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COP ENHANCEMENT OF VAPOUR COMPRESSION REFRIGERATION SYSTEM USING DEDICATED MECHANICAL SUBCOOLING CYCLE.

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ABSTRACT
This study focused on development of an improved vapour compression refrigeration system (IVCR system). Dedicated mechanical subcooling cycle is employed in attaining the developed IVCR system. The system is composed of two cycles cascade refrigeration system working with R134a. It consists of a rectangular shape with total storage space of 0.582 m^3, made of galvanized mild steel and internally insulated with 0.05 m polystyrene foam. Tests under a wide range operating temperature conditions were carried out on the developed IVCR system. Performance evaluation of the system was characterized in terms of cooling capacity and coefficient of performance (COP). Experimental results showed that the COP of the subcooled system improved better than that of the main system from 18.0% to about 33.5% over an evaporating temperature range of -10 to 30°C. It can be concluded that the use of dedicated sub cooling cycle in VCR system is more efficient and suitable for the betterment of thermal system performance.

Keywords: *Vapour compression Refrigeration system, Coefficient of performance, dedicated subcooled system, Condensation temperature, Evaporation temperature.*

1. INTRODUCTION

The rapidly growing world energy consumption has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc.). According to Xiaohui *et al. [1]*, Refrigeration systems consumed a large amount of energy in maintaining thermal comfort for occupants and suitable climatic conditions for cooling cases, which made up 50% of building energy consumption.

The ambient temperature of some region in West Africa countries like Nigeria is as high as 40°C and higher during the dry season. This necessitates ever increasing demand for ice blocks for cooling and preservation of food and drinks (Nasir *et al., [2]*). It is also interesting to point out that, high demand for ice blocks for cooling and preservation of food and drinks has created a booming business opportunity in cities, towns and villages across Nigeria. The process of transforming water to ice by refrigerating it below the freezing point of water 0°C is termed ice formation. This ice formation processes are common practice using vapour compression refrigeration system. It should be highlighted that a considerable part of the energy produced worldwide is consumed by refrigerators reported by [3]. Moreso, Oyebola, [4], in his study pointed out that some of the existing ice block making machines take 12 to 24 hours to form ice blocks. Nasir *et al.* [2]) also established that the time of freezing of the water is of considerable importance when designing an ice block making machine. With a view to reducing the time of cooling and freezing water in order to improve the performance of refrigeration system several researches have been carried out in the open literatures by various authors, such as ([5-8]), either with an attempt to produce a system that is both effective and environmental friendly, or addressing the energy consumption challenge being posed by compression-based heating and cooling systems, but no satisfactory effort has been made to achieve the optimum results in this regard. Thus, this research seeks to contribute to the findings on previous work done by earlier researchers on how

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subcooling can improve the performance of the refrigeration system.

In this study, dedicated mechanical subcooling is employed. Dedicated mechanical subcooling cycle employs a second vapor-compression cycle solely for the purpose of providing subcooling to the main refrigeration cycle. The subcooling cycle is coupled to the main cycle by the use of a subcooler located at the exit of the basic cycle condenser. The refrigerant in this case enters the evaporator with a lower enthalpy since it is subcooled somewhat before it enters the throttling valve. For this reason, the coefficient of performance (COP) of the subcooled vapour compression refrigeration system in which the subcooler acts as the evaporator for the subcooling cycle is significantly higher than that of the main refrigeration cycle. The focus of this research is to carry out experimental investigations of the employed dedicated mechanical subcooling cycle on the performance of the existing vapour compression system.

2. MATERIAL AND METHOD

2.1 Design Analysis of the improved Vapour Compression Refrigeration System

In this section, the design of each component of the refrigeration system is presented. The design analysis regarding the refrigeration cycle process flow investigated in this study is carried out using the Pressure-Enthalpy in Figure 1.

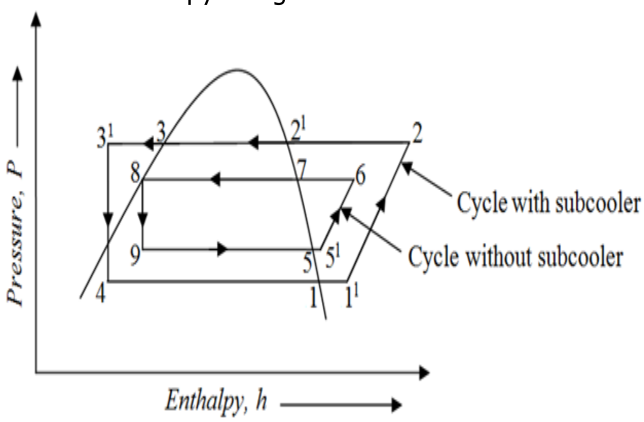


Figure 1: Pressure-enthalpy diagram of vapour compression refrigeration system with subcooled cycle

2.1.1 Evaporator Design and Analysis

The total energy, ($\dot{Q}_{ice}$), needed to freeze water from ambient temperature to its final desired temperature is given by:

$$\dot{Q}_{ice} = \dot{m}\left[Cp_{water}(T_a - T_0) + h_{fg} + Cp_{ice}(T_0 - T_1)\right] \quad (1)$$

where, $\dot{m}$ is the mass flow rate, Cp_{water} is the heat capacity of water, Cp_{ice} is the heat capacity of ice, T_a is the ambient temperature, T_0 is the freezing temperature, T_1 is the final temperature, h_{fg} is the enthalpy to freeze water

Thus, the rate at which heat is removed from the system refrigerated space in lieu of attaining and maintaining a desired temperature referred to Evaporator load, ($\dot{Q}_{Evap1}$) is obtained by Eq. (2) extracted from the study of Andrew *et al.*, [9] given as follow:

$$\dot{Q}_{Evap1} = \dot{Q}_U + \dot{Q}_L + \dot{Q}_S \quad (2)$$

where, $\dot{Q}_U$ is the usage load as a result of freezing, $\dot{Q}_L$ is the load due to leakages, $\dot{Q}_S$ is the supplementary load incorporated to account for the factor of safety and is defined to be 15% of the usage load as established by Abubakar *et al.* [10]

Hence,

$$\dot{Q}_U = \dot{Q}_{ice} \quad (3)$$

$$\dot{Q}_S = 0.15\dot{Q}_U \quad (4)$$

The term $\dot{Q}_L$ in Eq. (2) is obtained as follows:

$$\dot{Q}_L = \frac{A\Delta T}{R_T} \quad (5)$$

Where; $\Delta T = (T_1{}^1 - T_3)$ is the temperature difference between inlet and exit of the evaporator, A is the surface area of the evaporator and R_T is the total resistance of the insulators provided for system wall heat leakages.

2.1.2 Determination of the system Evaporator Length

The length of the evaporator pipe coiled round the freezing tube is obtained as follows:

$$L = \frac{\dot{Q}_{Evap1}}{\pi D U \Delta T} \quad (6)$$

where, L is the length of the evaporator pipe, A is the surface area of the evaporator, ΔT is the temperature difference between ambient and the fluid in the pipe. D is inside diameter of the evaporator tube and U is the overall heat transfer coefficient.

2.1.3 Determination of the System Product Load

The total heat absorbed through product load is given as:

$$D_{Total} = Q_1 + Q_2 + Q_3 \quad (7)$$

$$Q_1 = mc_{w1}(t_1 - t_2) \quad (8)$$

$$Q_2 = mh_{fg} \quad (9)$$

$$Q_3 mc_{w3}(t_2 + t_3) \quad (10)$$

where, Q_1 is sensible heat load above freezing of water,

Q_2, is the latent heat of freezing and Q_3 is the sensible heat load below freezing of water

c_{w1}, c_{w3} and h_{fg} are obtained as 3.94 kJ/kgk, 2.01 kJ/kgk and 310.24 kJ/kgk respectively.

2.1.4 Determination of the cooling system Compressor Power

The compressor power required by the sub-cooling system is estimated using Eq. (11) as follows:

$$P_{sub} = \dot{m}_{sub}(h_2 - h_{1^1}) \quad (11)$$

Where $\dot{m}_{sub}$, is the mass flow rate of the refrigerant in the main cycle compressor and subscripts 2 and 1^1 depicted in Figure 1 refer to the enthalpies of the refrigerant at the discharge and suction of the compressor

2.1.5 Selection of the system Condenser

In this work, the condensers were designed using logarithmic mean temperature difference (LMTD). The quantity of heat to be removed by the condenser during the condensation process is expressed mathematically as:

$$\dot{Q}_{cond1} = \dot{m}_{sub}(h_2 - h_{3^1}) \quad (12)$$

For the air-cooled condenser, the quantity of heat given out is expressed as:

$$\dot{Q} = AU\Delta T_{lm} \quad (13)$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\Delta T_1 / \Delta T_2\right)} \quad (14)$$

where, A is the surface area of the condenser, U is the overall heat transfer coefficient of the condenser (W/m^{2}K), ΔT_{lm} is the logarithmic mean temperature difference, ΔT_1 is the maximum temperature difference between the cooling fluid and condenser refrigerant (^{0}C), ΔT_2 is the minimum temperature difference between the cooling fluid and condenser refrigerant (^{0}C), $\dot{m}_{sub}$ is the mass flow rate of refrigerant entering the condenser (kg/s), h_2 is the enthalpy of compressed vapour entering the condenser (kg/kJ), h_{3^1} is the enthalpy of liquid leaving the condenser (kg/kJ).

2.1.6 Main Cycle System Condenser design

The rate of heat transfer between the refrigerant flowing through the main cycle is equal to the total heat coming from the subcooled condenser. Therefore, the total heat absorbed by the main cycle, $\dot{Q}_{main}$, is given in Eq. (15) as:

$$\dot{Q}_{main} = \dot{Q}_{cond1} \quad (15)$$

While the heat transfer rate from the sub-cooler cycle condenser is given by:

$$\dot{Q}_{cond1} = \dot{m}_{main}(h_{5^1} - h_9) \quad (16)$$

Where $\dot{m}_{main}$ is the mass flow rate of refrigerant entering the subcooler (kg/s).

It is interesting to highlight that, in this work, gross heat rejection, ambient temperature and condensing temperature as detailed above were carefully considered in designing the condensers. Thus, the commonly used type air-cooled condenser is selected in this study.

2.1.7 Main Cycle Compressor design

With reference to Figure 1, the compressor size of the subcooling cycle is obtained using Eq. (17) as follows:

$$\dot{W}_{main} = \dot{m}_{main}(h_6 - h_{5^1}) \quad (17)$$

Where;

h_{5^1} is the enthalpy of refrigerant at compressor suction,

h_6 is the enthalpy of refrigerant at compressor discharge.

2.1.8 Determination of the improved Vapour Compression Refrigeration System (IVCR system) Coefficient of Performance

The coefficient of performance (COP) of the improved Vapour Compression Refrigeration System is obtained as follows:

The COP of the main cycle of the cooling system defined as the COP at the same evaporator and condenser temperatures of the system is estimated using Eq. (18).

$$COP_{main} = \frac{Refrigerating\ effect}{work\ done\ by\ compressor} \quad (18)$$

The coefficient of performance of the improved Vapour Compression Refrigeration System is calculated as:

$$COP_{sub} = \frac{Q_{Csub}}{P_{sub}} \quad (19)$$

Where, Q_{Csub} and P_{sub} are obtained using Eqns. (11) and (12) respectively.

Thus, performance improvement of the system COP_{imp} is obtained using Eq. 20 as proposed by Xiaohui *et al*, [1] given by:

$$COP_{imp} = \frac{COP_{sub} - COP_{main}}{COP_{main}} \times 100\% \quad (20)$$

2.1.9 Materials selection for construction of the designed IVCR system

The selection of materials was based on its properties, availability, economic implication and ease of fabrication. Presented in Table 1 are the materials selected for development of a freezer-type subcooled vapour compression refrigeration system in this study.

Table 1: Material selection

Parts	Materials	Reasons for selection
Support frame	Mild steel	High tensile strength, availability
Lagging material	Polystyrene	Lightness, low thermal conductivity and durability
Refrigerant	R134a	Eco-friendly, availability, high COP, good compressor size requirement, non-flammability
Evaporator	Copper tube	Cost effectiveness, workability, high thermal conductivity, resistance to corrosion
Freezing chamber	Galvanized steel	Weldability and high thermal conductivity

Presented in Figs. 2, 3 and 4 are the isometric view, detailed drawing and exploded view of the designed IVCR system in this work. All drawings were carried out using Solidworks software package because of its extensive attributes that favor easy creation of excellent computer aided designs.

2.2 Working Principle of the IVCR system

In this work, dedicated mechanical subcooling cycle is employed to enhance the performance of the VCR system. Dedicated mechanical subcooling cycle uses a second vapor-compression cycle solely for the purpose of providing subcooling to the main refrigeration cycle. The subcooling cycle coupled to the main cycle by the use of a subcooler located at the exit of the main cycle condenser as presented in Fig 5.

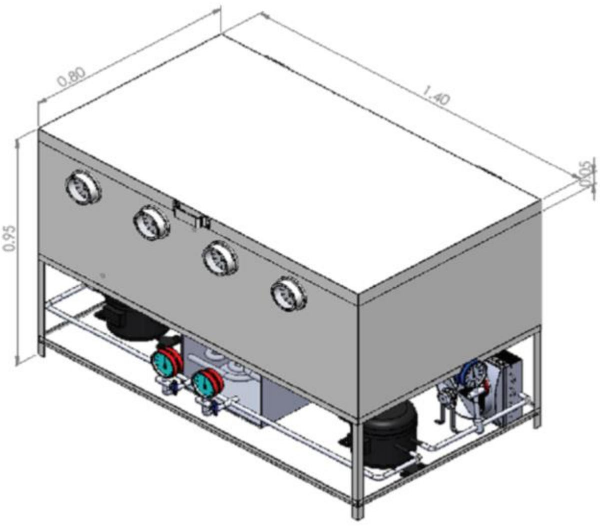
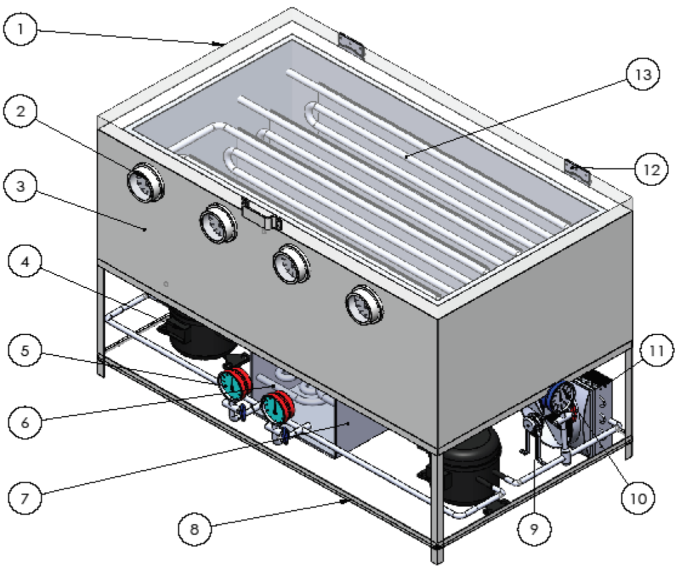
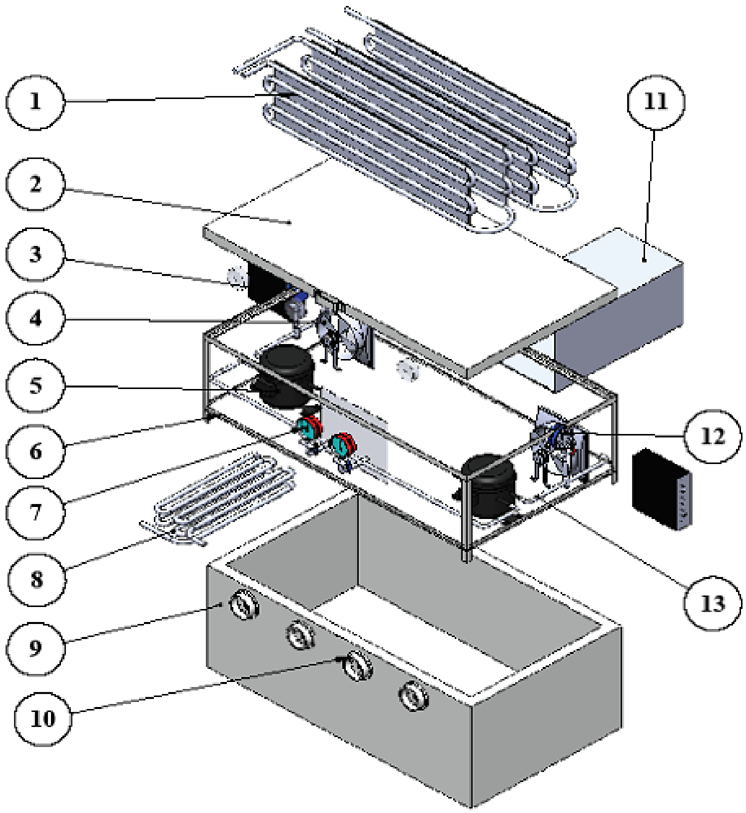


Figure 2: Isometric view of the designed freezer-type subcooled vapour compression refrigeration system



Part	Description
13	Main Evaporator
12	Cover Hing
11	Air-cooled Condenser
10	Pressure Gauge1
9	Condenser Fan
8	Frame
7	Subcooling Evaporator Housing
6	Subcooling Evaporatror
5	Pressure Gauge2
4	Compressor
3	Cooling Chamber Housing
2	Temperature Display
1	Cooling Housing Cover

Figure 3: Detailed view of the designed freezer-type subcooled vapour compression refrigeration system



ITEM NO.	PART DESCRIPTION	QUANTITY
1	Main Evaporator	1
2	Cooling Housing Cover	1
3	Air-cooled Condenser	2
4	Condenser Fan	2
5	Compressor	2
6	Frame	1
7	Pressure Gauge1	2
8	Subcooling Evaporator	1
9	Cooling Chamber Housing	1
10	Temperature Display	4
11	Subcooling Evaporator Housing	1
12	Pressure Gauge2	2
13	Piping	1

Figure 4: Exploded view of the developed freezer-type subcooled vapour compression refrigeration system

Figure 5 shows a schematic diagram of the improved vapour compression refrigeration system (IVCR system) with dedicated subcooling cycle. The components of the subcooling cycle are designed and coupled to the main VCR system. Process 2-3 (Condensation process) represents the removal of latent heat which changes the dry saturated refrigerant into liquid refrigerant. The process 3-4 represents the subcooling of the liquid refrigerant leaving the main VCR system condenser before passing through the expansion valve (4-5) for the onward throttling of the liquid refrigerant from the condenser pressure to the evaporator pressure and then evaporate in the evaporator (5-1), in this study these processes are enhanced using a dedicated subcooling cycle (6-7-8-9). With the dedicated subcooling modification, liquid refrigerant leaving the condenser is further cooled at constant pressure to an intermediate temperature, T_4, as shown in Figure 5. Finally, the vaporized refrigerant is circulated through the compressor (1-2) and then condensate in the condenser (2-3). In this way, less work is used to operate the compressor of the IVCR system and, consequently, enhance the performance of the system.

3. APPARATUS AND EXPERIMENTAL SET-UP

Figure 6 presents the IVCR system where the temperature measurements at evaporator and condenser unit of the system were performed. The CAD designs of the IVCR system was constructed as shown in plate 1. Plate 2 shows the cabinet (freezing chamber), loaded with 21.5 kg of water package into twenty-five pieces. The weight of each piece was 861.8 g.

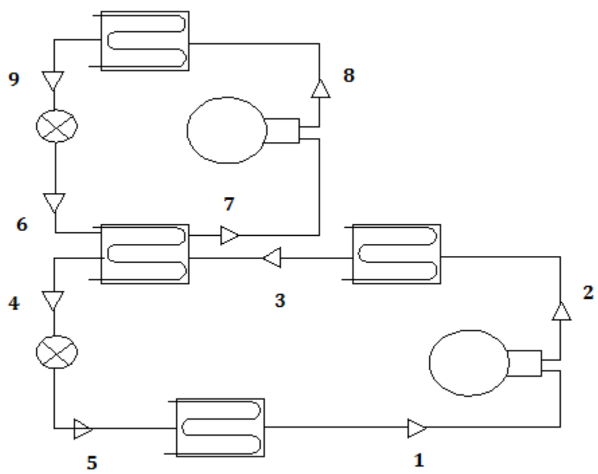


Figure 5: schematic diagram of the vapour compression refrigeration system with subcooling cycle.

The developed IVCR system freezer-type was tested under two conditions: (i) subcooled cycle in this case, the combine cycles made up subcooled cycle and main cycle was set in operation for durations of 12 hours while reading were taken at interval of 30 minutes. Similar experimental test and readings were observed for (ii) main cycle, that is, a condition when the subcooler section of the IVCR system was switched off leaving only the main cycle system in operation for 12 hours duration. The outcomes of the tested specimens using the developed cooling system are as shown in plate 3 and plate 4 respectively.

4. RESULTS AND DISCUSSION

Analyses of the experimental results obtained are presented in this section. The performance measures considered in the experimental test rig (Plate 1 and 3) are coefficient of performance, refrigerating effect, degree of sub-cooling, condensing temperature, evaporating temperature and cabinet temperature.

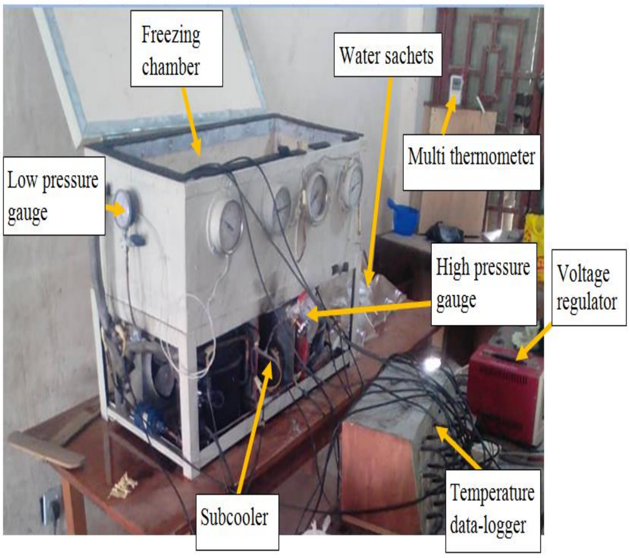


Plate 1: Experimental test rig for the developed IVCR system

Plate 2: An array of 25 sachets of water

Plate 3: Ice blocks formed within 11 hours of running the main VCR system

Plate 4: Ice blocks formed within 6 hours of running the sub-cooled system

Figure 6: Pictures of the experimental setup

4.1 Effect of Condensation Temperature on COP of the System

Fig 6 shows the graph of COPs of the main and sub-cooled system plotted obtained with time. Both COPs for main and sub-cooled systems increase at different rates as the condensation temperatures decrease from 56.5 to 56.9. The COP of the main system increased from 1.6 to 2.3 while the COP of the subcooled system increased from 1.8 to 2.9. This implies that the COP of the subcooled system improved better than that of the main system from 12.5% to 26.1% over a condensing temperature range of 56.5 to 56.9. This observation is similar to the trend observed by [11]. Basically, increase in the condensation temperature causes increase in the compressor power, this behavior is observed to be more pronounce with the tested main cycle system in this study thereby decreasing the system cooling capacity, and consequently decrease the COP of the system.

Figures 7 and 8 show the variation of evaporating temperature and the cabinet temperatures (refrigerated space temperatures) with time, respectively. As expected, both cycle temperatures decrease with increase in time. It can be noticed that over the same tested time duration, the main system attained a steady lower evaporating temperature of -3.9°C while an evaporating temperature as low as -9.4°C was observed for the subcooled system. This shows that the developed subcooled system has 141% faster cooling rate than the main system. This typical behavior is similar to those observed in the studies of Nasir *et al.* [2] and Kalyani *et al.* [12].

4.2 Effect of Evaporating Temperature on COP of the System

The obtained evaporating temperature effect on the system performance is presented in Figure 9. The result from this Figure showed that the coefficient of performance of the subcooled system increased from 2.6 to 3.0 compared to the obtained COP value of 2.1 to 2.3 observed for the main system under the same operating condition. This is similar to the trend observed by [11] and [13]. This observation demonstrates that power consumption per ton of refrigeration reduces as the evaporating temperature increases for the subcooled system consequently making the IVCR system to be more energy efficient and resulting in faster cooling rate than the basic system as displayed in Figure 6.

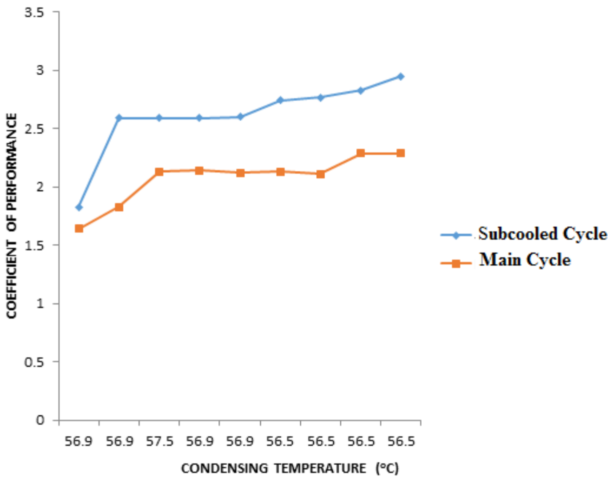


Figure 6: Variation of condensation temperature with COP of the system

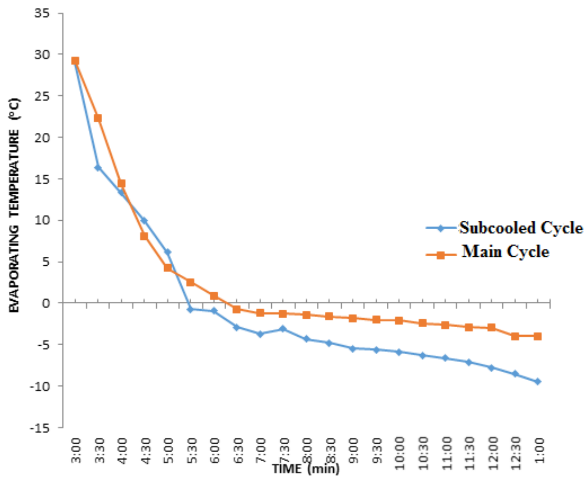


Fig 7: Variation of evaporation temperature with time

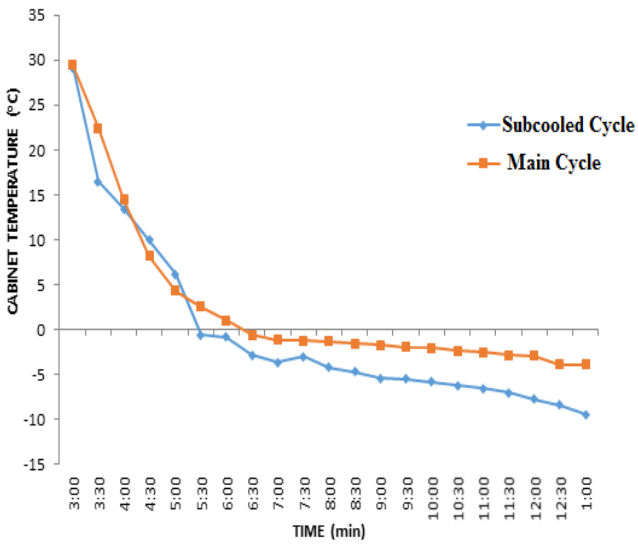


Figure 8: Variation of cabinet temperature with time

Similarly, the attained performance of both cycles relating to refrigerating effect displayed in Figure 10 revealed that as evaporation temperature increases from -5°C to 30°C the subcooled system has a better cooling capacity than the main system. This behavior is related to the fact that less work is used to operate the compressor of the IVCR system. Thus, dedicated subcooling modification is responsible for the betterment of the system performance.

The performance improvement of the developed subcooled system was obtained using equation 20. As shown in Figure 11, It can be seen that for the system increase in evaporating temperature, the COP improvement ratio increases from 18.0% to about 33.5%. This behavior is due to the reduction of the system condenser exit temperature consequently, caused an increase in the system subcooling degree and refrigerating effect. This result confirms better performance of the dedicated subcooling cycle VCR system compared to main cycle (convectional) VCR system.

5 CONCLUSION

This research work developed a subcooled freezer-type vapour compression refrigeration system (VCRS) using R134a as the refrigerant and appraised the developed system. Experimental results showed that the subcooled system attained a steady evaporating temperature of -9.4°C while it was only -3.9°C for the basic system for the same hours of operations of the cooling systems. This shows that the subcooled system has 141% faster cooling rate than the basic system. The results also showed that the COP of the subcooled system improved better than that of the main system from 18.0% to about 33.5% over an evaporating temperature range of -10°C to 30°C. It can be concluded that the use of dedicated sub cooling cycle in VCR system is more efficient and suitable for the betterment of thermal system performance.

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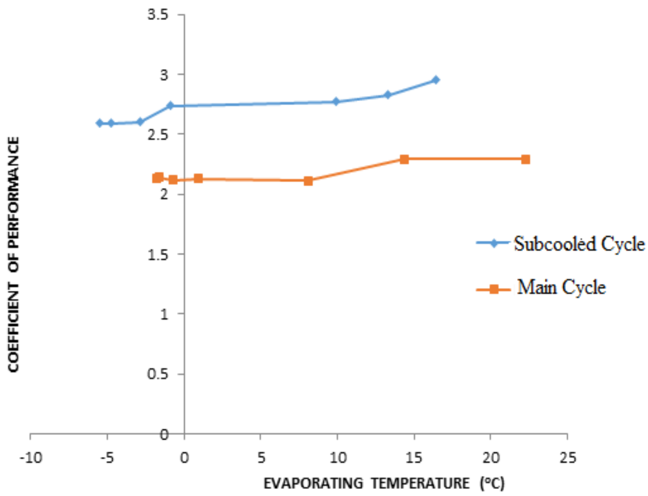

Figure 9: Variation of coefficient of performance with evaporating temperature

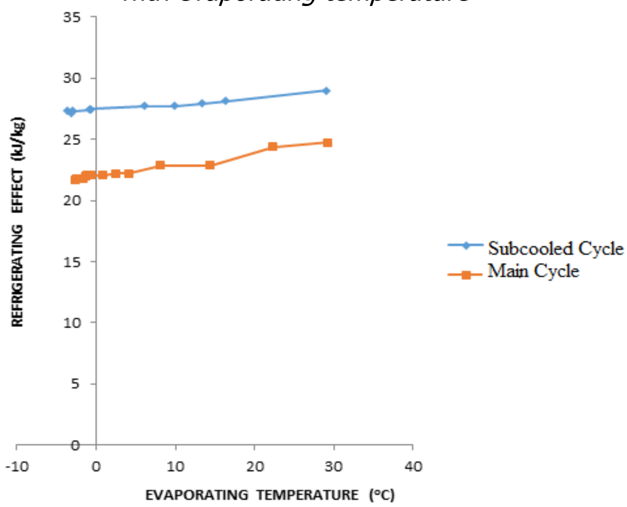

Figure 10: Variation of the refrigerating effect with evaporating temperature

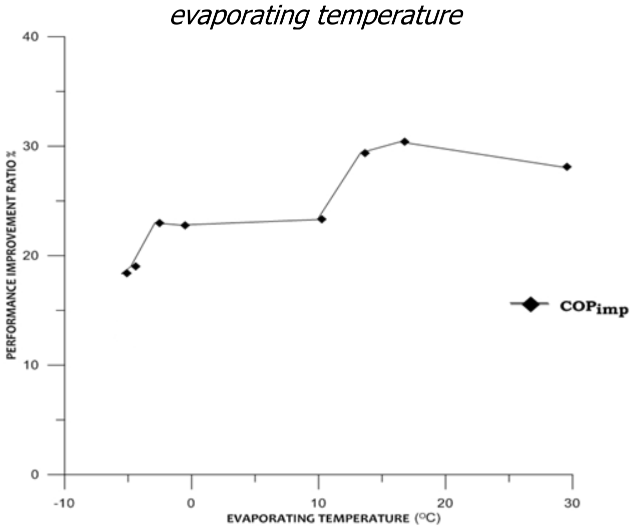

Figure 11: Variation of performance improvement against evaporating temperature

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