



RESEARCH ARTICLE

PERFORMANCE EVALUATION OF REFRIGERATION SYSTEM BASED ON BELL-COLEMAN CYCLE

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ARTICLE INFO

Article History:

Received 14th, March, 2015
Received in revised form 23th,
March, 2015
Accepted 13th, April, 2015
Published online 28th,
April, 2015

Key words:

Compressor, Water cooled
condenser, Air cooled condenser,
Nozzles, Evaporator cabin,
C.O.P.

ABSTRACT

Bell-Coleman Cycle also known as Reverse Brayton Cycle or Joule cycle comprises four process as compression, condensation, expansion and evaporation process. Our main focus was towards open cycle air refrigeration system that is based on Bell-Coleman Cycle. In this compressor taken fresh air from atmosphere and leave it in cooling chamber. For the analysis purpose we have used various equipment's such as- Compressor, Condenser, Expansion device, Evaporator coil and measuring equipment's like digital temperature indicator, pressure gauges, energy meter etc. The air refrigerator (as air as a refrigerant is used) has been studied and a prototype of this refrigerator has been fabricated. The prototype is analysed for theoretical, actual and relative C.O.P with water cooled condenser. Refrigeration effect of the system, work done by the compressor and COP of the system for Refrigeration system has been studied. It is seen that in case of water cooled condenser we have required less power for compression and achieve more refrigeration effect. The improved COP is obtained at higher refrigeration effect and lesser compressor work input.

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INTRODUCTION

A Refrigeration system can be defined as a system in which main focus is to achieving and maintaining a temperature below that of the surroundings. A Bell-Coleman air refrigeration machine is developed by Bell-Coleman and Light Foot by reversing the Joule's air cycle. It is the earliest types of refrigerators used in ships carrying frozen meat. Air cycle refrigeration system belongs to the general class of gas cycle refrigeration systems, in which a gas (air) is used as the working fluid. The air does not undergo any phase change during the cycle. All the internal heat transfer processes are sensible heat transfer processes.

Aircrafts, ship carrying frozen meat and submarine refrigeration systems as well as the liquefaction of various gases are one of the important applications of Bell-Coleman cycle based Refrigeration system. In this system we have used water cooled condenser for rapid cooling of compressed refrigerant used in this system that is air. As specific heat of water at constant pressure is **4.18 kJ/kg K** and of air is **1.005 kJ/kg K**, it means to say that water have more heat carrying capacity than air so that we can get better refrigeration effect by using water cooled condenser compared to air cooled condenser.

Here we improve the performance of air refrigerator by using water-cooled-condenser. The design of condenser is of open rectangular box type in which a net of the cooling coil with fins is fitted. This box is filled with water for cooling the refrigerant which is flowing through the tube. Refrigerant give its sensible heat to the cold water.

LITERATURE REVIEW

Air refrigeration system

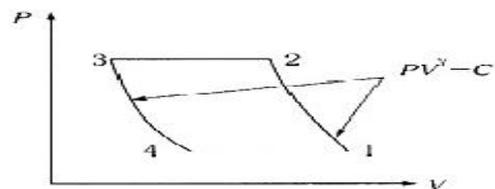


Fig. 1a P-v Diagram of air refrigeration cycle

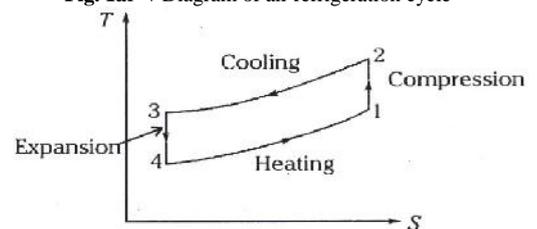


Fig. 1b T-s Diagram of air refrigeration cycle

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In air refrigeration system atmospheric air is compressed as a refrigerant. As air always remains in the gaseous phase and only sensible heat is removed that result low coefficient of performance (C.O.P). In any air refrigerating system air is compressed from atmospheric temperature and in ideal condition it cools to atmospheric condition. After isentropic expansion in expender the temperature of air drops below atmospheric temperature. Now low temperature air comes in to evaporator and absorbs the heat. Working of the air refrigeration cycle is represented by P-v and T-s diagram in fig. 1a and fig. 1b.

Refrigerant

In this system air is used as a refrigerant. Air cycle is not a new technology. At the turn of the century air cycle or ‘cold air machine’ were available from companies such as J & E Hall. There were on board ships and by food producers and retailers to provide cooling for their food stores. Reason behind not widely used of air as a refrigerants is that there is no change of phase, it is too inefficient to be practical. Yet, by using good quality compressor and expansion technology, air can be used as refrigerant. It is free of pollution and almost completely harmless to plants and animals.

Advantages of refrigerant Air

- Air is a cheaper refrigerant and it is easily available as compared to others refrigerants.
- Air is non –flammable and non-toxic.
- The weight of air refrigeration system per tonne of refrigeration system is very low.
- Easily and regularly available.
- The leakage of air is small and tolerable.

Fabrication Of Experimental Set-Up-



Fig. 2 Complete Air Refrigerator

A prototype have been designed to fabricate a set-up of air refrigerator using primary and secondary components involved along with measuring instruments such as Pressure gauge, Temperature gauge, Ammeter, watt meter and voltmeter etc. In this prototype model the inlet condition of compressor is atmospheric and we have assumed unit mass flow rate of air (1kg/min).

Firstly the physical measurement of space to be cooled is done to determine the capacity of refrigerator. For finding the capacity of refrigerator, assume the temperature T_4 is equal to the 15°C and the compressor inlet temperature T_1 is equal to

40°C , then the capacity of refrigerator is 0.1196 TR. After determining the capacity of refrigerator body, study of other components also done to complete the entire set up for testing and analysis. Our project is combined fabrication of refrigerator component and measuring component.

Fabrication of refrigerator component

Compressor

We have used a hermetically sealed reciprocating air compressor in the system. We have used $\frac{1}{4}$ inch copper tube for discharge line of compressor to condenser and that is fitted by flare joint. Specification of the compressor is given as:

Application

For Air, **Type** – Hermetically sealed reciprocating compressor, **Electrical circuit** - CSIR, 220V, 5Hz, single phase, **Power** - 1 H.P.

Condenser

For this system a shell and tube type water cooled condenser is manufactured. In this type of condenser air, as a refrigerant will flow in the tube and water will stay in the shell. Condenser coil is $\frac{3}{8}$ inch in diameter and made of copper which is of high thermal conductivity 385 W/m K . Stainless steel is used for making shell. Copper tube is fixed in the shell in three columns and each column contains 10 tubes of 30 cm long. In this way total length of condenser coil is around 900 cm with the fins. The size of fins with the copper tube is $30\text{cm} \times 2.5\text{cm} \times 25\text{cm}$ and this assembly is put in the shell of $43\text{cm} \times 20\text{cm} \times 34\text{cm}$ size. Capacity of condenser to store water is 27 liters. The condenser outlet connected with $\frac{1}{4}$ inch diameter copper tube goes to the nozzle. A pressure gauge is fixed in between this tube and for fixing the compressor and condenser on foundation nut and bolts are used.

Cooling space (refrigerator body)

All the components are designed according to the size of refrigerator. The wall of the refrigerator body is made by the plywood in rectangular shape with the door and for the insulation of the evaporator thermacole is used. The total area of the refrigerator body is $0.6\text{m} \times 0.6\text{m} \times 0.9\text{m}$ and the effective cooling space is $0.43\text{m} \times 0.43\text{m} \times 0.71\text{m}$. The refrigerator body is fitted on the same foundation.

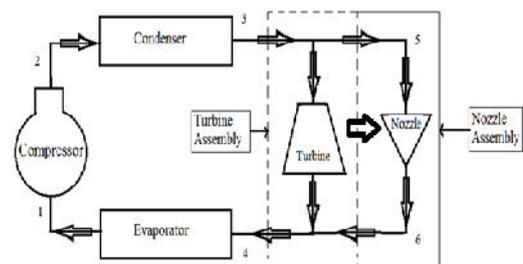


Fig.3 Block diagram of air refrigeration system with turbine and nozzle assembly.

Nozzle

In this prototype we use the nozzle as an expansion device in place of turbine, reason of replacing the turbine is that we can't manufacture a small turbine as compressor used for this system is small. Usually turbine is manufactured on the big size for power plants and other uses and it is too difficult to manufacture single turbine according to this prototype. Nozzle expands the air in cooling space directly.

Fabrication of measuring instrument

Ammeter

Ammeter is used to measure the current flow in ampere. The coil in the ammeter is of very low resistance and is always connected in series with the load. This is wired in series after outlet of wattmeter. It is fitted on the board which is fixed on the foundation.

Energy meter

The energy meter is used to measure the power in watts or kilowatts. Since power is the product of voltage, current and power factor, both voltage and ammeter connections are to be made to the wattmeter. Watt meters in conjunction with potential and current transformers are used to measure higher ranges of power (watts). Energy meter used to measure the energy used by the compressor per unit time. Electric supply to compressor is through wattmeter. It is also fitted on the board which is fixed on the foundation.

Specification

Static watt hour meter, AC single phase two wires CI-1, Rating = 5 - 20 Amp, 240V, 50Hz, 3200 amp/kWh.

Volt meter

A voltmeter shows the voltage or potential across a circuit. The coils of these meters are of high resistance and are connected in parallel. It is fitted on the board parallel to the ammeter.

Digital temperature indicator for measuring the temperature at different sections of refrigerating system is used. We have used six temperature gauges, four for measuring the temperature of refrigerant (air) at different sections, one in condenser and one in evaporator. Its digital screen is fitted on the board. Sensor of first temperature gauge is fixed before compressor, second temperature gauge after compressor, third after condenser, fourth in evaporator box adjacent to nozzle.

Specification

Temperature range = -50°C to $+120^{\circ}\text{C}$, Using environment temperature = -20°C to $+100^{\circ}\text{C}$, Accuracy = $+1$ to -1°C , Humidity = 5% to 80%, Power = single battery (LR 44, 1.5V)

Pressure Gauge

only one pressure gauge is used in this system and this gauge measure higher side pressure. For lower pressure side we have not used any pressure gauge because this refrigerating system is open loop air refrigeration system and so lower pressure will be atmospheric pressure. For joining the pressure gauge we have used flare fitting.

Specification

Type = bourdon tube type pressure gauge, Quantity = One, Capacity = 150 psi.

Analysis of Experimental Setup

The Pressures, Temperatures and states of the refrigerant in different parts of the Refrigerating System are shown in T-s diagrams.

There are mainly two pressures operating in the refrigeration cycle, commonly known as the high pressure side and low pressure side. From compressor outlet to the condenser up to expansion is high pressure side and after expansion to the suction of the compressor is called the low pressure side.

Table 1 Calculation of performance while using water cooled condenser

Sr. No.	1	2	3	4	5	6	7	8	9	10
Sr. No.	Time (t _{min})	P ₁ (bar)	P ₂ (bar)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	Ampere (I)	Voltage (V)	P _{in} (kWh)
1.	05	1.013	2.26	35.3	63.1	32.6	28.3	4.1	240	0.06
2.	10	1.013	2.26	35.3	68.9	31.3	27.1	4.0	240	0.06
3.	15	1.013	2.26	35.3	74.5	31.2	26.3	4.2	240	0.06
4.	20	1.013	2.26	35.3	79.2	31.2	25.6	4.2	240	0.06
5.	25	1.013	2.26	35.3	84.6	31.2	24.5	4.2	240	0.06
6.	30	1.012	2.26	35.3	90.2	31.3	24.4	4.1	240	0.06

11	12	13	14	15	16	17	18
P _{in} (kW)	W _{compressor} (kJ/kg)	R.E. (kJ/min)	R.E. (kW)	R.C. (TR)	Actual COP	Theoretical COP	Relative COP
0.72	34.57	7.03	0.1172	0.0335	0.1625	0.2034	0.7999
0.72	41.78	8.24	0.1375	0.0392	0.1909	0.1972	0.9680
0.72	48.75	9.04	0.1507	0.0431	0.2093	0.1855	1.1281
0.72	54.59	9.74	0.1624	0.0464	0.2255	0.1785	1.2630
0.72	61.43	10.85	0.1809	0.0516	0.2512	0.1766	1.4219
0.72	68.27	10.95	0.1825	0.0521	0.2534	0.1604	1.5795

Table 2 Calculation of performance while using air cooled condenser

Sr.NO.	1	2	3	4	5	6	7	8	9
Sr.	Time	P ₁	P ₂	T ₁	T ₂	T ₃	T ₄	Ampere (I)	Voltage
NO.	(t _{min})	(bar)	(bar)	(°C)	(°C)	(°C)	(°C)		(V)
1.	05	1.013	2.26	35.5	76.1	37.3	32.5	4.1	240
2.	10	1.013	2.26	35.5	80.4	36.4	31.7	4.0	240
3.	15	1.013	2.26	35.5	84.6	35.9	31.3	4.2	240
4.	20	1.013	2.26	35.5	88.3	35.6	30.4	4.2	240
5.	25	1.013	2.26	35.5	94.6	35.6	29.2	4.2	240
6.	30	1.013	2.26	35.5	99.4	35.6	29.1	4.1	240

10	11	12	13	14	15	16	17	18
P _{in}	P _{in}	W _{compressor}	R.E.	R.E.	R.C.	Actual	Theoretical COP	Relative COP
(kWh)	(kW)	(kJ/kg)	(kJ/min)	(kW)	(TR)	COP		
0.6	0.72	50.74	2.81	0.0469	0.0134	0.0651	0.0554	1.1750
0.6	0.72	56.09	3.61	0.0603	0.0172	0.0837	0.0645	1.2976
0.6	0.72	61.31	4.02	0.0670	0.0191	0.0930	0.0655	1.4198
0.6	0.72	65.91	4.92	0.0820	0.0234	0.1138	0.0747	1.5234
0.6	0.72	73.75	6.13	0.1021	0.0291	0.1418	0.0831	1.7063
0.6	0.72	79.72	6.23	0.1038	0.0296	0.1441	0.0781	1.8450

Where P₁= Suction pressure (atmospheric pressure for open air refrigeration cycle), P₂= Discharge pressure from compressor, T₁= Temperature compressor (atmospheric temperature), T₂= Temperature after compression, T₃= Temperature after condenser, T₄= Temperature after expansion, V= Voltage (V), I= Ampere (I), V*I= Power input.

CALCULATIONS

All calculation is done by assuming unit mass flow rate of air. Formula used for calculating refrigeration effect = m c_p(T₁ - T₄), compressor work = $\left(\frac{n}{n-1}\right) R (T_2 - T_1)$.

Actual Coefficient of Performance

The actual coefficient of performance is defined as the ratio of heat extracted in the evaporator (kW) to the power consumption by compressor (kW). Actual C.O.P. = Heat extracted in the evaporator (Q) / Power consumption by compressor (PI)

Theoretical Coefficient of Performance

The theoretical COP is defined as the ratio of the ratio of refrigeration effect (kJ/kg) to the compressor work done (kJ/kg).

Theoretical COP = Refrigeration effect (Q) / Compressor work done (W)

Relative COP

It is the ratio of Actual COP (COP_{act}) to the Theoretical COP (COP_{theo}).
 $COP_{rela} = (COP_{act} / COP_{theo})$

RESULTS AND DISCUSSION

RESULTS

With certain assumption keeping environmental consideration i.e. average T_{surr}, average humidity, constant air refrigerant

flow etc. fixed the observations noted for Actual COP, Theoretical COP and Relative COP is depicted below:

- A. The actual COP of system is improved by using the water cooled condenser instead the air cooled
- B. Condenser because the heat removed by water as a cooling medium is more than the air.
- C. In case of water cooled condenser, work done by compressor decreases with respect to air cooled condenser as compressor work depend upon the temperature T₂ which is less in case of water cooled condenser.
- D. It is observed that the refrigeration effect is quite higher that is because of high cooling rate in condenser and less compressor work while using water cooled condenser.
- E. While water cooled condenser is used then rate of extracting heat from hot air refrigerant is more with comparison to air cooled condenser as water has more heat removing capacity than air.
- F. It is observed from experiment that there is no pressure drop in condenser. This is because of no phase change of refrigerant.
- G. In case of water cooled condenser maximum droop in temperature of air is approximate 11°C while 6°C while using air cooled condenser.
- H. In case of water cooled condenser the heat removed from air refrigerant due to natural convection on the other hand as water is not circulated in the condenser, so the temperature of water of water cooled condenser increase after few hours.

DISCUSSIONS

The observations enable a strong basis to give out reasons and possible causes for a comparative study. Analysis of water cooled condenser over air-cooled condenser is given below:

Fig. 4, shows the actual and theoretical t-s diagram of Bell-Coleman cycle. The actual cycle is denoted by process 1-2'-3-4' and theoretical cycle is by 1-2-3-4. In actual practice we have seen that after compression (process 1-2') the temperature

increase from 35.3⁰C to 90.2⁰C, pressure increase from 1.01 bar to 2.26 bar and entropy increased from 6.89 kJ/kgK to 6.91 kJ/kgK but in theoretical practice the entropy have constant in compression process (process 1-2), the reason of increasing entropy is irreversibility involved in compression process. The temperature at the point 2 is equal to the 83.7⁰C. It is calculated by using this formula:

$$S_2 - S_1 = C_p \ln(T_2'/T_2)$$

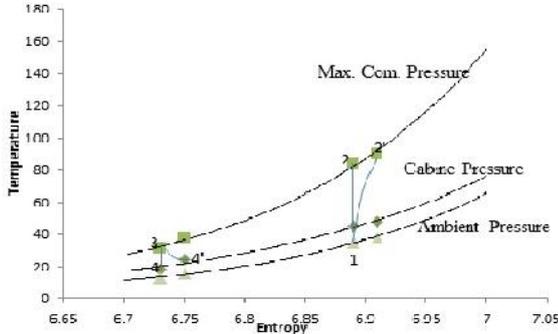


Fig.4 T-s Diagram of air refrigeration system

In the constant pressure cooling process (2`-3) the temperature of hot air is reduce from 90.2⁰C to 31.2⁰C at constant pressure and entropy reduce from 6.91 kJ/kgK to 6.73 kJ/kg K. In the process of isentropic expansion the process 3-4 defined theoretical expansion process and process 3-4' defined as the actual expansion process. In actual process the temperature decrease from 31.2⁰C to 24.4⁰C, pressure reduced from 2.25 bar to 1.97 bar (cabin pressure) and entropy increased from 6.73 kJ/kg K to 6.75 kJ/kgK but in theoretical practice the entropy irreversibility involved in expansion process. The cabin pressure is calculated by using this formula: $P_3/P_4 = (T_3/T_4)^{(\gamma-1)/\gamma}$ and the temperature at the point 4 is 18.7⁰C.

Compressor discharge temperature v/s Time

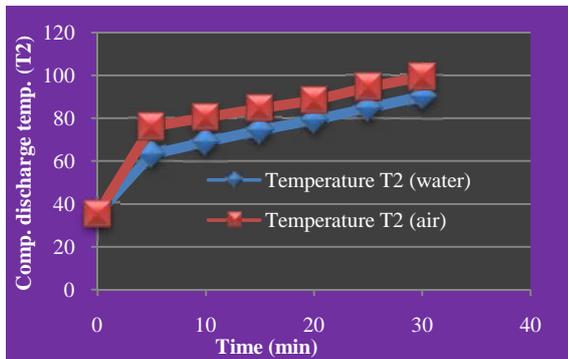


Fig.5 Compressor discharge temperature v/s Time

It is seen that compressor discharge temperature is more in case of air cooled condenser with compression of water cooled condenser. The reason for this the digital temperature gauge is set in our project is near about the condenser inlet so in case of water cooled condenser the heat transfer take place fast with comparison of air cooled condenser. The distance of digital temperature gauge from compressor outlet is near about 1.5 feet.

Condenser discharge temperature (T3) v/s Time

It is seen that initially the condenser discharge temperature (T3) first increases and then decrease in case of air cooled condenser

while in case of water cooled condenser the discharge temperature always decreases and the discharge temperature is more less than air cooled condenser. The reason for this, when we use the air cooled condenser then at the time of starting the condenser outlet temperature is equal to the atmospheric temperature, after starting of 5 min the temperature air refrigerant from compressor outlet increase rapidly but the heat is not extracted effectively in case of air cooled condenser. When we continued next 25 min the temperature of air refrigerant increased initially so the heat transfer take place better and the condenser discharge temperature decreases initially and remain constant. In case of water cooled condenser at starting time the discharge temperature is equal to the water temperature and after starting the pressure and temperature increases of refrigerant due to better heat convection of water the discharge temperature of condenser decreases and remain constant after some time.

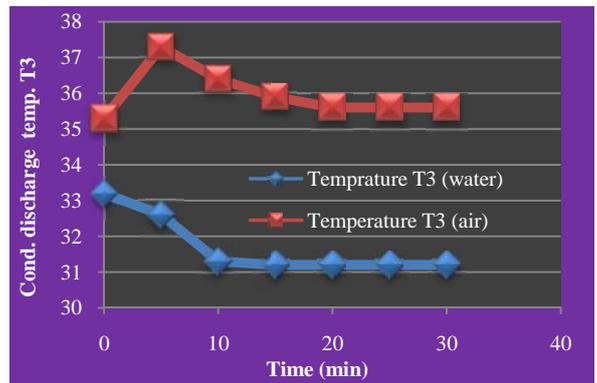


Fig.6 Condenser discharge temperature v/s time

Nozzle discharge temperature (T4) v/s Time

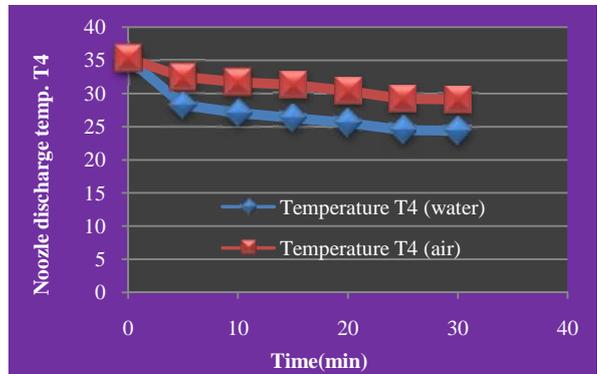


Fig.7 Nozzle discharge temperature (T4) v/s Time

It is obvious from above fig. that nozzle discharge temperature (T4) decreases more in case of water cooled condenser comparison of air cooled condenser. The reason for this is the discharge temperature of condenser. In case of water cooled condenser the discharge temperature of condenser less than the air cooled condenser so the better expansion take place in case of water cooled condenser.

Compressor work v/s Time

It is seen from above fig. that the compressor work more in case of water cooled condenser comparison of air cooled condenser. The reason is that the compressor work is a function of T1 (compressor inlet temperature) and T2 (compressor discharge temperature).

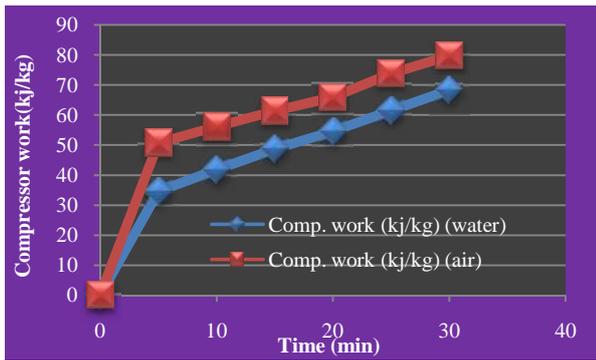


Fig.8 Compressor work v/s Time

The compressor work increases with time because T_2 increases with time. The increase in compressor work for air cooled condenser is more than water cooled condenser because the rise in temperature discharge temperature T_2 is more for air cooled condenser than water cooled condenser.

Refrigeration effect v/s Time

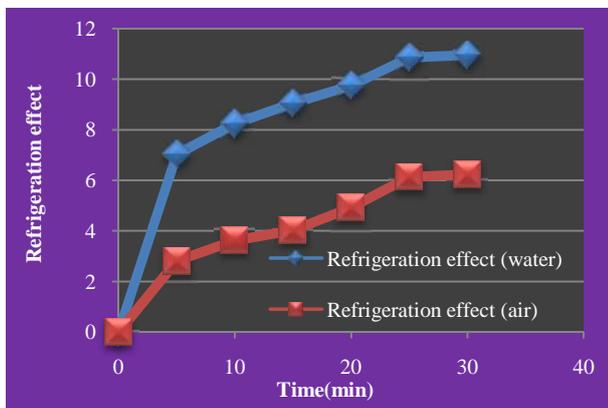


Fig.9 Refrigeration effect v/s Time

From above graph we have seen that the refrigeration effect increases more in case of water cooled condenser comparison of air cooled condenser with time. It is because the refrigeration effect is a function of nozzle discharge temperature (T_4) and compressor inlet temperature (T_1).

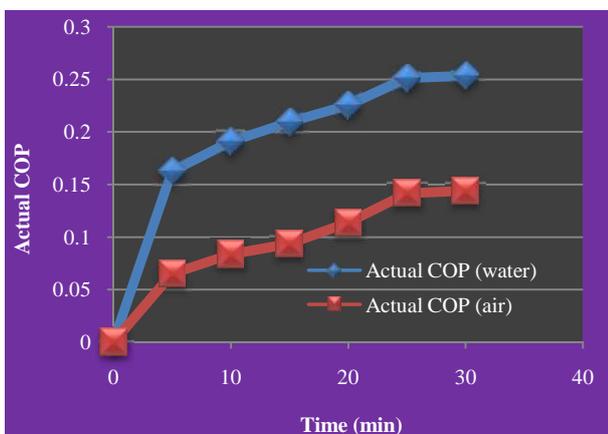


Fig.10 Actual COP v/s Time

The temperature T_4 decreases with time more for water cooled condenser so the refrigeration effect is more in case of water cooled condenser comparison.

Actual COP v/s Time

It is seen from above that the actual COP increases with time in case of both air and water cooled condenser but the actual COP is more increase in case of water cooled condenser. It is because the actual COP is ratio of cooling effect and power consumed by compressor. The increase in actual COP is more in case of water cooled condenser than air cooled condenser because the increase in the cooling effect is more for water cooled condenser than air cooled condenser.

Theoretical COP v/s Time

It is seen from above graph that the theoretical COP increases with time in case of air cooled condenser and decrease in case of water cooled condenser because theoretical COP is a function of cooling effect and compressor work, in case of water cooled condenser the refrigeration is more than the air cooled condenser and compressor work less than the air cooled condenser so the theoretical COP increase in case of air cooled condenser and decrease in case of water cooled condenser.

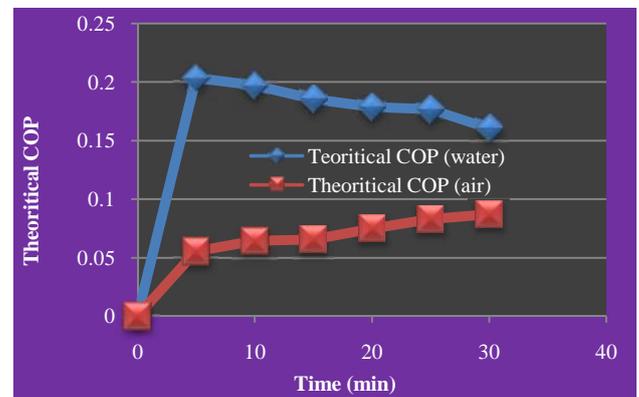


Fig.11 Theoretical COP v/s Time

Relative COP v/s Time

It is seen from above graph that the relative cop for both air and water cooled condenser increases rapidly with time.

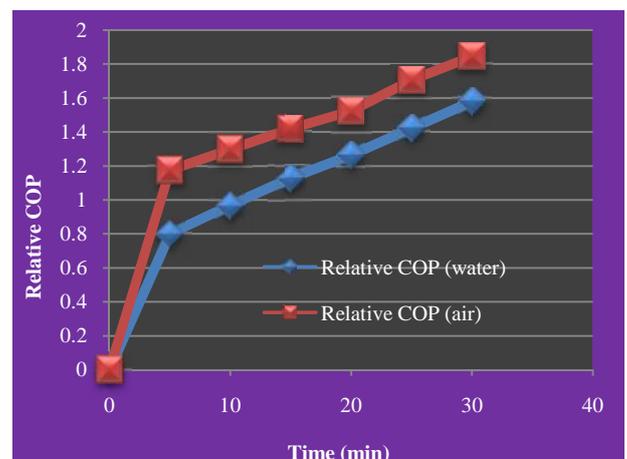


Fig.12 Relative COP v/s Time

The relative COP for air cooled condenser is more than that for water cooled condenser because the actual COP is more than

theoretical COP in case of air cooled condenser than in case of water cooled condenser at any time.

CONCLUSION

Air Refrigeration System based on Bell-Coleman cycle has been carried out. On the basis of the result and discussion shown in the previous chapter following conclusion comes out.

1. The actual COP of system is improved by using the water cooled condenser instead of air cooled condenser, the maximum actual COP of the system in case of water cooled condenser is 0.2534 and air cooled condenser is 0.1441.
2. The maximum refrigeration effect in case of water and air cooled condenser are 0.1825 kW and 0.1038 kW respectively.
3. The compressor work increase in case of air cooled condenser, the maximum compressor work in case of water cooled condenser is 68.27 kJ/kg and air cooled condenser is 79.72 kJ/kg. The compressor work is reduced by using water cooled condenser.
4. The capacity of refrigerator is depend upon the refrigeration effect which is more in case of water cooled condenser, so the capacity of refrigerator improved by using water cooled condenser. The maximum capacity of refrigerator is 0.0521 and 0.0296 in case of water and air cooled condenser respectively.
5. The temperature of air refrigerant in case of water and air cooled condenser after compression increase rapidly in starting of 5 minute from 35.3 °C to 63.1°C and 35.3°C to 76.1°C respectively and next 25 minute the temperature increase gradually.
6. Water in the condenser is not circulatory so heat is extracted from air refrigerant due to natural convection and this is why is required to change the condenser water after 24 hour of continuous operation.
7. It is important to operate compressor at low pressure for safety operation without overheating.

Acknowledgement

The author is highly thankful to mechanical engineering department for extending help and support in fabricating the experimental set up. The contribution of B. Tech final year student viz. Anubhav Singh, Prabhat Kumar Bajpai, Atul Kumar and Pradeep Kumar Bharatiin fabrication / retrofitting during their project work is gratefully acknowledged under my supervision.

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How to cite this article:

Er. Rahul Patel and Er. Ramji Tripathi., Performance Evaluation of Refrigeration System Based on Bell-coleman cycle. *International Journal of Recent Scientific Research Vol. 6, Issue, 4, pp.3321-3327, April, 2015*

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