficiency is very important as higher efficiencies represent that physical size of the compressor can be reduced at a given refrigeration capacity. Hence, volumetric efficiency is the ratio of actual induced volume of vapour to swept volume of compressor and it is given as: (Please refer to Sample of calculations Task2 in **appendix)**

$$Volumetric\ efficiency, \eta_v = \frac{rate\ of\ actual\ volume\ induced, \dot{V}}{rate\ of\ compressor\ swept\ colume, \dot{V_s}}$$

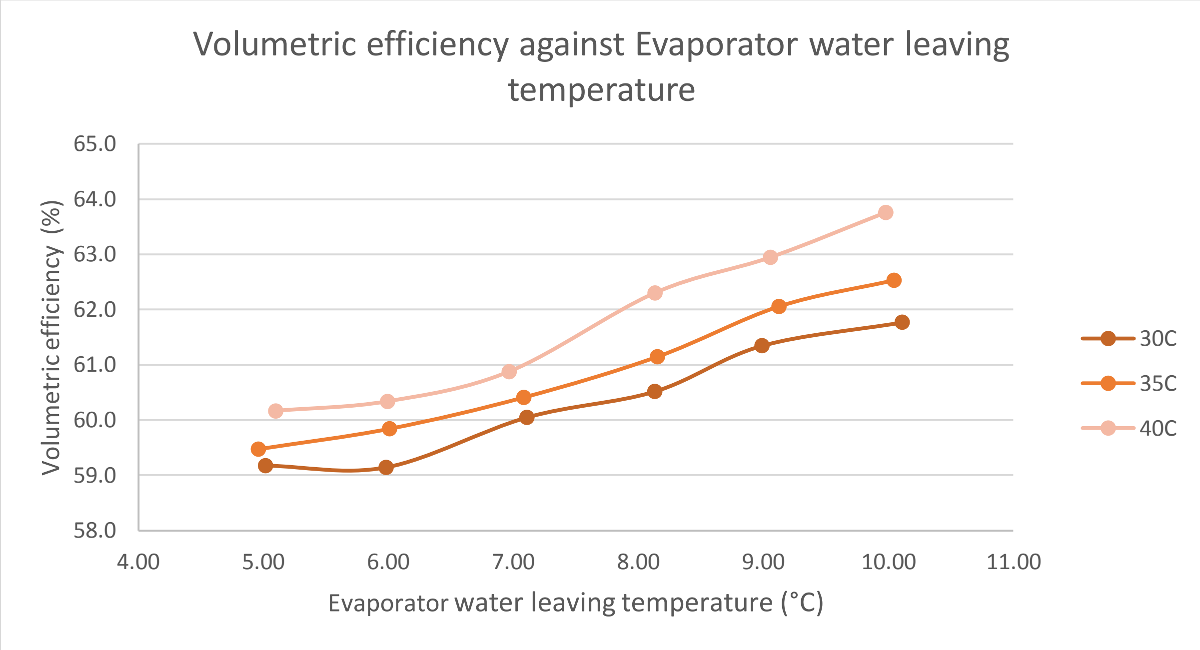

Figure 5: Volumetric efficiency against Condenser water leaving temperature

Figure 5 shows that the volumetric efficiency at each set condenser temperature of 30, 35 and 40℃ are increasing at an average rate of 0.66, 0.65 and 0.68 per condenser water leaving temperature, respectively. Even though, the gradients are positive and have similar behaviour, the curves for condenser water leaving temperature of 30℃ and 40℃ are both displaying moderate fluctuations. Additionally, the increase in temperature difference between the condenser and evaporator leaving temperatures results in increase in volumetric efficiency of the refrigeration system, and in extension, higher condenser water temperatures represented higher efficiency at each varying evaporator water leaving temperature.

2.3 Overall Compressor Efficiency

The overall compressor efficiency is the combined efficiency of isentropic, mechanical, drive and electrical efficiencies, which can be defined as ratio of the isentropic efficiency to the work delivered to shaft or the electrical power input to motor, hence overall (combined) compressor efficiency is expressed as: (Please refer to Sample of calculations Task2 in **appendix)**

$$Overall\ compressor\ efficiency, \eta_{cs} = \frac{m_r(h'_1 - h_4)}{W_e}$$

The overall compressor efficiency vs condenser water leaving temperature in figure 6 shows that higher condenser water temperatures represent higher overall efficiency at each varying evaporator water leaving temperature. The curves at each set of condenser water leaving temperature suggest that the dependence of overall efficiencies on evaporating temperature is not significant. At 30℃ and 35℃**,** curves are following similar path with considerable fluctuation in their characteristic. On the other hand, slightly greater fall in the overall efficiency as the evaporator water temperature is reduced at condenser temperature of 40℃**.**

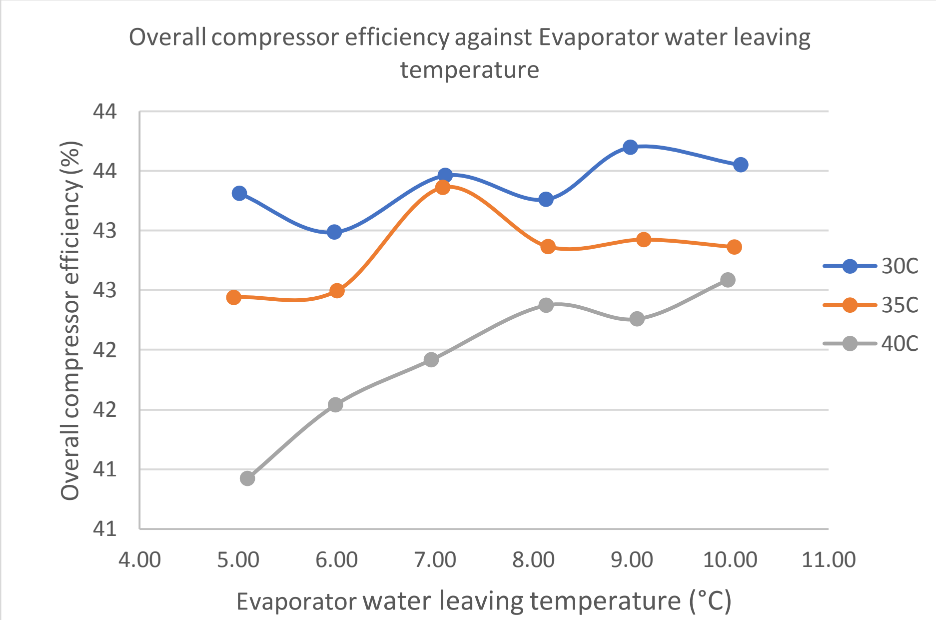

Figure6: Overall compressor efficiency against Condenser water leaving temperature

Experiment 3:

An ideal Carnot cycle comprises of isentropic compression, isentropic expansion, isothermal heat rejection and isothermal heat addition process, where all processes are assumed to be reversible and all heat transfers occur with constant temperature. It is a most efficient cycle as it gives the highest theoretical COP. However it cannot be approximated in actual cycle due to irreversible processes and definite change in temperatures in actual cycle.

In order to determine the Carnot COP for the given refrigeration cycle, saturated vapour temperature T6(sat) and T8(sat) were determined, in which two assumptions were taken for the process. Assuming the pressure across the condenser is constant, the saturated vapour temperature at pressure P1 from the experiment results were used to determine the T6(sat) from R404A Saturated properties table 1, and T8(sat) was taken as temperature,T3 as it is assumed to be in saturated region, as shown in figure 7.

Hence, Carnot COP for the given cycle is expressed as:

Approximate constant refrigerant condensing temperatures (sat.vap) andarange of evaporator water leaving temps. Constant ref. evaporating temperatures (sat.vap)

$$Carnot\ COP = \frac{T_8(K)}{T_6(K) - T_8(K)} = \frac{1}{\frac{T_6(K)}{T_8(K)} - 1}$$

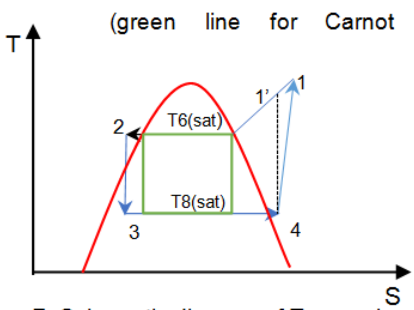

Figure7: Schematic diagram of T-s graph

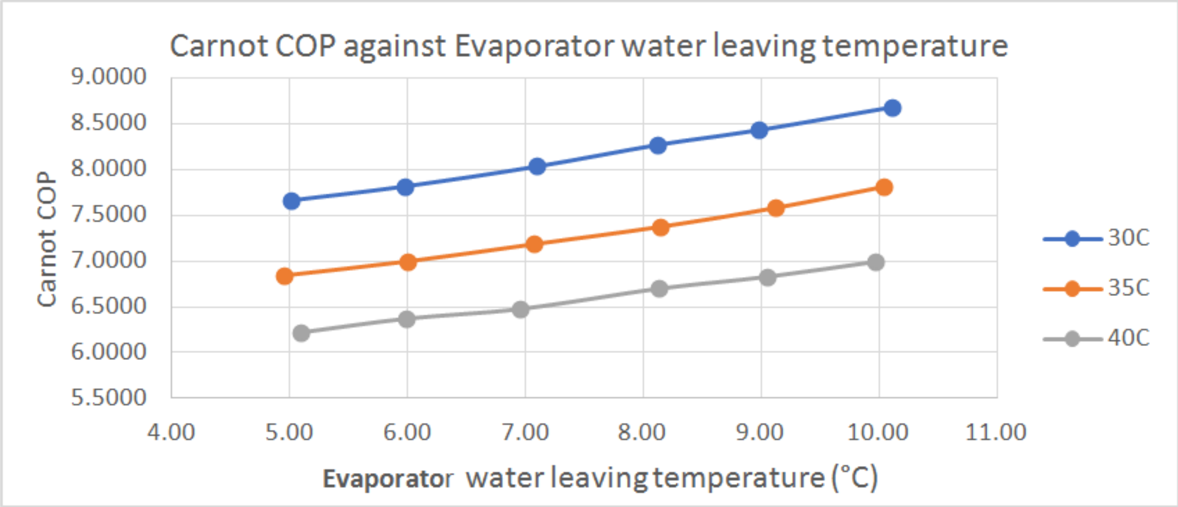

Figure8: Carnot COP against Condenser water leaving temperature

The figure 8 shows that for all three curves have slight fluctuation, however the increase in temperature difference between the condenser and evaporator leaving temperatures are almost directly proportional to the Carnot COP of the refrigeration system. Furthermore, higher the condenser water temperature meant higher COP at each varying evaporator water leaving temperature. Figure 8 suggests shows that the Carnot COP at each set condenser temperature of 30, 35 and 40℃ are increasing at an average rate of 0.19 per condenser water leaving temperature, which is much higher that of the actual cooling COP gradient of 0.047. Through comparison, it suggests that the actual COP of the refrigeration cycle is much lower that of the Carnot COP, as it is assumed to most efficient cycle with zero frictional and heat exchange loss across the compressor.

Experiment 4:

In this experiment, a study of the operating characteristics and thermodynamic performance of commercial reciprocating chiller was carried out. Through analysing the cooling capacity and the cooling COP of the refrigeration system, the heat (energy) transfer across the evaporator and efficiency of the cycle are improved greatly with reduction in the temperature difference between water leaving temperatures of the condenser and the evaporator, where the cooling capacity is increased by 8.3 when the temperature difference reduced from maximum value of 34.9℃ to minimum value of 19.8℃, for which the cooling COP is also increased by 2.9. With the effect of increase in cooling capacity and COP, power consumption of the compressor is progressive as shown figure 3, for which, the power consumption was increased while temperature difference between water leaving temperatures of the condenser.

The isentropic efficiency resulted in increased values when increasing the temperature difference between the condenser and evaporator leaving temperatures, showing that the heat energy loss across the compressor is reduced significantly with the reduction in the temperature difference. In other words, the actual process of the cycle gets closer to that of the ideal process of a cycle, signifying smaller entropy difference. Therefore, the improvement of isentropic efficiency involves minimising the friction as the vapour passes through the inlet and outlet valve of the compressor and heat exchange between the wall of the cylinder and the vapour. Another important aspect is the response of the isentropic efficiency to an increment in Pressure Ratio. Figure 4-1 shows that when increasing slightly the pressure ratio, the isentropic efficiency decreases considerably, with a sharp negative slope for each leaving evaporating water temperature scenario.

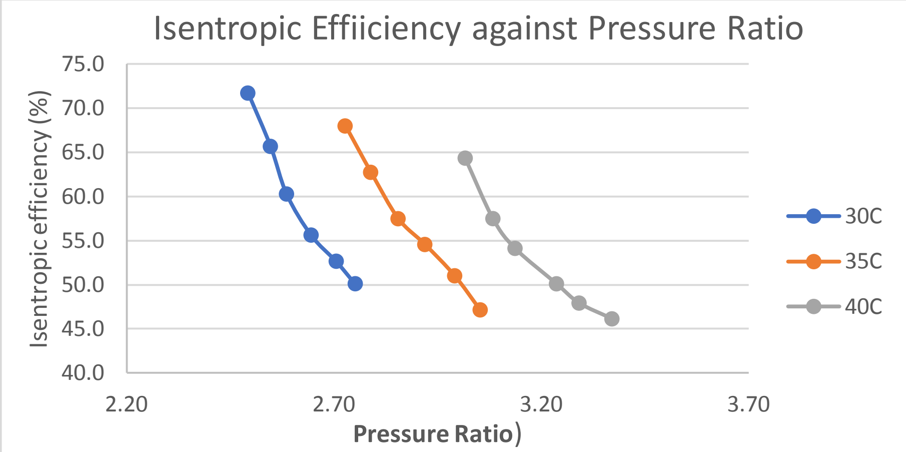

Figure4-1: Isentropic compressor efficiency against Pressure Ratio

Similarly, volumetric efficiency is also increased by a small margin of 4.7% as the temperature difference is increased by 6°C. Since the energy efficiency does not have any influence on volumetric efficiency, the slight increase in the efficiency is occurred due to slight increase in refrigerant mass flow rate, based calculated results (see spreadsheet for reference). The highest volumetric efficiency was 63.9% at condenser water leaving temperature of 40°C. Since the compressor does not compress actual volume of vapour compared to its swept volume, the flow rate is reduced due to expansion of the vapour in the clearance volume. Hence, by improving the mechanical design of the compressor the volumetric efficiency can be increased, for which includes minimising the clearance volume and also it is important to ensure there are no vapour leakage. Another important aspect is the response of the volumetric efficiency to a slight increment in Pressure Ratio. Figure 5-1 shows that when increasing slightly the pressure ratio, the volumetric efficiency decreases considerably, with a sharp negative slope for each leaving evaporating water temperature scenario.

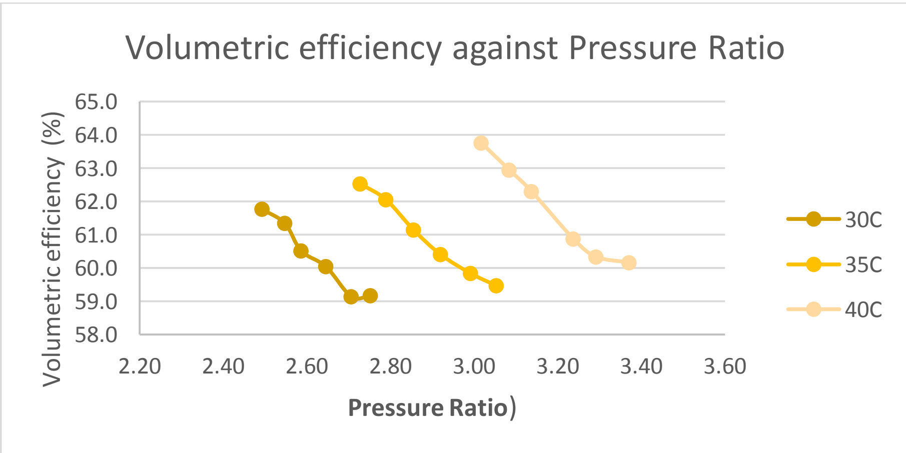

Figure5-1: Volumetric compressor efficiency against Pressure Ratio

Even though the overall compressor efficiency is improved with increase in condenser temperature, the rate which the efficiency is not consistent as there are some fluctuation in the efficiency, as shown in figure 6. The highest overall efficiency of 43.7% is given at a temperature difference of 21.01°C and the lowest efficiency of 40.9% at a temperature difference of 34°C, which shows that the efficiency does not improve greatly with temperature difference. Since, the overall compressor efficiency was determined using the ratio of isentropic work to the electrical work input, efficiency is greatly reduced by fictional and mechanical loss. Furthermore, figure 6-1 shows that when increasing slightly the pressure ratio, the overall compressor efficiency decreases considerably, with a sharp negative slope for each leaving evaporating water temperature scenario.

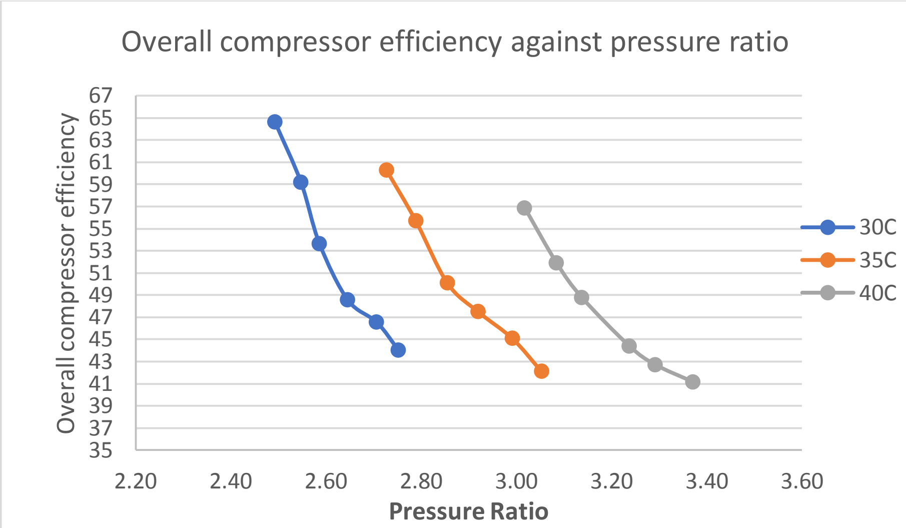

Figure6-1: Overall compressor efficiency against Pressure Ratio

In conclusion, the temperature and the pressure of vapour/liquid in the condenser and evaporator (heat exchanger) are not constant in which vary across the heat exchangers as heat transfer rate is different along each point. Also, the irreversible compression and expansion results increase in entropy, for which the refrigerant leaves the condenser as a pure liquid state. Hence, enthalpies across the expansion valve are not constant in throughout the actual cycle.

Further potential system analysis regarding the working fluid selection would be highly recommended in order to select the most suitable combination of working fluid in terms of overall coefficient of performance, refrigerating capacity per unit of mass flow rate and chilled water yielded. Different refrigerant compositions would lead to more optimum refrigerant condensing temperatures and eventually higher COP. Finally, optimizing the systems components in order to minimize the friction losses (less frictions in expansion valve, suitable lubricant of compressor, etc.) would result in smaller discrepancies between actual COP and Carnot COP.

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