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THE PERFORMANCE OF A BENCH SCALE LIQUEFACTION OF CARBON DIOXIDE

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ABSTRACT

Presently, the use of liquefied carbon dioxide in research centers and industry is becoming important due to the various research activities and applications in industry. The aim of this work is to liquefy carbon dioxide gas insitu using an appropriate cryogenic system. Carbon dioxide is non-toxic, non-flammable, has zero ozone depletion potential and negligible global warming potential as refrigerant as compared to hydrocarbon and freon gases. The analysis has been carried out using a bench scale liquefaction test rig, with capacity of about 1 kg/min. The test rig operates at condensing pressures between 50 to 120 bar and chiller temperatures between -15 to 7°C in order to produce the liquid carbon dioxide. Liquified carbon dioxide has many applications, such as refrigerant, fire extinguishing agent, supercritical extraction fluid and in the beverage industry. The properties of carbon dioxide at different states of the liquidification process are obtained from the property diagram and are used to evaluate the performance of the liquefaction bench scale test rig.

Keywords : *, Bench scale test rig, carbon dioxide, efficiency of liquefaction, supercritical performances, transcritical.*

1.0 INTRODUCTION

Carbon dioxide is the fourth most-abundant gas in the Earth's atmosphere. It was first identified in the 1750s by Joseph Black, a Scottish chemist and physician. Carbon dioxide is a compound made from two oxygen atoms covalently bonded to a single carbon atom. At room temperatures, carbon dioxide is an odorless, colorless gas, which is faintly acidic and non-flammable. Although carbon dioxide is mainly exists in the gaseous form, it also has a solid and a liquid form. Carbon dioxide in solid state is called dry ice and can only be solid when temperatures are below -78°C. Carbon dioxide has the ability to absorb many infrared wavelengths of the Sun's light and is an important greenhouse gas. Carbon dioxide is created naturally from exhale by animals and utilized by plants during photosynthesis.

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Additional carbon dioxide comes from the combustion of fossil fuels or degradation process of vegetable matter, [1, 2, 3]

Carbon dioxide is one of the oldest refrigerants as it was already employed at the end of the nineteenth century. However in 1931, synthetic refrigerants came into use and carbon dioxide usage as a refrigerant declines because the new fluids provided better efficiency with cheaper and more reliable equipment. High critical pressure of 73.8 bar and rather low critical temperature of 31.06^{o}C summarize the main drawbacks of carbon dioxide. Typically, the liquefaction process comprises of compressing the gaseous carbon dioxide to a pressure above atmospheric pressure and then removing the latent heat of vaporization to condense the compressed gas. In this way, although the sublimation temperature of solid carbon dioxide is approximately - 78.5 ºC at Triple Point, the compressed gaseous carbon dioxide can be condensed at much higher temperature, [4, 5, 6]. However, carbon dioxide is more difficult to handle because it is a solid at atmospheric pressure. It can be transported under pressure as a liquid, but at any stage of depressurization, solids can form which can clog valves and lines. The liquid carbon dioxide is used as a commercial refrigerant especially in freezing and chilling food products. It is also used as a fire extinguishing agent in portable and built in fire extinguishing systems, [7, 8].

The most familiar uses of carbon dioxide are in soft drinks and beer. This carbon dioxide will make the drinks and beer fizzy. Carbon dioxide is released by baking powder or yeast which makes cake rise. The other application is its use in some fire extinguishers because it is denser than air. Carbon dioxide acts as a blanket in a fire because it prevents oxygen from getting to the fire and as a result, the burning material is deprived of the oxygen it needs to continue burning. Carbon dioxide is also used in arc welding where it acts as inert gas. Liquid carbon dioxide is a good solvent for many organic compounds and used to remove caffeine from coffee. Lately, carbon dioxide is used in supercritical fluids extraction technology, [9,10,11].

2.0 EXPERIMENTAL TEST RIG AND METHODOLOGY

The experimental test rig for the CO_2 liquefier consists of a compressor, a heat exchanger, an expansion valve, a one way valve and liquid reservoir as shown in Figure 1. The compressor is basically a single stage gas booster, typically use for low temperature application. The bottled carbon dioxide is used as the supply gas. The initial supply condition of carbon dioxide was at a pressure of 50 bar and a temperature of 30^{o}C. The R134a chiller and CO_2 condenser are counter flow-type heat exchangers with concentric dual tubes. Ethylene glycol and water mixture (40:60 by mass) was used as a secondary heat transfer fluid in the chiller. The liquid reservoir is used to collect the liquid carbon dioxide. The diameter of the reservoir is 11.5 cm while the height is 13.5 cm.

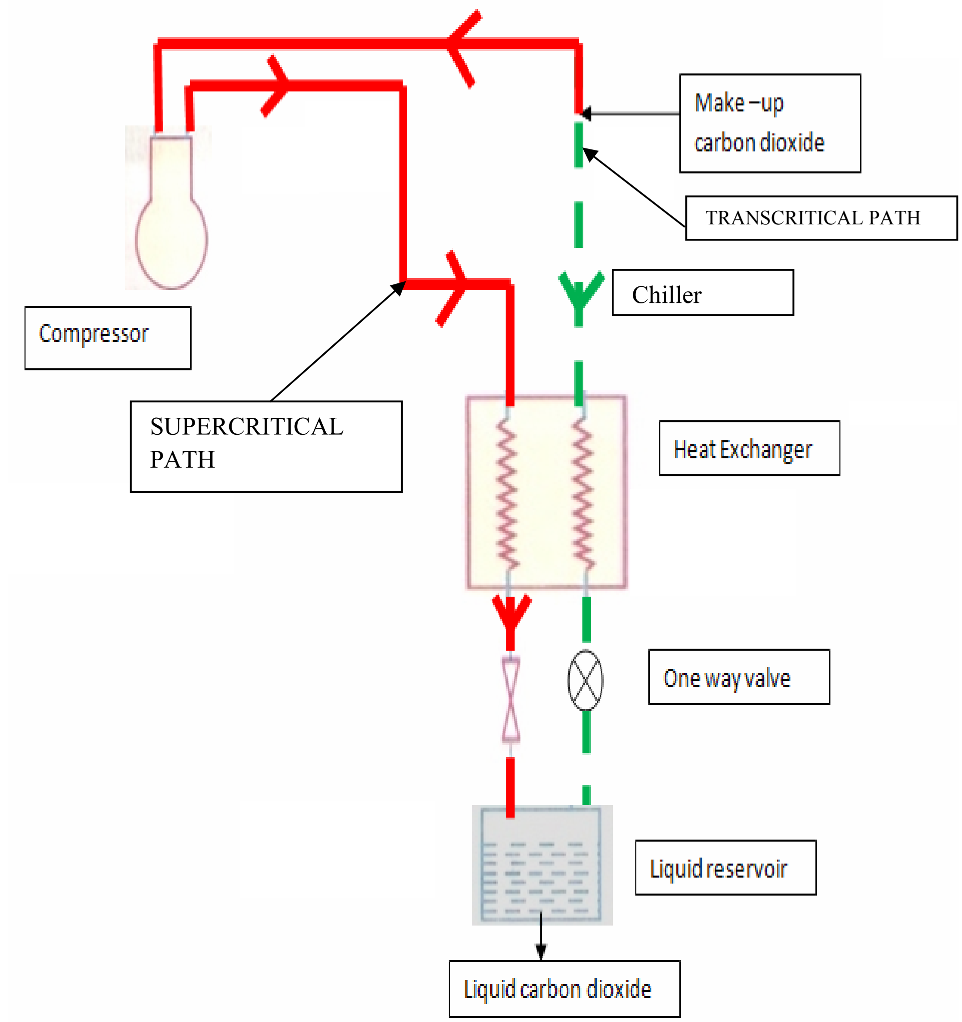

Figure 1 : Schematic diagram of liquidification of carbon dioxide

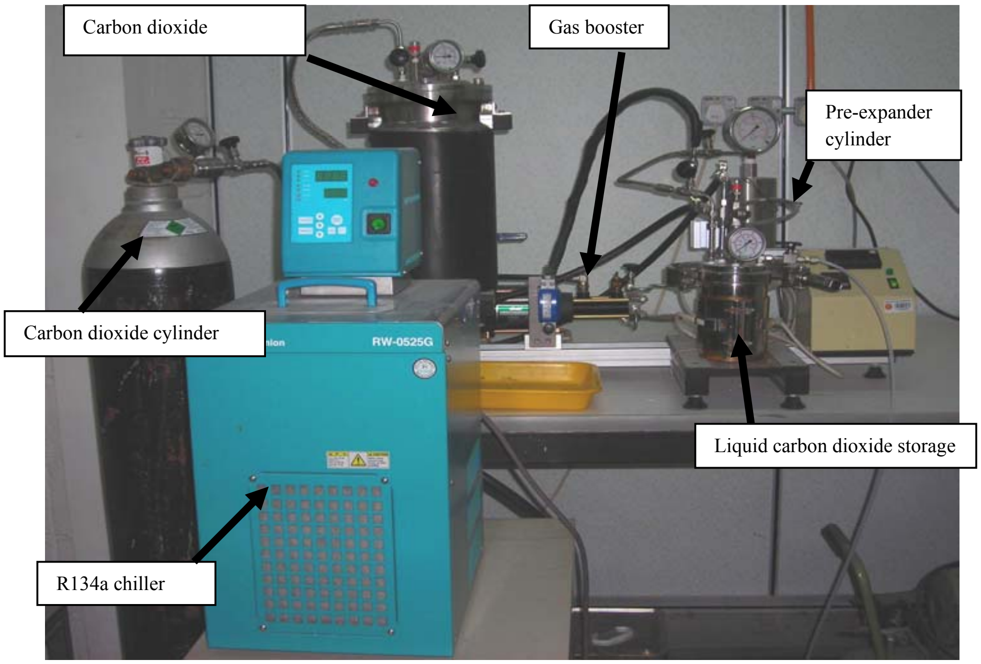

Figure 2 : The apparatus used for the liquidification of Carbon Dioxide.

The normal procedures to liquefy carbon dioxide gas are as follows:

i. Compressing the supply gas to a pressure at least equal to its critical pressure

ii. Cooling the compressed gas to produce cold supercritical fluid.

iii. Expanding the cold supercritical liquid to produce liquid carbon dioxide.

iv. The liquid carbon dioxide is collected as the desired product.

Initial test was performed to obtain the mass flow rate of carbon dioxide at supply pressure of 50 bars. The supply coolant temperature of chiller was varied from -15°C to 7°C. The volumetric flow rate of carbon dioxide was taken at various chiller temperatures before condensation. These values are used to determine the mass flow rate through the compressor. The cooling capacity was measured by the heat loss in the vessel and the work input to the compressor was calculated. Rotating speed of the compressor was kept at about 770 rpm. When the variation of temperature measurement was within ±0.3°C, the pressure measurement was within ± 5 kPa and the change of the flow rate of carbon dioxide was within ± 0.01 ml/min, the system was assumed to be at steady state and experiment data were collected. The start up time required was about 1 hour. Figure 2 shows the apparatus for liquidification of carbon dioxide which is situated at the Zeolite Laboratory, Universiti Teknologi Malaysia

There are three techniques to liquefy the carbon dioxide gas. Figure 3 shows the experimental path using heat exchanger (transcritical path) to obtain the liquid carbon dioxide. Using both compressor and heat exchanger (supercritical path) also liquefies the carbon dioxide gas as shown in Figure 4. Comparison studies were done using the combination of both transcritical and supercritical path as shown in Figure 5.

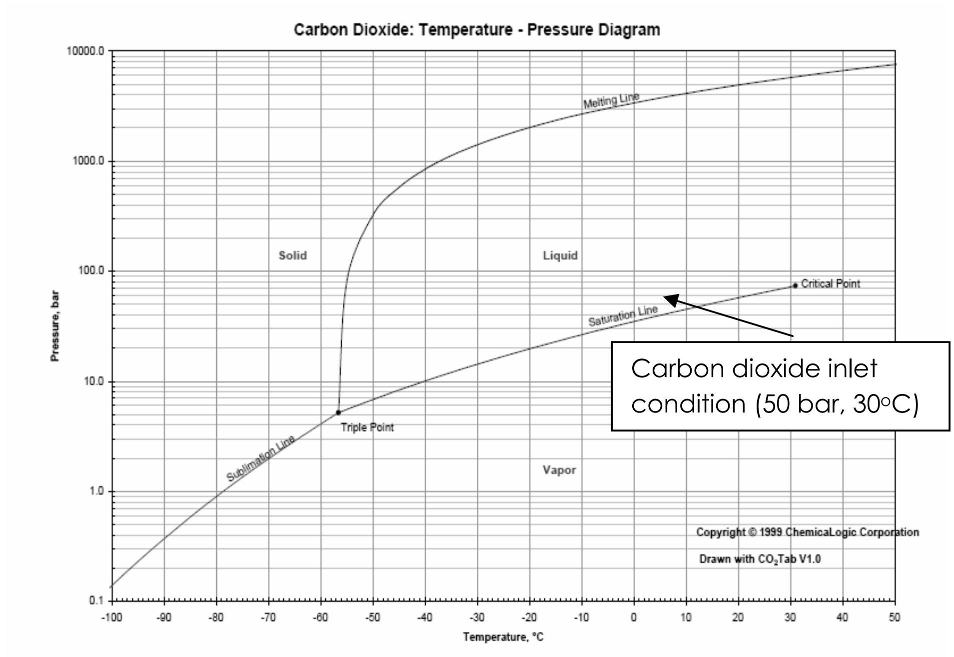

Figure 3 : Carbon dioxide pressure-temperature phase diagram for liquefaction using heat exchanger (transcritical path).

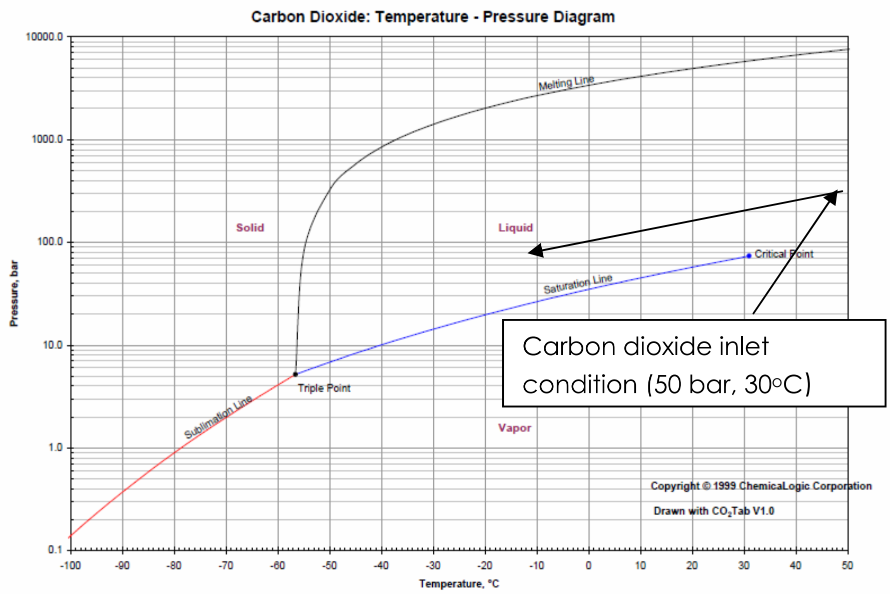

Figure 4 : Carbon dioxide pressure-temperature phase diagram for liquefaction using compressor and heat exchanger (supercritical path).

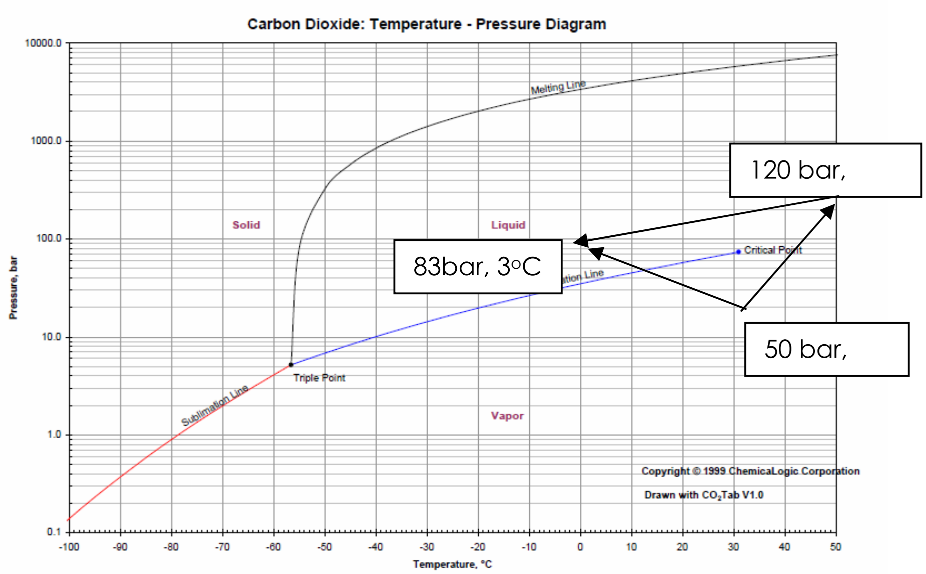

Figure 5 : Carbon dioxide pressure-temperature phase diagram for liquefaction using both of transcritical and supercritical path.

3.0 RESULT AND DISCUSSION

The three parameters that were studied are the liquefied mass flow rate, efficiency of carbon dioxide liquefier and liquid reservoir temperature.

3.1 Mass Flow Rate through the Compressor.

The mass flow rate through the compressor is required because it is used to calculate the efficiency of carbon dioxide liquefier. The mass input is measured from the carbon dioxide cylinder by using volume flow meter. The data collected during the experiments are shown in Table 1

Table 1: Mass flow rate through the compressor.

Experiment No	Chiller temperature,T (^oC)	Volumetric flow rate (ml/min)	Density (kg/m^3)	Mass flow rate through compressor (kg/s)
1	-15	300	681	0.003405
2	-10	410	681	0.00465
3	0	400	681	0.00454
4	5	375	681	0.00426
5	7	150	681	0.00170

3.2 Liquefying using Compressor and Heat Exchanger (Supercritical path).

The steps required to liquefy carbon dioxide gas for this technique is to compress the supply gas to a pressure of at least equal to its critical pressure and then cooling the compressed gas to produce the cooled supercritical fluid. After that, expanding the cooled supercritical fluid to produce liquid carbon dioxide and lastly the liquid carbon dioxide is collected as the desired product. The data collected for the experiments are shown in Table 2 and Table 3. The efficiency of CO_2 liquefaction was evaluated using the ratio of the theoretical compression work to the actual compression work. The carbon dioxide pressure enthalphy diagram was used to evaluate the theoretical compression work.

Table 2: Total mass flow rate liquefied using compressor and heat exchanger (supercritical path).

Experiment No.	Chiller temperature, T (°C)	Compressor outlet pressure, (bar)	Liquid reservoir pressure, (bar)	Liquid reservoir temperature, (°C)	Level CO_2 Liquefied (cm)	Volume CO_2 liquefied (ml)	Time CO_2 liquefied (sec)	Volume flow rate, (m^3/s)	Density, ρ2 (kg/m^3)	Total mass flow rate liquefied, (kg/s)
1	-15	120	90	-10	11	800	77	0.0000103	895	0.0093
2	-10	100	85	-8	9	700	63	0.0000111	875	0.0097
3	0	90	80	-2	8	650	48	0.0000135	845	0.0114
4	5	85	75	6	6.2	500	36	0.0000138	785	0.0109
5	7	80	70	10	4.5	300	22	0.0000136	775	0.0105

Table 3: Efficiency of CO_2 liquefier using compressor and heat exchanger (supercritical path).

Experiment No	Chiller Temperature,T (^{0}C)	W theoretical (kW)	W actual (kW)	Efficiency of CO_2 liquefier
1	-15	0.0413	0.4184	0.10
2	-10	0.0830	0.3880	0.21
3	0	0.1264	0.3990	0.32
4	5	0.0786	0.3270	0.24
5	7	0.0329	0.2100	0.15

3.3 Liquefying using Heat Exchanger only

The technique to liquefy carbon dioxide gas using heat exchanger only, consist of varying the supply gas to a pressure until its critical pressure and cooling the gas to produce cooled supercritical fluid. The cooled supercritical fluid becomes supercritical liquid and finally the liquid carbon dioxide is collected as the desired product. The data collected during the experiments are shown in Table 4 and Table 5.

Table 4: Total mass flow rate using heat exchanger only

Experiment No	Chiller temperature, T (^oC)	Chiller vessel pressure, (bar)	Volume flow rate, (ml/min)	Liquid reservoir pressure, (bar)	Liquid reservoir temperature, (^oC)	Level CO_2 liquefied (cm)	Volume CO_2 liquefied (ml)	Time CO_2 liquefied (sec)	Volume flow rate, (m^3/s)	Density, ρ2 (kg/m^3)	Total mass flow rate liquefied, (kg/s)
1	-15	25	300	100	-9	12	900	90	0.0000100	890	0.0089
2	-10	30	250	90	-6	11	850	75	0.0000113	860	0.0098
3	0	40	200	85	2	10	800	60	0.0000133	850	0.0113
4	5	46	170	80	8	8	650	45	0.0000144	760	0.0110
5	7	50	150	70	12	6	400	30	0.0000133	780	0.0104

Table 5 : Efficiency of CO_2 liquefier using heat exchanger only

Experiment No	Chiller temperature,T (^oC)	W theoretical (kW)	W actual (kW)	Efficiency of CO_2 liquefier
1	-15	0.0144	0.1100	0.13
2	-10	0.0578	0.1960	0.29
3	0	0.0343	0.1130	0.45
4	5	0.0415	0.1248	0.33
5	7	0.0343	0.1130	0.30

3.4 Liquefying Using Combination of Both Compressor and Heat Exchangers

The technique to liquefy carbon dioxide gas using a combination of both the heat exchangers and compressor involves simultaneous application to produce the supercritical liquid and finally the liquid is collected as the desired product. The purpose of using this technique is to compare the performance of liquefaction of carbon dioxide without combination and with combination of both compressor and heat exchangers. The data collected during the experiments are shown in Table 6 and Table 7.

Table 6 : Total mass flow rate liquefied using both transcritical and supercritical path.

Exp No.	Chiller temperature, (°C)	Compressor outlet pressure, (bar)	Chiller Vessel Pressure, (bar)	Volume flowrate, (ml/min)	Liquid reservoir pressure, (bar)	Liquid reservoir temperature, (°C)	Level CO_2 Liquefied (cm)	Volume CO_2 liquefied (ml)	Time CO_2 liquefied (s)	Volume flow rate, (m^3/s)	Density, ρ2 (kg/m^3)	Total mass flow rate liquefied, (kg/s)
1	-15	120	25	300	95	-7	12	900	86	0.000023	894	0.0209
2	-10	100	30	250	88	-4	10	800	69	0.000025	868	0.0219
3	0	90	40	200	83	3	9	750	54	0.000027	848	0.0227
4	5	85	46	170	78	11	7	700	41	0.000026	773	0.0195
5	7	80	50	150	70	14	5.3	500	26	0.000022	778	0.0182

Table 7 : Efficiency of CO_2 liquefier using both transcritical and supercritical path.

Experiment No	Chiller temperature,T (^oC)	W theoretical (kW)	W actual (kW)	Efficiency of CO_2 liquefier
1	-15	0.0236	0.0590	0.4
2	-10	0.0704	0.1303	0.54
3	0	0.0804	0.1044	0.77
4	5	0.0465	0.0877	0.53
5	7	0.0372	0.1328	0.28

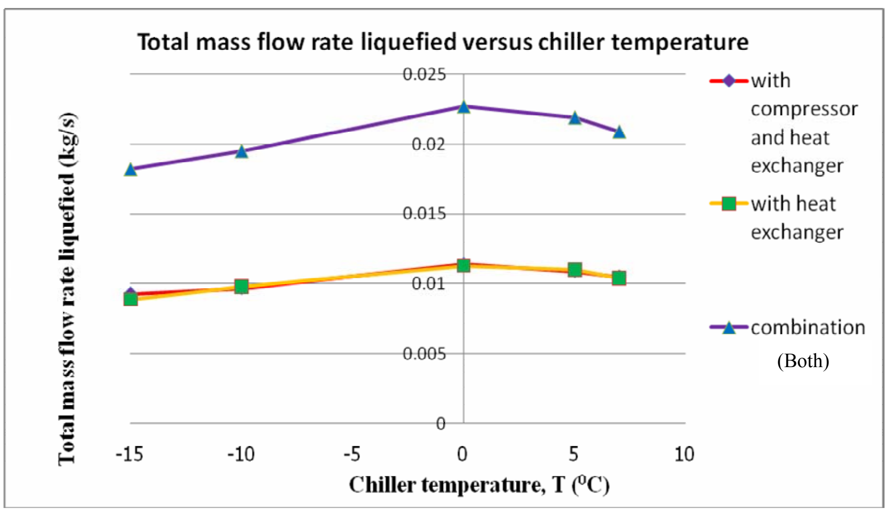

Figure 7 The total mass flow rate liquefied versus chiller temperature

Figure 7 shows mass flow rate of the carbon dioxide varies with the chiller temperature for all techniques described earlier. The carbon dioxide mass flow rate liquefied using heat exchanger or without heat exchanger increases when the chiller temperature increases up to maximum at 0^oC. This happens due to the thermodynamic conditions at the compressor suction increases causing a compression work to increase due to decreasing of density of the carbon dioxide when the chiller temperature changes. The refrigerant temperature at the compressor suction increases with the carbon dioxide specific volume consequently the mass flow rate increases.

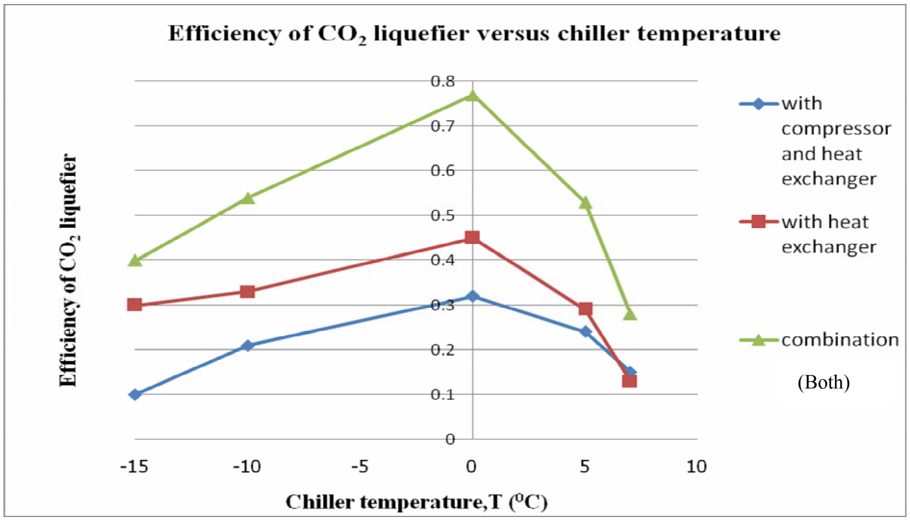

Figure 8 The efficiency of CO_2 liquefier versus chiller temperature

In Figure 8 the efficiency of CO_2 liquefier versus the chiller temperature is presented, for heat exchanger only, compressor and heat exchanger and the combination mode. The efficiency of CO_2 using heat exchanger only, is better compared with the use of the chiller and compressor. Using the heat exchanger, the carbon dioxide is further supercooled so that the fluid can be completely in the liquid phase. When the heat exchanger is not used, the supercooling is avoided at the suction of the compressor and therefore the enthalpy vaporization decreased. It is important that the measured efficiency of carbon dioxide liquefier is used in this experiment and using other design it could obtain different efficiency of liquefier values.

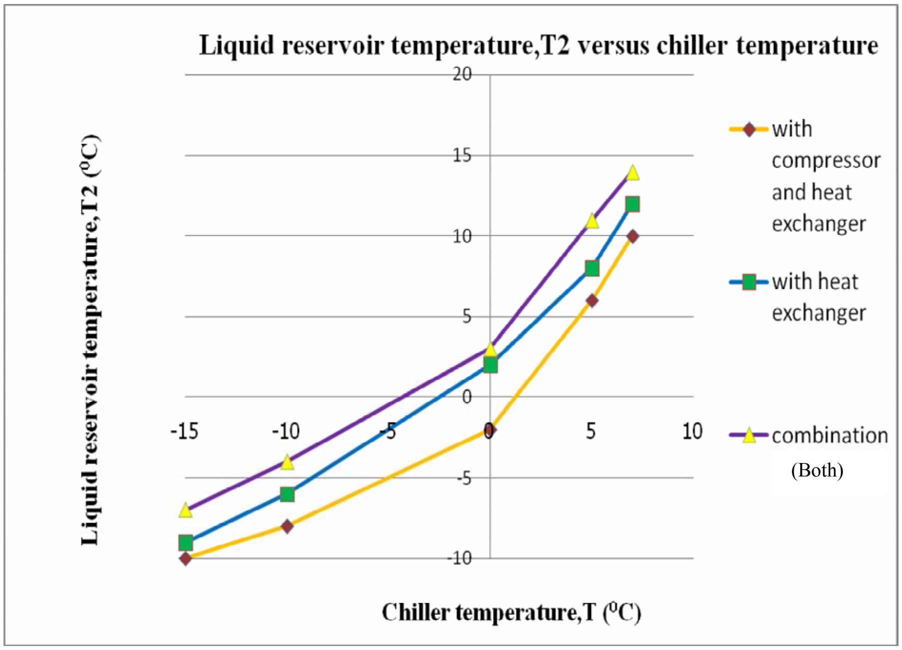

Figure 9 The liquid reservoir temperature versus chiller temperature

Figure 9 indicates that the liquid reservoir temperature remained approximately constant during the tests both when the experiment runs with and without heat exchanger. It is due to the small oscillations at the chiller inlet and air compressor inlet. The maximum carbon dioxide temperature at the discharge compressor line has been about 110°C. This value has been carried out without using heat exchanger which has caused a further superheating of carbon dioxide before it enters in the compressor.

4.0 CONCLUSION

As mentioned earlier in the introduction, the purpose of this study was to liquefy the carbon dioxide gas using appropriate cryogenic system. This study has shown that the total mass flowrate of liquefied fluid can achieve 0.0227 kg/s with pressure and temperature of 83 bars and 4°C respectively. The best mode to liquefy the carbon dioxide gas is by using the simultaneous both transcritical and supercritical path as compared to individual path. The performance test shows that the liquefied temperature increases with the efficiency of carbon dioxide liquefier as the compressor power decreased. Furthermore, as the mass rate liquefied increased, the efficiency of carbon dioxide liquefier also increased until optimum condition at 0°C.

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