

The Performance Analysis of Cascade Refrigeration System with and Without Phase Change Material

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Abstract: As the technology is developing in the field of refrigeration and air conditioning, remarkable comfort and saving are achieved. Maintaining the required low temperature and the cost is low. The main aim is to improve & extend the self life. The low temperature is obtained mostly by vapour compression refrigeration cycle, but it has its own limitations in producing low temperature. Hence for low temperature production multiple compression binary vapour cycle is used. The concept is that the cooling produced in first cycle evaporator is used to cool the condenser of second cycle, which reduces the cooling capacity in condenser and enables to produce very low temperature for various cold storage applications. Further the low temperature side cooling is given to a Phase Change Material (PCM) and the cooling is stored in PCM, this cooling is sustained up to 20 hours without operation of cycle, thus maintaining the low temperature of the products even without continuous power supply. In this project a binary vapour cycle is designed to produce a temperature of -20°C .

Keywords: Cascade, Phase Change Material, Refrigeration

I. Introduction

Cascade refrigeration system is a low temperature refrigeration system and is used for very low temperature range about (-40°C to -130°C). At such low temperature simple Vapour Compression Refrigeration Cycle (VCRS) is not efficient due to very high compression ratio that further leads to high discharge problem and low volumetric efficiencies. Whereas, cascade refrigeration is much efficient for such conditions. Cascade refrigeration cycle is nothing but simply a combination of two VCRS cycles named as low and high temperature circuit that are combined together by a cascade condenser. This cascade condenser unit acts as evaporator for low temperature circuit and condenser for high temperature circuit, the low temperature circuit uses low boiling refrigerants such as R23, R744 etc. and high temperature uses high boiling point refrigerants such as R717, R290, R404A, R1270, R507A etc.

Principle of cascade refrigeration system.

To condense refrigerants that are capable of achieving ultra-low temperatures that would not be able to condense at room temperature. This is achieved by using a low temperature evaporator of one system as the condenser of the other, condensing and sub cooling the liquid before entering the metering device.

Two Stage Cascade Systems:

A two-stage cascade refrigeration system uses two types of compressor devices, they run individually with different refrigerants, connected among them so that evaporator of first cycle used for cooling of second cycle condenser (i.e. the evaporator with the first unit cools the condenser of the second unit). In practice, an alternative approach using a common capacitor with a booster circuit to provide two separate temperature limits of the evaporator

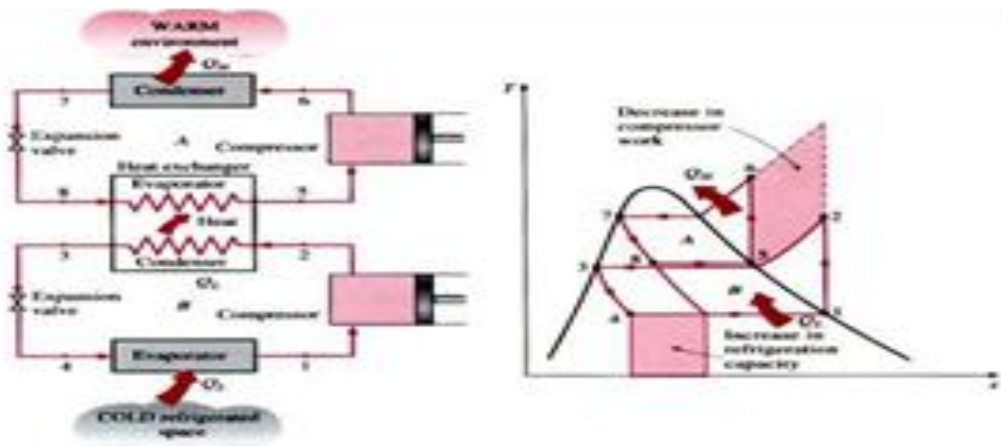


Fig:1 Cascade system

Cascade Refrigeration System Description

The cascade refrigeration cycle is a combination of two vapour compression cycles which utilizes two different refrigerants. The primary refrigerant flows from low temperature circuit evaporator to low stage compressor and condensed in cascade condenser which also acts as evaporator for high temperature circuit. The heat rejected from condenser of low temperature circuit is extracted by evaporator of high temperature circuit containing secondary refrigerant then, this secondary refrigerant gets compressed in high stage compressor and finally condensed to outer atmosphere. The desired refrigerating effect is occurred from evaporator of low temperature circuit. The temperature difference in cascade condenser is an important design parameter that decides the COP of the entire refrigeration system.

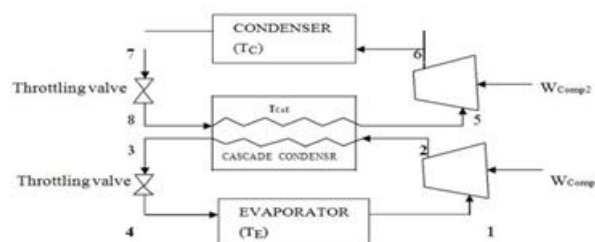


Fig 2: systematic cascade refrigeration cycle with evaporator, condenser and cascade condenser

Advantages of cascade systems

- In cascade system using different refrigerants, so, that it is possible to select a refrigerant that is best suited for that different temperature range. In the manner of Very high or very low pressures can be avoided for extend.
- In this system migration of lubricating oil from one compressor to the other compressor is prevented.
- The saving of energy is more because the system allows use of refrigerants that have suitable temperature limits characteristics for each of the higher-temperature side and the lower-temperature side.
- It allows especially for stable ultra-low-temperature operation.
- Repair and maintenance is easy.

II. Motivation For Present Work

As the technology is developing in the field of refrigeration and air conditioning, remarkable comfort and saving are achieved. Maintaining the required low temperature for the common food we take will surely reduce the cost, as this process can be done at a time when the availability is plenty and the cost is low. Generally they are two ways to maintain the low temperature in the evaporator coil.

1. To bring down the pressure from condenser outlet to expansion outlet as very low.
2. To increase the heat rejection capacity in condenser at constant pressure.

From case 1:

- If we decrease the pressure to very low from condenser to expansion valve, it leads to there is a problem of flow of refrigerant in evaporator coil.(i.e. the refrigerant will not flow at vacuum pressure .so, that we should above atmospheric pressure from expansion outlet to evaporator outlet.

In normal cascade refrigeration system the heat exchanger is used for the transfer of heat from low temperature cycle condenser to high temperature cycle evaporator. In heat exchanger the heat transfer rate is very slow for a long period of time, it effects on the performance of the system as follows,

- Decrease in evaporator temperature.
- Decrease in refrigeration effect.
- Lack of continues supply of cooling water.
- Slow hear transfer rate.
- It will take place long period of time for getting lower temperature.

To overcome the above problems we are introducing a new design for cascade refrigeration system; a pump is introduced between high temperature cycle evaporator and low temperature cycle condenser. Further the low temperature side cooling is given to a Phase Change Material (PCM) and the cooling is stored in PCM, this cooling is sustained up to 20 hours without operation of cycle, thus maintaining the low temperature of the products even without continuous power supply.

In this project a binary vapour cycle is designed to produce a temperature of -20°C .

III. Phase Change Materials

The idea to use phase change materials (PCM) for the purpose of storing thermal energy is to make use of the latent heat of a phase change, usually between the solid and the liquid state. Since a phase change involves a large amount of latent energy at small temperature changes, PCMs are used for temperature stabilization and for storing heat with large energy densities in combination with rather small temperature changes. The successful usage of PCMs is on one hand a question of a high energy storage density, but on the other hand it is very important to be able to charge and discharge the energy storage with a thermal power, that is suitable for the desired application. One major drawback of latent thermal energy storage is the low thermal conductivity of the materials used as PCMs, which limits the power that can be extracted from the thermal energy storage. A phase change material is defined as (PCM) is a substance with a high heat of fusion process in which, melting and solidifying at a certain temperature, and is capable of storing and releasing large amounts of heat energy. The Heat is absorbed or released when the material changes from solid state to liquid state and vice versa; thus, PCMs are classified as latent heat of storage (LHS) units system.

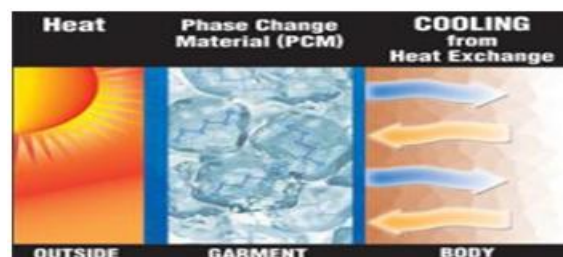


Fig 3: Phase change transformation.

Selection Criteria Thermo dynamic properties.

The phase change material should possess:

1. In the desired operating temperature range Melting temperature should be available.
2. They have high latent heat of fusion per unit volume.
3. They should possess High specific heat, high density and high thermal conductivity properties.
4. And they possess Small volume changes on phase transformation and small vapour pressure at operating temperatures to reduce the containment problem.
5. High congruent melting.

Kinetic properties

1. They should possess High nucleation rate for the avoid of super cooling of the liquid phase.
2. Process high rate of crystal growth, so that the system can meet demands of heat recovery from the storage system.

Chemical properties

1. Should maintain the Chemical stability.
2. Process Complete reversible freeze/melt cycle
3. It should have No degradation after a large number of freeze/melt cycle.

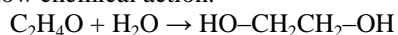
4. Process Non-corrosiveness, non-toxic, non-flammable and non-explosive materials.

Economic properties

1. Less cost
2. Plenty availability

Ethylene Glycol

(IUPAC name: ethane-1, 2-diol) is an organic compound initially they have been used as a raw material in the manufacture of polyester fibers and fabric industry, and polyethylene terephthalate resins (PET) used in bottling process. A small per cent is used in industrial applications like antifreeze formulations and other industrial products. It process odorless, colorless, syrupy, sweet-tasting liquid properties. Ethylene glycol is initially toxic, with children has been particularly at risk because of its sweet taste, and it became common to add bitter flavoring to consumer antifreezes containing it. Ethylene glycol is produced from ethylene (ethane), via the intermediate ethylene oxide. Ethylene oxide reacts with the water to produce ethylene glycol according to the below chemical action.



IV. Objective Of Present Work

The objectives of the performance improvement of the cascade refrigeration system by using the phase change material (PCM) are given below,

1. To fabricate the experimental set up by modifying the cascade refrigeration system as introducing the pump in the place of heat exchanger with PCM based refrigerator.
2. To bring down the system up to -200c.
3. To reduce power consumption.
4. To retain cooling effect for long period of time without power supply.
5. To compare the performance of single stage cycle with binary cycle.
6. To observe the system with PCM and without PCM.

V. Design And Experimental Studies

Experimental study on a system helps to evaluate its performance experimentally under varying operating conditions. Comparing this performance with that of the theoretical studies help in understanding the acceptability limits. In this line, the performance of the designed cascade refrigeration system is studied experimentally.

Test rig is cascade refrigeration system. Figure 6.1 shows the schematic diagram of the experimental setup. This test rig mainly consists of compressors, condenser, expansion devices, cascade condenser, evaporator, water pump and PCM.

This cascade refrigeration system is generally divided as two vapour cycles. These two vapour cycles are run by individually, the cycles are

- 1) Higher temperature cycle
- 2) Lower temperature cycle

Higher temperature cycle

- In high temperature cycle, the high-pressure gas from compressor flows through an oil separator where the compressor lubricant oil and refrigerant are separated and oil is fed back to the compressor.
- The high pressure refrigerant from the compressor entering into the air cooled condenser.
- The condenser is cooled by fan which is run by compressor 1. in condenser high pressure vapour refrigerant is converted into high pressure liquid refrigerant due to latent heat of evaporation.
- This high pressure liquid refrigerant is entering into the expansion device, in expansion device throttling process will takes place the pressure is reduced as condenser to evaporator pressure.
- The low pressure liquid refrigerant is entering into the evaporator, where the liquid refrigerant takes the heat from the refrigerated space and converted into vapour



Fig 4: Working model of Cascade system

Refrigerant due to latent heat of evaporation, and this vapour refrigerant is entering into the compressor, and then the cycle is repeated.

Lower temperature cycle

- The working process of lower temperature cycle is same as higher temperature cycle, but the differences are as follows.
- The lower temperature condenser is cooled by the higher temperature evaporator; which is achieved by keeping the pump between the higher temperature evaporator and lower temperature condenser.
- The pump can supply the refrigerated water which is generated by higher temperature cycle to the lower temperature cycle condenser, where the heat transfer takes place from refrigerant which is flowing in the coils to the cooling water, and this cooling water is converted into hot water, this hot water is again supplied to the higher temperature cycle evaporator by using pump. so, in this way the cold and hot water is supplied in between high temperature cycle evaporator and lower temperature condenser by using pump.

PCM

- In this system the ethylene glycol is used as a phase change material.
- The PCM is incorporated between lower temperature evaporator coil and refrigerated space.
- Initially the PCM is in liquid state, the refrigerant which is flowing in lower temperature evaporator gives cooling to the PCM.

The PCM can store this cooling for a long period of time and extract the heat from the refrigerated space. Temperatures at various locations were measured using digital thermo meter. Various locations at which temperature was measured are shown in Table 1.

Different pressures

- Discharge pressure of compressor
- Suction pressure of compressor
- Pressure at the outlet of condenser
- Pressure at the capillary tube outlet Specifications of the Components:

The design details of the model are as follows:

Mass of refrigerant (R134a) (m) = 250gm. In both cycle

Compressor details Used in both cycles

- Compressor Power = 0.167 H.P
1 H.P = 746 W
So Power = $0.167 \times 746 = 124.582$
We use Reciprocating piston type compressor.
- Phase 1
- Speed = 2850 R.P.M
- Volts = 160/250
- Temperature = 40°C

- Cycles = 50 Hz
- Current = 4 A.M.

Higher temp cycle (In Second Cycle)

- A tank of GI Sheet capacity 15 Litres surrounded by PUF insulation



Expander details

In first cycle

- Diameter of capillary tube = 0.040 inch.
- Length of capillary tube = 10ft.

In Second Cycle

- Diameter of capillary tube = 0.036 inch.
- Length of capillary tube = 10FT Water Circulation Pump

We use centrifugal impeller type water circulation pump.

- Capacity= 1/4H.P.
- Head = 9M
- Volts = 230V AC
- Current = 0.6 AMP
- Cycles = 50Hz Evaporator

In First Cycle

It is in the form of a tank of GI sheet of capacity 15 Litres

Length of the evaporator coil = 25ft.

Diameter of the evaporating coil = 1/4 inch

In Second cycle

- It is surrounded by PUF insulation in Ethylene Glycol solution mixed with water (1:3)
- Capacity of cold storage 25 Liters.
- Length of the evaporator coil = 30ft.
- Diameter of the evaporating coil = 1/4 inch

To improve temperature stability during power loss in cold storage, the dimensions of vertical cabin as follows

- 0.2794m H x 0.2794mWx0.325m D (11"x11"x11") and a storage volume of 25.7 L was used.
- The PCM with Anodized aluminum panels (a ethylene glycol solution with a melting point of -20°C)

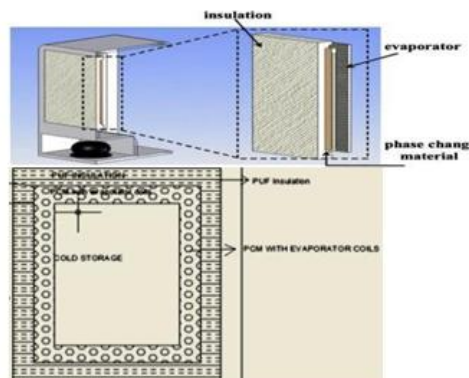


Fig 6: Schematic diagram showing incorporation of PCM and Insulation.

The evaporator coil and phase change material (PCM) are placed in one panel, the PCM will absorb the energy from evaporator coil cools and stores this energy by changing its phase. During power cuts or off peak time the pcm will releases its energy and cools and maintains the cold cabin at constant required temperature.

VI. Experimentation

The entire system was pressure tested using nitrogen gas pressurizing to 30 bar. The system was left at that pressure for a period of 24 hours. System was evacuated using a vacuum pump. By adapting triple vacuum technique it was ensured that the non-condensable gases present in the CASCADE system were removed. Vacuum was held for 24 hours and finally estimated quantity of R134a in liquid form was charged into the system and ensured that bubble is not seen in the sight glass while system is at steady state operating condition.

Experimental Procedure

➤ Experimental procedure, which is carried out during the experiment, is given below:

- 1) Initially the first cycle is run till the evaporator temp becomes 0°C, and then stopped were placed against the walls of the cold storage in the arrangement shown in Figure. The PCM is in an aluminium panels with a dimensions of 0.0254m x 0.33m x 0.38m (t x w x h) contained 3 liters of ethylene glycol and 12 liters of water as a PCM is occupying a volume of 4.735 L was used for experimental investigation. The PCM panels were placed vertically against the entire walls of the cold storage to minimize the amount of usable storage space lost as shown in Figure 1. The poly urethane foam is used for This PCM panels of dimensions 0.05m x 0.43m x 0.43m (t x w x h). This foam material will reduce the heat transfer from outside to inside the cabin as shown in figure.
- 2) Now simultaneously the second cycle and water circulation pump is started.
- 3) Circulation of water continuously cools the condenser of second cycle and hence performance increases.
- 4) All the Temperature, Pressure and timings are recorded with the help digital thermometers, Pressure gauges and stop watches respectively.
- 5) The second cycle is to be stopped after the temperature of cold storage reaches around -20°C.
- 6) Without pcm, the time for temperature decrement in cold storage for every degree centigrade is recorded, till the temperature reaches 0°C.
- 7) With pcm, the time for temperature decrement in cold storage for every degree centigrade is recorded, till the temperature reaches 0°C
- 8) Calculations are made for Refrigeration Effect, work done & COP for the binary cycle and single cycle.

VII. Results And Discussion

After conducting experimentation the readings are noted and tabulated as follows.

Table 2: Noted readings

CALCULATION OF COP

Without PCM panel:

$COP = Q_C / W$ Where,

W = Amount of power supplied.

Q_C = Heat removed from the cold reservoir.

$Q_C = mc_p dt$

m = amount of water stored, i.e. 0.5 kg

C_p = Specific heat of water, i.e. 4.2 kJ/kg - °C $dt = T_i - T_f$

T_i = Initial temperature of water, i.e. 20 °C T_f = Final temperature of Water, i.e. 5 °C Heat rejected $Q_C = mC_p dt$
 $= 0.5 \times 4.2 \times (20 - 5)$
 $= 31.5 \text{ kJ/kg} - ^\circ\text{C}$

Time required for cooling is 60 sec.

Therefore, $Q_C = mC_p dt / \text{time}$

$$= 31.5 / 60$$

$$= 0.525 \text{ KW}$$

Power consumed by the compressor = $VI \cos \phi$, Where, V = Voltage

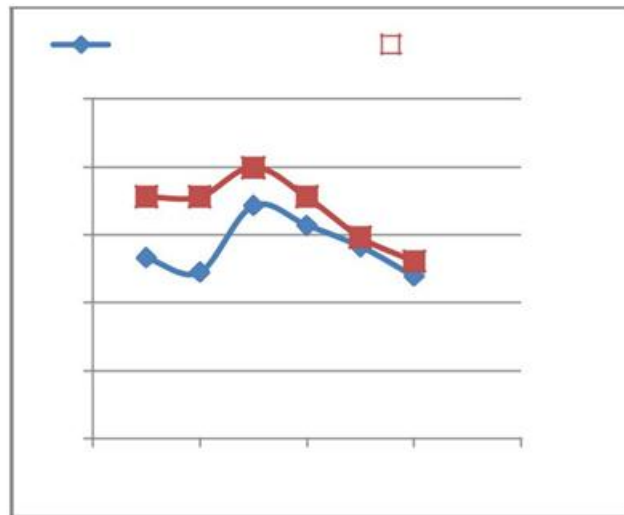
$$= 230 \text{ volts } I = 1.5 \text{ amps}$$

$\cos \phi$ = utilization factor = 0.857

Therefore, power consumed = $230 \times 1.5 \times 0.857 = 295.665 \text{ W}$

C.O.P = Heat removed from cold cabin / power consumed by compressor
 $= 1.333$

From the graph 1, for the case without PCM: it is evident that the COP is decreasing by increasing the load from 0.5 k to 1kg, and again the COP is increasing by increasing the load to 1.5 kg after that the COP is decreasing gradually by increasing the load. The Max COP obtained is 1.713 and is obtained at 1.5 Kg load. Also from the graph for the case with PCM: it is evident that COP is not changing by increasing the load from 0.5 k to 1kg, and again the COP is increasing by increasing the load to 1.5 kg after that the COP is decreasing up to a certain load. Finally from the graph with PCM panel, the maximum COP is found to be 1.994 and is obtained at 1.5Kg load. It is clear from the graph that COP with PCM is superior to COP without PCM at all tested loads. Especially it is observed that performance at lower loads COP with PCM is far higher than COP without PCM.

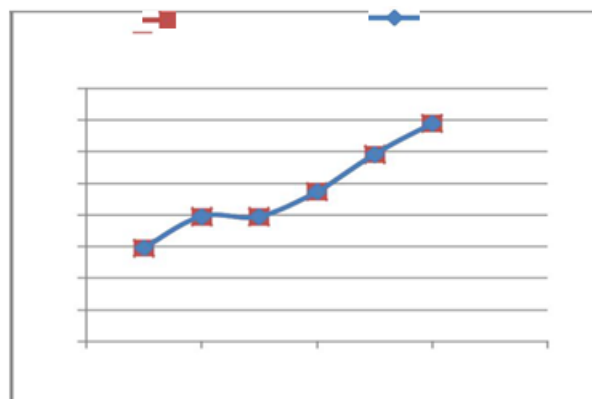


Graph 1: Effect of load on COP with and without PCM

◆ Heat rejected without PCM

Graph 3 shows that power consumed is increasing with increase of load as expected. Also it shows that power consumed is same in both the cases either with PCM or without PCM. Using PCM does not affecting the power consumed, so only initial cost is the additional amount to be bared whereas the running cost is same even after using PCM.

The graph 4 shows the relation between the Time Vs Temperature with and without PCM panel for cascade system. From the graph for the case without PCM: it is evident that the temperature is decreasing slowly with respect to time up to a temperature of -10°C which takes a time of 3.6 hours, after that for fall of temperature from -10°C to 0°C it takes a time of only 1.9 hours. Finally without PCM panel in cascade refrigeration system for getting a temperature from -20°C to 0°C , it takes totally a time of 5.5 hours the case with PCM: it is evident that the temperature is decreasing almost uniformly with respect to time from a temperature of -20°C to 0°C . Finally in cascade refrigeration system with PCM panel, for getting a temperature from -20°C to 0°C , it takes totally a time of 14.5 hours. With this by using PCM panel we retain the cooling effect for a long period of time. The retained time using PCM is 2.63 times than that the retained time without using PCM.

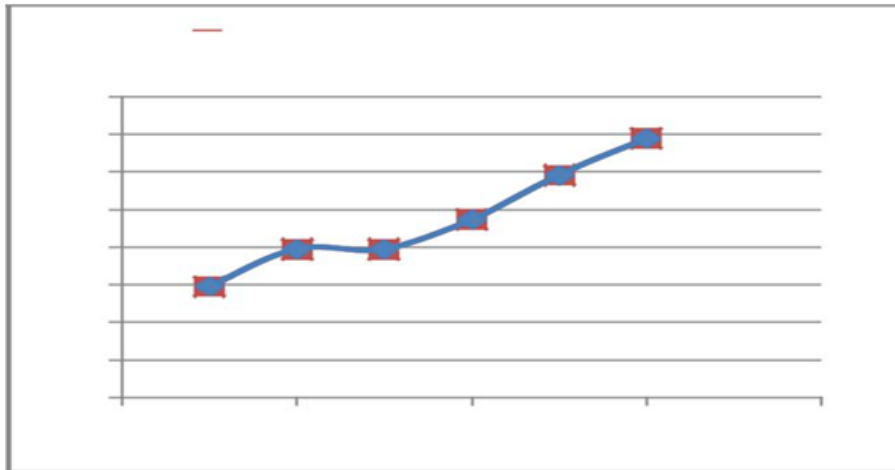


Graph 3: Effect of load on power consumed with and without PCM.

The graph 4 shows the relation between the Time Vs Temperature with and without PCM panel for cascade system. From the graph for the case without PCM: it is evident that the temperature is decreasing slowly with respect to time up to a temperature of -10°C which takes a time of 3.6 hours, after that for fall of temperature from -10°C to 0°C it takes a time of only 1.9 hours. Finally without PCM panel in cascade refrigeration system for getting a temperature from -20°C to 0°C , it takes totally a time of 5.5 hours

For the case with PCM: it is evident that the temperature is decreasing almost uniformly with respect to time from a temperature of -20°C to 0°C . Finally in cascade refrigeration system with PCM panel, for getting a temperature from -20°C to 0°C , it takes totally a time of 14.5 hours. With this by using PCM panel we retain the cooling effect for a long period of time. The retained time using PCM is 2.63 times than that the retained time without using PCM.

Calculations for Cascade (Binary) Cycle:



From p-h Diagram

- $h_1=430 \text{ KJ / Kg}$
- $h_{2a}=470 \text{ KJ / Kg}$
- $h_a=420 \text{ KJ / Kg}$
- $h_b=450 \text{ KJ / Kg}$
- $h_e=525 \text{ Kj/Kg}$
- $h_d=190 \text{ Kj/Kg}$
- $h_5=240 \text{ Kj/Kg}$

i) Actual Cycle (1-2a-3-4) Theoretical Cycle (1-2-3-4)

$$W_1 = \text{Work of Compressor} = h_{2a} - h_1 = 470 \text{ Kj/Kg} - 430 \text{ Kj/Kg} = 40 \text{ Kj/Kg}$$

ii) Second Cycle (A-B-C-D)

$$W_2 = \text{Work of Compressor} = h_b - h_a = 450 \text{ Kj/Kg} - 420 \text{ Kj/Kg} = 30 \text{ Kj/Kg}$$

$$N = \text{Refrigeration Effect} = h_a - h_d = 420 \text{ Kj/Kg} - 190 \text{ Kj/Kg} = 230 \text{ Kj/Kg}$$

$$W = \text{Total work of Compression} = W_1 + W_2 = 70 \text{ Kj/Kg}$$

$$\text{COP} = N/W = 230/70 = 3.28$$

Calculations for Single Cycle (A-E-3-5) : $W = \text{Work of Compressor} = h_e - h_a$

$$= 525 \text{ Kj/Kg} - 420 \text{ Kj/Kg} = 105 \text{ Kj/Kg}$$

$$N = \text{Refrigeration Effect} = h_a - h_5 = 420 \text{ Kj/Kg} - 240 \text{ Kj/Kg} = 180 \text{ Kj/Kg}$$

$$\text{COP} = N/W = 180/105 = 1.71$$

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1.2 advantages Of Cascade System

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3.1 Ethylene Glycol

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VIII. Conclusion

After conducting tests on designed cold storage plant of cascade refrigeration system with and without phase change material(PCM), following conclusions are drawn.

- From the experimentation it is observed that in Cascade (Binary) refrigeration system the refrigeration effect can be increased by 27.7% as compared to single system for producing -20°C in the cold storage.
- By using cascade system the actual work can be reduced by 33.3% as compared single system for producing -200C in the cold storage.
- Experimental results show that the coefficient of performance (COP) of cascade refrigeration system is higher than single refrigeration system.
- Experimental results shows that for fall of temperature from -200C to 00C without phase change material, takes 5.5 hours' time whereas the same by using phase change material it takes 14.5 hours' time. So with phase change material (PCM) panels at the walls of a cold storage, temperature can be retained for long period of time.
- Reduction of a temperature in a cascade cold storage plant using PCM panels has observed that reduction of 10C approximately for every one hour.
- Max COP of the refrigeration system using PCM is 16.4% higher than that of maximum COP of the system without PCM.
- Moderate load of 1.5Kg yields optimum performance of refrigeration system.

It is understood that present day due to intermittent power supply and power crisis it has become compulsory to have continuous cooling to the frozen items. It is also observed from the system that during power cut this method is cheapest when compared to all other alternate power source systems.

Acknowledgements

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