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CHARACTERISTICS AND COP CASCADE REFRIGERATION SYSTEM USING HYDROCARBON REFRIGERANT (PROPANE, ETHANE AND CO_2) AT LOW TEMPERATURE CIRCUIT (LTC)

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ABSTRACT
Global warming is a very pertinent issue these days because the effects of extreme climate change are becoming quite apparent. Therefore, the first problem to address is the formation of strict regulations regarding emissions into the air. The main emissions to tackle are CFC and HCFC refrigerants. Conventional cascade refrigeration systems until now have been dependent on refrigerants and it is time to find a substitute that is environmentally friendly. This study builds a prototype cascade refrigeration machine using the environmentally friendly hydrocarbon refrigerants (propane, ethane and CO_2). Resulting from this research, the characteristics of the pressure and temperature of each component and the COP value at low temperature circuit of load variations using an electric heater at 90 W, 120 W and 150 W result in a COP value of 0.35, 0.48 and 0.60 respectively.

Keywords: Cascade Refrigeration; CO_2; Ethane; Propane; Refrigerant

1. INTRODUCTION
In recent decades many countries have paid more attention to environmental pollution caused by various kinds of fuel use and CFC. Burning fossil fuels cause water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2) in the atmosphere to absorb radiation, leading to increased global warming. Furthermore, gases emitted from several industries especially containing perfluorocarbons (PFC) derivatives such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFCs), methane (CH_4), sulfur hexafluoride (SF_6) etc. have also led to a more serious increase in global warming. The phenomenon of gas in atmosphere that absorbs and emits radiation within the thermal infrared range is called a greenhouse gas (GHG), while the relative measure of how much heat a GHG traps in the atmosphere is defined as the Global Warming Potential (GWP). It compares the amount of heat trapped to the amount of heat trapped by CO_2. GHGs act as a blanket of solar radiation on the earth's surface, thus making the average global temperature increase. It can be concluded that the more GHGs produced, the higher the average global temperature. CFCs and HCFCs used by conventional refrigeration systems not only have a global warming potential (GWP), but also have a high value of ozone depleting potential (ODP).

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Biomedical preservation requires cold storage for storing biological specimens like stem cells, sperm, blood and other organs. To prevent damage to biomedical specimens, it is necessary to achieve a storage temperature of around -80^{o}C. For long-term storage of biological materials, temperatures below -120^{o}C are generally considered to provide safety from the effects of devitrification and crystal growth (ASHRAE Handbook 2006). The use of a single-cycle refrigeration system is only able to achieve effective cooling of about -40^{o}C, and the efficiency begins to deteriorate under -35^{o}C because of a lower evaporation pressure. Thus, in order to reach a lower temperature, a cascade refrigeration system is used (Wu et al., 2007). Cascade refrigeration systems consist of at least two refrigeration systems that work independently. The two refrigeration systems are connected by a cascade heat exchanger where heat is released in the condenser low-temperature circuit (LTC) and is absorbed from the evaporator high temperature circuit (HTC) (ASHRAE Handbook 2006).

Meanwhile, low-temperature circuit cascade refrigeration systems still use ozone-depleting or global warming (CFC and HCFC) refrigerants. Thus, there is a preference for an alternative refrigerant that natural, and one of them is carbon dioxide (Lee et al., 2006). Carbon dioxide is non-toxic, is nonflammable, is easily obtained, does not damage the ozone and has very low global warming potential (Cox, 2007). However, the high pressure and temperature required of the triple block of carbon dioxide when used for a low-temperature circuit is undesirable (Niu et al., 2007). One way to overcome this deficiency is to mix carbon dioxide with another natural refrigerant such as hydrocarbon. For low temperature applications beside R23, ethane has a better refrigeration effect and performance (Rahadiyan, 2007). A mixture of carbon dioxide and ethane is a promising alternative refrigerant. Simulation studies and experiments indicate a mixture of carbon dioxide and ethane is able to achieve the minimum temperature of -80^{o}C (Nasruddin et al., 2011; Nasruddin et al., 2012). Propane shows the best performance compared to R410a and R134a, while R744 (CO_2) is inflammable and a green refrigerant.

Nasruddin et al. (2011) concluded that the operational parameter of cascade refrigeration system is influenced by refrigerant composition. On cascade refrigeration experiments, Nasruddin et al. (2012) used 70% R170 mixed with 30% R744 as the refrigerant on 6 meters and 0,054 inch capilarry tube. The expansion pressure was 1.88 bars, the refrigerant evaporates at temperature –81^{o}C and surrounding (box) temperature could reach –79.5^{o}C. Alhamid et al. (2010) also mentioned that the mixture of carbon dioxide, and ethane-propane on the cascade system is a prospective candidate and a solution to the HFC refrigerant, while the mass flow rate should be controlled to be optimum in order to get the maximum COP.

This study has the objective to develop a low temperature cold storage with a refrigerant mixture of carbon dioxide and ethane that has high energy efficiency and is safe, meaning it has low flammability and is non-toxic for use in a low-temperature circuit in a cascade refrigeration system whose application is aimed at the biomedical field and most importantly this refrigerant is environmentally friendly.

2. EXPERIMENTAL

The prototype cascade refrigeration machine consists of two refrigeration circuits, the first is the high-temperature circuit (HTC) using environmentally friendly refrigerant propane (R290) and the second is the low temperature circuit (LTC) which uses refrigerant mixture R744/R170. Both systems are connected to the cascade condenser plate heat exchangers. The system consists of a cascade refrigeration compressor, oil separator, condenser, plate heat exchanger, filter dryers, expansion valves, capillary tube, evaporator, and accumulator, ASHRAE Handbook (2006).

The components can be seen in Figure 1 below. The cascade refrigeration system is located at the University of Indonesia. This system uses two compressors with equal capacity of 1 HP. HTC uses an expansion valve as the expansion device while LTC uses capillary. The different expansion devices of HTC and LTC are due to the fact that working pressures are not the same between the two circuits. The working principle between HTC and LTC are the same as a refrigeration cycle in general.

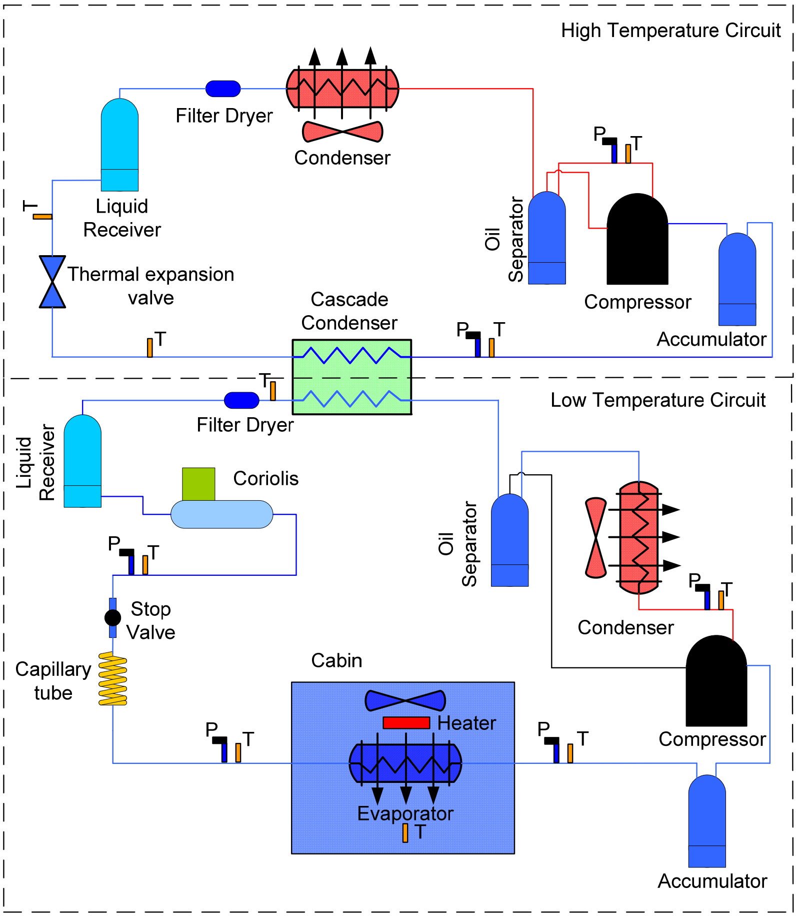

Figure 1 Cascade refrigeration system

At HTC discharge, the refrigerant and oil from the compressor goes into the oil separator and then the high pressure refrigerant gas phases goes towards the condenser. The refrigerant changes its state to liquid in the condenser. The condensation temperature is assumed to be the same as the ambient temperature. Then the refrigerant goes through the condenser refrigerant dryer and is filtered before heading into the expansion valve. The refrigerant evaporates and takes the heat from the condenser at plate heat exchanger (PHE), then the refrigerant is returned to the compressor. Temperatures were measured at the high temperature circuit at four locations i.e. at the outlet of compressor and condenser exit; and at the inlet of heading PHE and the compressor. Temperatures were measured by a thermocouple type K with the value of reading ± 0.14% accuracy. Meanwhile pressure was measured only at the discharge and suction locations. Pressure measurements were taken with a pressure transmitter type Druck PTX 1400 with readings of ± 0.15% accuracy.

At LTC, the refrigerant should be cooled before entering the condenser, to ensure the oil enters the oil separator in the liquid phase so as not to be carried to the expansion device. Once out of the oil separator it moves into the condenser refrigerant cascade (PHE) at a reduced-temperature below 10°C which aims to convert the CO_2 into a liquid phase with low pressure. Then the refrigerant passes through the filter dryer before heading to the capillary tube to be expanded according to the desired temperature. The preferred temperature of this low temperature circuit system is below-60^{o}C. This low temperature refrigerant enters into the evaporator inside a box, where there is a fan blowing air into the evaporator and a heater which is used to adjust cooling load. The box is made of styrofoam with a thickness of 40 mm. Then after the evaporator refrigerant flows into the accumulator, it returns into the compressor. The location of temperature measurements are at the inlet and outlet of compressor; PHE; evaporator; in front of the capillary tube and inside the box. Measuring the rate of the refrigerant using a coriolis mass has an accuracy of ± 0.1% reading. Data obtained from the test results of the refrigeration system performance are in the form of pressure, temperature and mass flow rate, and will be used as the design and operating parameters of a cascade refrigeration system.

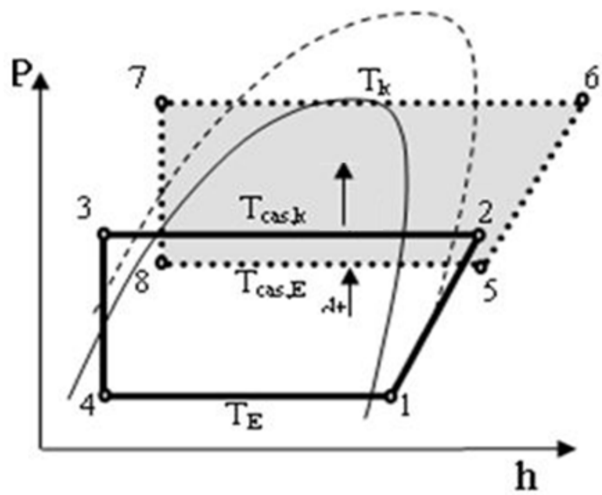

Figure 2 P-h diagram cascade refrigeration

The model consists of three equations based on classical thermodynamic processes in a cascade refrigeration machine. By referring at Figure 2 above, some stated points shown in the picture are the equations used for the thermodynamic analysis. These three equations are as follows:

Capacity evaporation cascade refrigeration system is defined as:

$$\dot{Q}_E = \dot{m}_r (h_1 - h_4) \tag{1}$$

Compressor power needed for low-temperature circuit is:

$$\dot{W}_r = \dot{m}_r (h_2 - h_1) \tag{2}$$

So the performance is measured using a cascade refrigeration machine Coefficient of Performance (COP) at low temperature circuit:

$$COP = \frac{\dot{Q}_E}{\dot{W}_r} \tag{3}$$

Then testing is done by varying the cooling load at the low temperature circuit. The variation of cooling load are at 90 Watts, 120 Watts, and 150 Watts. Once all the parameters of pressure, mass flow rate of refrigerant in the LTC, and box temperature is obtained, the value of the COP cascade refrigeration system at LTC can be calculated. Thermophysical properties of the refrigerant are derived from the software REFPROP 8.

3. RESULTS AND DISCUSSION

The experimental results show that the use of a refrigerant mixture of CO_2 and ethane at the low temperature circuit and then the use of a capillary tube expansion device with a diameter of 0.054 inch and 6 meters length can reach temperatures below -60^{o}C in the evaporator.

The cascade system was tested at temperature higher than 201 K, Boulian (2007) reviewed R744/R290 blending of R744/R290 (71/29, mole fraction) was good cycle performance compared and good substitute for R13 when the temperature was higher than 201 K. At high temperature circuit, the refrigerant is propane and the expansion pressure is maintained at a constant of 2 bar. The characteristics of the cascade refrigeration system, especially in the low temperature circuit can be seen in Figures 3 through 10.

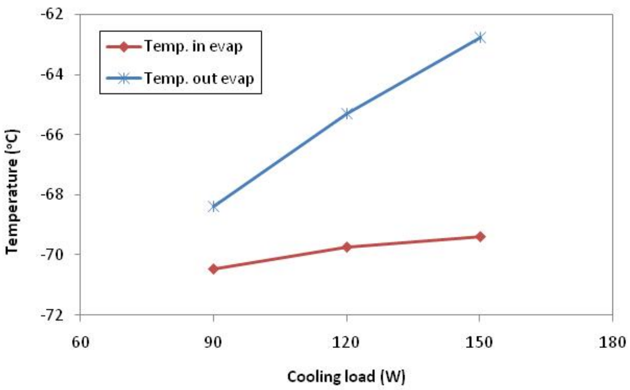

Figure 3 Inlet and outlet temperature at LTC evaporator

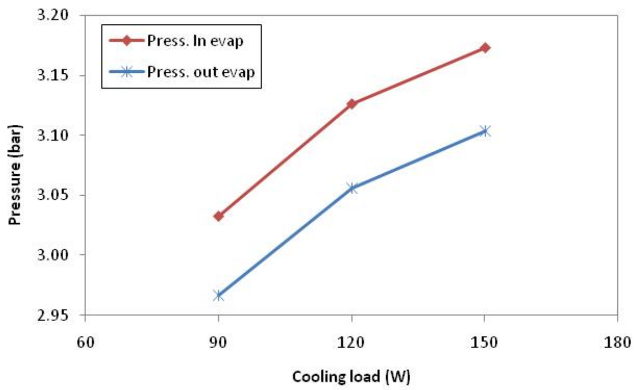

Figure 4 Inlet and outlet pressure at LTC evaporator

Figure 3 and Figure 4 above show the characteristics of the temperature and pressure at the inlet and outlet evaporator. At 90 Watt cooling load the temperature difference between inlet and outlet evaporator is 2.1^{o}C, while at a higher cooling load (150 Watts) the temperature difference becomes higher (6.6^{o}C). Increasing temperature difference is 68.2%. Meanwhile the percentage pressure drop of the cooling load of 90 watts to 150 watts is not too large, namely 2.1%. The characteristics of the temperature and pressure at the compressor inlet and outlet are shown in Figure 5 and Figure 6 below.

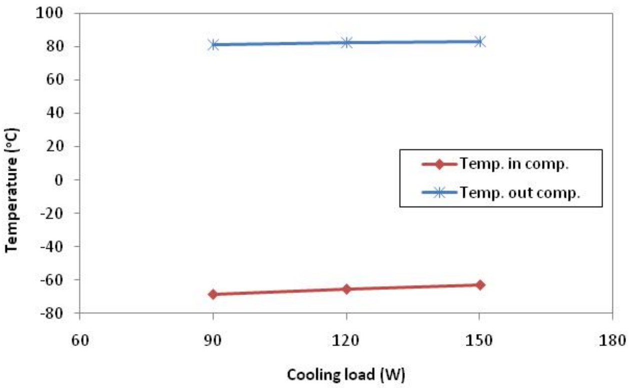

Figure 5 Inlet and outlet temperature at LTC compressor

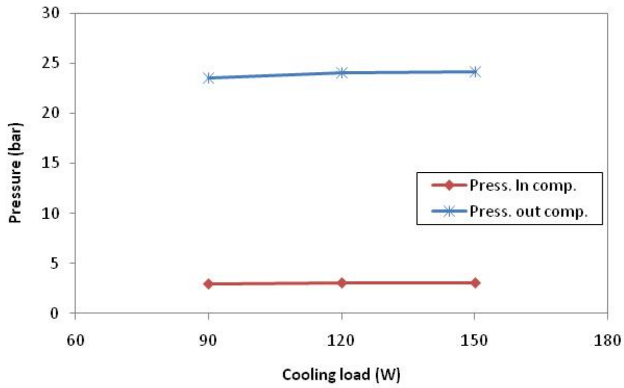

Figure 6 Inlet and outlet pressure at LTC compressor

The temperature difference at inlet and outlet compressor decreases when the cooling load increases from 90 Watts to 150 Watts and is equal to 2.4%. However, the increase of refrigerant pressure is compressed by 2.1%.

Figure 7 and Figure 8 show the characteristics of the temperature and pressure at the inlet and outlet condenser. The temperature difference increases when the cooling load increases from 90 Watts to 150 Watts and is equal to 1.3%. The pressure in the condenser increases when the cooling load increases from 90 Watts to 150 Watts.

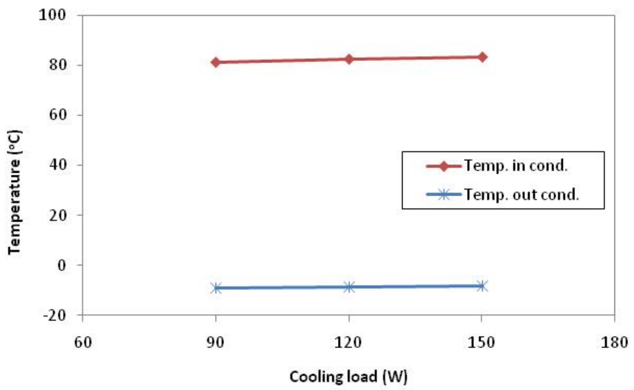

Figure 7 Inlet and outlet temperature at LTC condenser

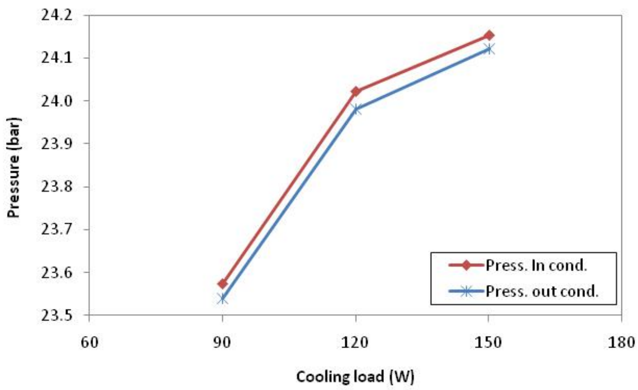

Figure 8 Inlet and outlet pressure at LTC condenser

Figure 9 and Figure 10 below show the temperature and pressure at the capillary tube. when the cooling load was increased from 90 Watts to 150 Watts, the expansion temperature and pressure increased insignificantly. This is due to the finding that the condensation and evaporation temperatures were almost at the same condition while the heat was taken by refrigerant as a function of the flow rate.

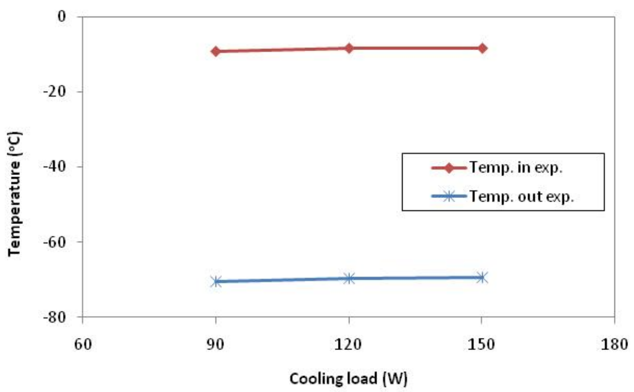

Figure 9 Inlet and outlet temperature at LTC expansion device

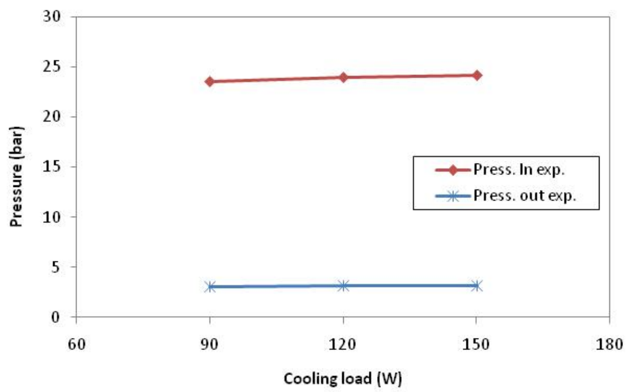

Figure 10 Inlet and outlet pressure at LTC expansion device

Figure 11 below shows the value of COP to changes in temperature evaporation in LTC. COP value decreases when the pressure has a lower evaporation level. The COP of cascaded system increases with rising refrigerated space temperature and decreases with rising heating outlet temperature as mentioned by Bhattacharyya et al. (2005). This happens because the lower evaporation temperature requires greater energy and it also affects the rate of the refrigerant mass to the lower temperature. When the compressor increases the energy level and decreases the value of cooling capacity it will decrease the value of the COP. Similar with Lee et al. (2010), the maximum COP increases with T_E, but decreases as T_C or ΔT increases.

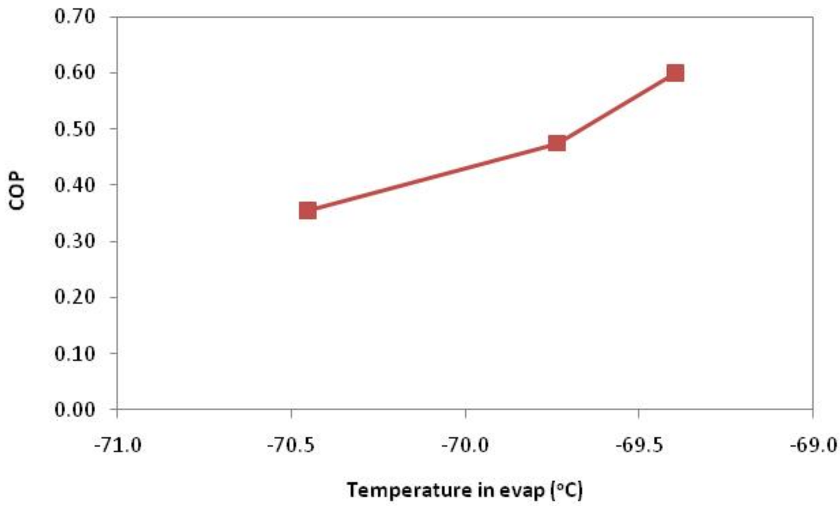

Figure 11 Effect of temperature changes on the value of COP

From Figure 12 it can be seen the effect of cooling load changes to the COP value in the LTC system. When the cooling load is 90 Watts COP in LTC system it is 0.35. The COP value will be increased to 0.48 after the cooling load in LTC is increased to 120 Watts. And then the COP value will be 0.60 when cooling load is 150 Watts. It means that the COP value will be increased when cooling load is added but this effect concerns the evaporator temperature that will be increased too.

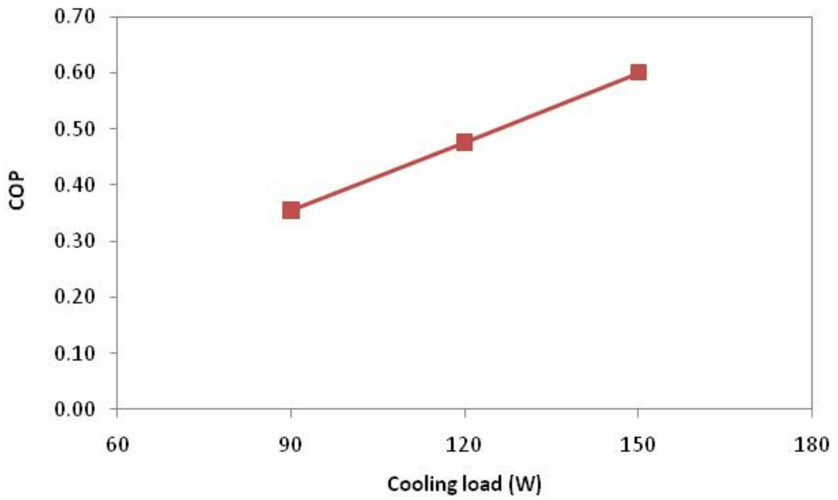

Figure 12 Effect of cooling load changes on the value of COP

Changing the rate of refrigerant mass flow rate in LTC is shown by Figure 13 below. The mass flow rate refrigerant in LTC systems influenced the evaporator temperature. When mass flow rate at LTC systems is low, the temperature in the evaporator will be low too.

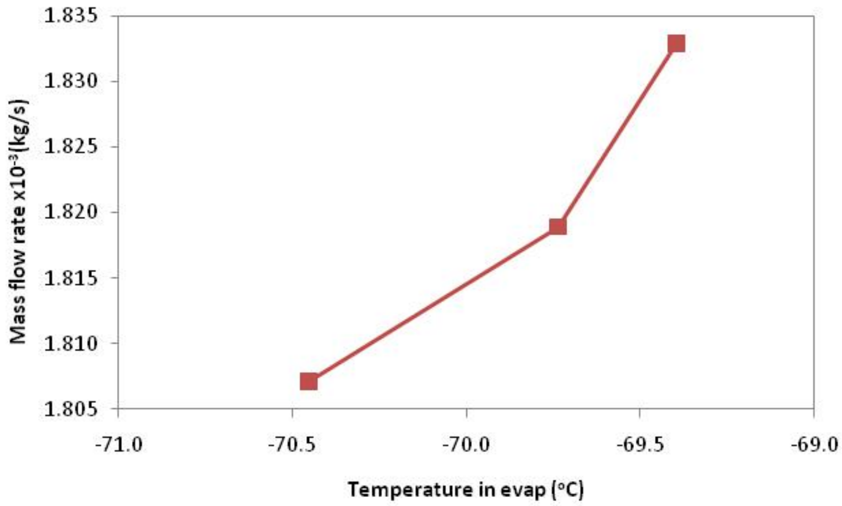

Figure 13 Effects of changes in temperature on mass flow rate in LTC

4. CONCLUSION

From the experimental results of cascade refrigeration system using a refrigerant mixture of CO_2 and ethane on LTC it was concluded that:

1. The increased cooling load, the evaporator inlet and outlet temperature difference will be increased, while the pressure difference is almost constant.
2. The COP values at LTC of the cooling loads are 90 Watts, 120 Watts and 150 Watts and result in 0.35, 0.48 and 0.60 respectively.

5. ACKNOWLEDGEMENT

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