International Journal of Scientific Research and Management Studies (IJSRMS)
ISSN: 2349-3771 Volume 4 Issue 1, pg: 20-30

THERMODYNAMIC ANALYSIS OF CASCADE SYSTEM WITH AND WITHOUT PCM

N.Ganesh Babu[1], M.Lava Kumar[2]
[1]PG Student, [2]Associate Professor,
Department of Mechanical Engineering,
G. Pulla Reddy College of Engineering, Kurnool, Andhra Pradesh, India.

ABSTRACT

In low-temperature applications, including rapid freezing and the storage of frozen food, the required evaporating temperature of the refrigeration system ranges from –15°C to –50°C, so a single-stage vapour-compression refrigeration system is insufficient, while two-stage or cascade refrigeration systems are used for low-temperature applications. In these, two single-stage systems are thermally coupled through a cascade condenser.

This paper investigates the performance improvement provided by a phase change material associated with the evaporator in a cascade refrigerator. That is in 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 10 hours without operation of cycle, thus maintaining the low temperature of the products even without continuous power supply. And the scope of the present paper is focused on the thermodynamic analysis of a cascade refrigeration system using as refrigerant isobutane (R 600a), because of its lower ODP properties, in low- temperature circuit and R 134a in high-temperature circuit.

KEYWORDS: *cascade refrigeration, pcm, cop*

NOMENCLATURE

HTC-high-temperature circuit
LTC-low-temperature circuit
COP-coefficient of performance
η-efficiency
Subscripts
E-evaporation
C-condensation
ME-evaporating temperature of HTC
MC-condensing temperature of LTC
H-high-temperature circuit
L-low-temperature circuit
OPT optimum

I. INTRODUCTION

Naturally, heat transfer occurs from the region of higher temperature to lower temperature without requiring any external devices. The reverse process that is from lower temperature to higher temperature cannot occur by itself. It needed specially designed device called refrigerators. Refrigerator works on vapour compression refrigeration cycle. Vapour compression refrigeration system is a system which is used to transfer heat from low temperature energy reservoir to the high temperature reservoir by the use of working fluid known as a refrigerant. Many industrial applications requires low temperature refrigeration such as quick freezing, biomedical preservations, manufacturing of dry ice, liquefaction of petroleum vapours, pharmaceutical reactions etc. Where evaporating temperature requires between - 20ºC to-70ºC.

Single stage vapour compression system is not feasible for such application and its performance decreases for such low temperatures due to very high compression ratio that leads to high discharge problem and low volumetric efficiencies. Whereas Multistage or cascade systems are much efficient for such conditions

A cascade refrigeration system, employs two or more individual vapour compression refrigeration cycles operating at different pressure and different temperatures. The duty of the lower temperature cycle is to provide the desired refrigeration effect at a relatively low temperature. The condenser in the lower-temperature cycle is thermally coupled to the evaporator in the higher-temperature cycle. Thus, the evaporator in the higher cycle only serves to extract the heat released by the condenser in the lower cycle. Then this heat is rejected into the ambient air.

II. CASCADE SYSTEM DESCRIPTION

A cascade system comprises two separate vapour compression refrigeration cycles, each working with a different refrigerants, best suited for the working conditions. It is necessary to use a cascade system when the difference between the temperature at which heat is rejected and the temperature at which refrigeration is required is so large that a single refrigerant with suitable properties cannot be found. A schematic diagram of a two-stage cascade refrigeration system is shown in Fig.1. This cascade system comprises of two separate refrigeration circuits, the high-temperature circuit (HTC) and the low-temperature circuit (LTC). Each refrigeration system consists of a compressor, a condenser, an expansion valve and an evaporator. In this study 1, 1, 1, 2-tetrafluoroetane(R 134a) is the refrigerant in HTC, whereas isobutane (R 600a), because of its thermo-physical properties, is the refrigerant in LTC. The circuits are thermally connected to each other through a cascade condenser, which acts as an evaporator for the HTC and a condenser for the LTC. Fig. 1 shows that the condenser in this cascade refrigeration system rejects a heat flow Q_H from the condenser at condensing temperature of T_C, to its condensing medium or environment. The evaporator of this cascade system absorbs the cooling load *QL* from the cooling space to the evaporating temperature T_E. The heat absorbed by the evaporator of the LTC plus the work input to the LTC compressor equals the heat absorbed by the evaporator of the HTC. TMC and TME represent the condensing and evaporating temperatures of the cascade condenser, respectively. ΔT=TMC – TME represents the difference between the condensing temperature of LTC and the evaporating temperature of HTC.

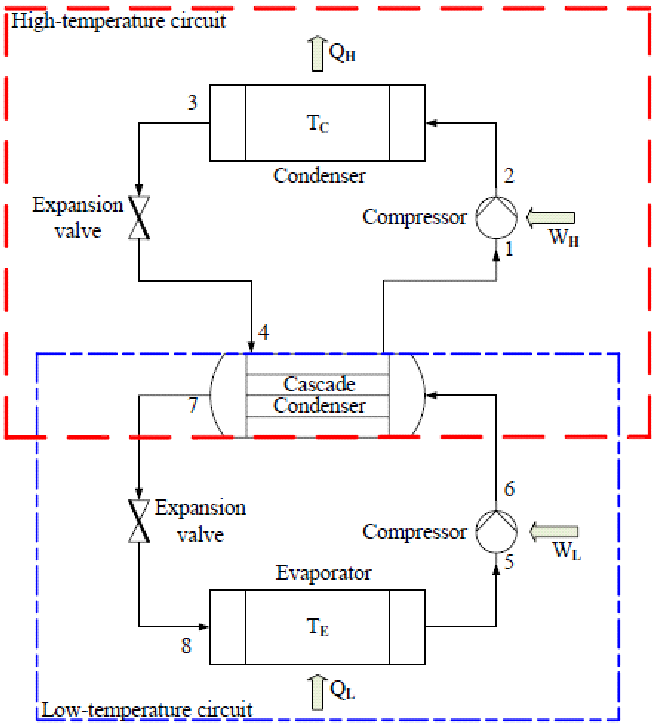

Fig.1 Pictorial representation of cascade system

The evaporating temperature TE, the condensing temperature TC, and the temperature difference in the cascade condenser are three important design parameters of a cascade refrigeration system.

III. PHASE CHANGE MATERIALS

Phase change materials (PCM) absorb and release heat as it undergoes a phase change from solid to liquid or liquid to gas or reverse. Phase change materials uses changes in phase (melting or freezing) to absorb large amounts of heat at nearly constant temperatures. The principle behind this is that phase change materials have large values of latent heat, and hence are able to absorb a lot of heat without any change in their temperature. When a solid material is getting heated, its temperature raises. If the amount of heat is large enough, the solid will start melting. At that point, during the melting process, the temperature will stay constant and the thermal energy is absorbed by the material. By absorbing this so-called latent heat, a temporarily cluster of energy is formed. The temperature will increase again if the material is totally molten and does so until it reaches its boiling point. Then the same process happens again and again, temperature during the phase change stays constant. When the material is cooled down, the process will take place in opposite direction.
A PCM behave like physical principle, but unlike conventional (sensible) storage materials, PCMs absorb and release heat at a nearly constant temperature. They store 5-10 times more heat per unit volume than sensible storage materials. Thus PCM is a material that is capable of storing latent heat and therefore might improve the total heat carrying capacity.

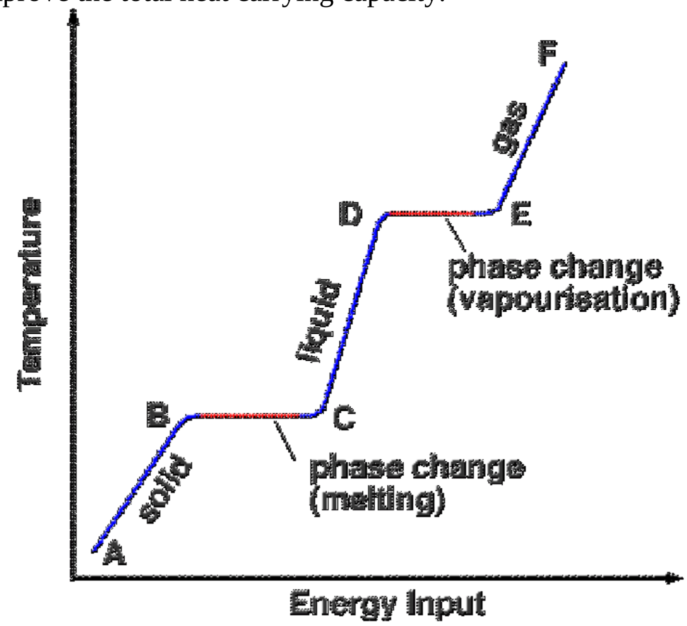

Fig.2 Phase transformation with respect to Temperature

Figure.2 explain the mechanisms of heat absorption and release in LHS materials. From the figure.2 it is clearly understood that at the melting point, as the temperature of the PCM rises, gradually their chemical bonds break up as the material changes its phase from solid to liquid. The phase change is a heat absorbing (endothermic) process and as a result the PCM absorbs large quantity of heat without getting hotter, i.e. while storing heat, the temperature of the PCM remains almost constant until the melting process completed. It is another means of storing energy by using phase change materials. The energy density could be increased by using PCM, having a phase change within the temperature range of the storage.

IV. USING PCM AS LATENT HEAT STORAGE SYSTEM

If PCM is used in the cabin then it will take most of the heat by changing its phase from solid to liquid. The temperature is constant until the melting process in finished. Moreover, if the PCM is touched with the evaporator coil the stored heat energy of PCM will be extracted by the refrigerant through conduction method during compressor on mode. The conduction transfer is faster than the natural convection heat transfer. In the conventional refrigerator the cabinet heat is extracted by the refrigerant through natural convection. So the PCM will improve the heat transfer performance of the evaporator also.

Types of PCM

PCMs are derived from several sources and are broadly categorized into three categories. Organic (naturally occur-ring petroleum by-products) Bio-based (fatty acids such as vegetable oils) and In-organic (engineered hydrated salt solution made from natural salts with water). Of these types, inorganic PCMs have a clear advantage over the others since they are man-made and can thus be tailored to meet specific requirements. For example, special nucleating agents are added to minimize phase change salt separation and super cooling. Traits that are otherwise characteristic of hydrated salts.

Method of selection of PCM materials

Thermo- physical properties

1. The melting point of a PCM must be lying in a practical range of operation.
2. The latent heat should be as high as possible to minimize the physical size of the heat storage.
3. It must have limited changes in density to avoid problems with storage tank
4. Low vapour pressure
5. Favorable phase equilibrium.

Chemical properties,

1. A suitable material should be non-toxic
2. Nonflammable,
3. Non-corrosive
4. Process complete reversible freeze/melt cycle
5. Non explosive

Economic properties

1. Less cost
2. Plenty available

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 percent 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.

$$C_2H_4O + H_2O \rightarrow HO–CH_2CH_2–OH$$

OBJECTIVES

a) To fabricate the experimental set up by modifying the cascade refrigerator with PCM based refrigerator.
b) To observe the effects of phase change material on COP.
c) To observe the difference on the Coefficient of performance of the refrigerator cycle with PCM and without PCM.
d) To observe the time taken for temperature drop from -20^{o}c to 0^{o}c with and without phase change material

V. DESIGN OF CASCADE SYSTEM

Test rig is cascade refrigeration system. Figure 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

Fig.3 Experimental setup

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 compressor1.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 vapor this vapour refrigerant is entering into the compressor, and then the cycle is repeated

Lower temperature cycle

Ø 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 places 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 materiel.
- 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 stores this cooling for a long period of time and extract the heat from the refrigerated space.

Compressor details Used in both cycles

- Compressor Power = 0.167 H.P

1 H.P = 746 W

So Power = 0.167×746=124.582

We use Reciprocating piston type compressor.

- Speed= 2850 R.P.M
- Volts= 160/250v AC

- Cycles = 50 Hz

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

- 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 30 liters

- Length of the evaporator coil = 30ft.
- 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 20 Liters.
- Length of the evaporator coil = 30ft.
- Diameter of the evaporating coil = 1/4 inch

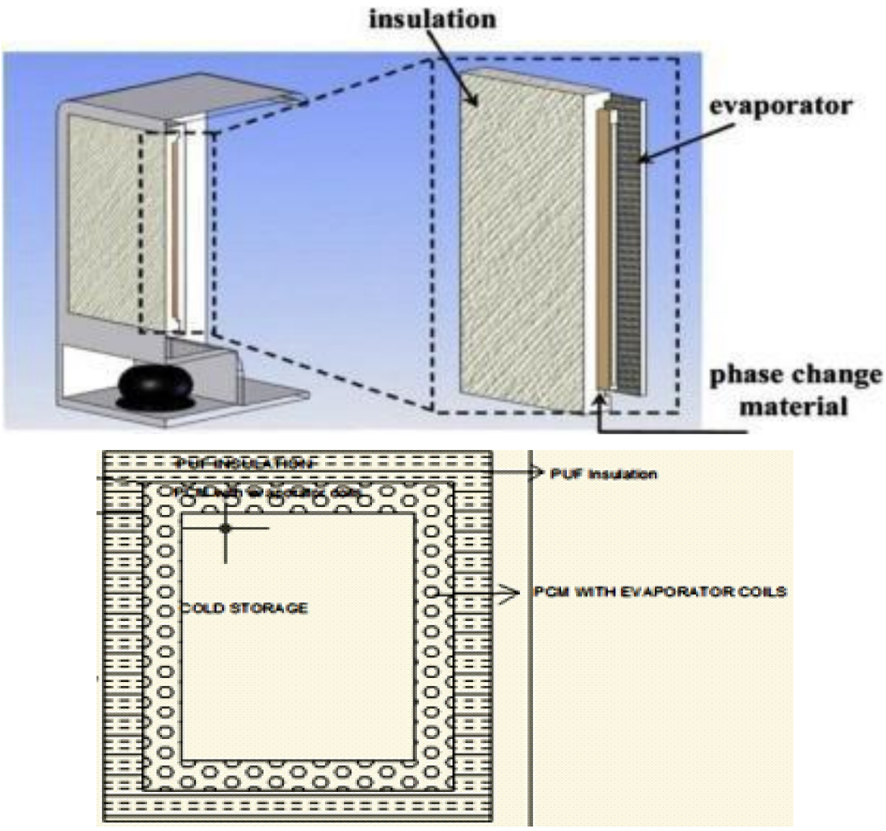

Fig.4 Schematic diagram of evaporator incorporated with PCM and insulation

The evaporator coil and phase change material (PCM) are placed in one panel, the PCM will absorbs 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

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 and R600a 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

1) Initially the first cycle is run till the evaporator temp becomes 0ºC, and then stopped.
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 -20ºC.
6) Without pcm, the time for temperature decrement in cold storage for every degree centigrade is recorded, till the temperature reaches 0ºC.
7) With pcm, the time for temperature decrement in cold storage for every degree centigrade is recorded, till the temperature reaches 0ºC
8) Calculations are made for Refrigeration Effect, work done &COP for the cascade cycle.

VI. THERMODYNAMIC ANALYSIS OF CASCADE SYSTEM

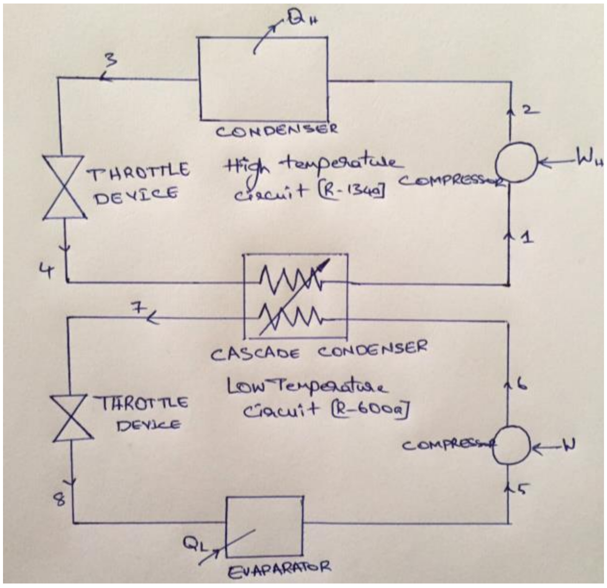

Fig.5 cascade system

Considering Figure the below equations were used for the thermodynamic analysis,
The evaporator load is given by "Equation (1)":

$$Q_E = m_L\,(h_5 - h_8)\ ....(1)$$

Work done by the compressor of higher-temperature circuit is given by "Equation (2)":

$$WH = m_H\,(h_2 - h_1)........(2)$$

Where,

m_L is the flow rate of refrigerant in the low temperature cascade system and
m_H is the flow rate of refrigerant in the high temperature cascade system.
Work done by the Compressor in low-temperature circuit, it is given by “Equation (3)”:

$$WL = m_L(h_6 – h_5)\text{...........}(3)$$

The rate of heat transfer in the cascade heat exchanger is given by “Equation (4)”:

$$Q_{CAS} = m_L(h_6 – h_7) = m_H(h_1 – h_4)\text{........}(4)$$

The rate of heat rejection by the condenser is given by “Equation (5)”:

$$QH = m_H(h_2 – h_3)\text{.........}(5)$$

The coefficient of performance of the system is given by “Equation (6)”:

$$COP=QW/(W_H+W_L+)\text{ ....}(6)$$

Assumptions

The following assumptions are made to simplify the thermodynamic analysis.
1. All components are assumed to operate at a steady state.
2. The high and low temperature circuit compressors are adiabatic but non isentropic.
3. Heat transfer process in heat exchanger is isobaric.
4. The heat loss and pressure drops in the piping connecting the components are negligible.
5. All throttling devices are isenthalpic.
6. The changes in the potential and the kinetic energy of the working fluids across each components are negligible.

Based on the assumptions described above, the balanced equations are applied to find the work input to the compressor, the heat transfer rates of condenser, and COP of the cascade system.

VII. RESULTS AND DISCUSSION

Cascade System without PCM

After conducting experimentation the readings are noted and tabulated as below:

Table 1 First cycle, cascade system without pcm

First cycle(higher temperature cycle)							
Compressor suction		Compressor discharge		Condenser outlet		Evaporator inlet	
Pressure	Temperature	Pressure	Temperature	Pressure	Temperature	Pressure	Temperature
1.765bar	20˚	11.772bar	75˚	11.772bar	35˚	1.765bar	-5˚

Table 2 second cycle, cascade system without pcm

Second cycle(low temperature cycle)							
Compressor suction		Compressor discharge		Condenser outlet		Evaporator inlet	
Pressure	Temperature	Pressure	Temperature	Pressure	Temperature	Pressure	Temperature
1.17bar	9˚	7.2bar	59˚	7.2bar	19˚	1.17bar	-25˚

Cascade System with Pcm

Table 3 First cycle, cascade system with pcm

First cycle(higher temperature cycle)							
Compressor suction		Compressor discharge		Condenser outlet		Evaporator inlet	
Pressure	Temperature	Pressure	Temperature	Pressure	Temperature	Pressure	Temperature
1.765bar	20˚	11.772bar	75˚	11.772bar	35˚	1.765bar	-5˚

Table 4 Second cycle, cascade system with pcm

Second cycle(low temperature cycle)							
Compressor suction		Compressor discharge		Condenser outlet		Evaporator inlet	
Pressure	Temperature	Pressure	Temperature	Pressure	Temperature	Pressure	Temperature
1.5bar	10˚	6.5bar	53˚	6.5bar	16˚	1.5bar	-25˚

From the noted compressor and temperature readings we plot on the LOG P versus H for R-134a and R-600a separately and extract the corresponding specific enthalpies from log P versus H plot. We substitute this enthalpies in above thermodynamic analysis and we find the cop.

cop without pcm=3.709

cop with pcm =4.156

Time for Every 1°c Decrement without Pcm Graph

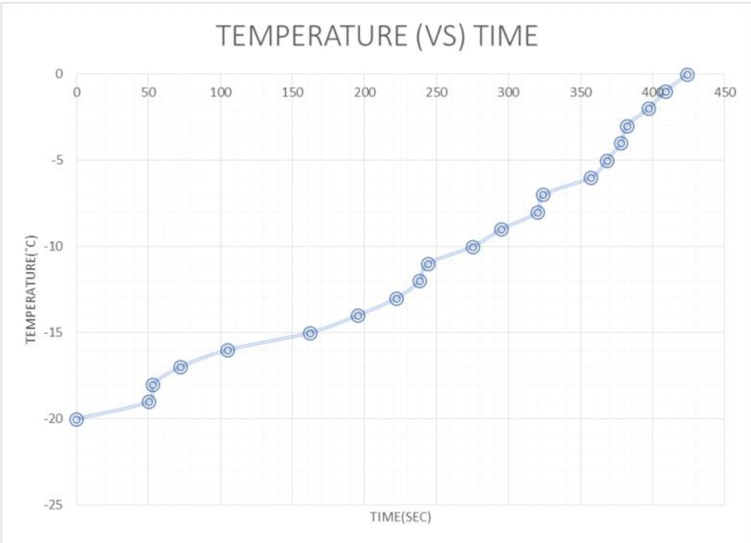

Fig.6 Time for Every 1°c Decrement without Pcm Graph

Time for Every 1°c Decrement with Pcm Graph

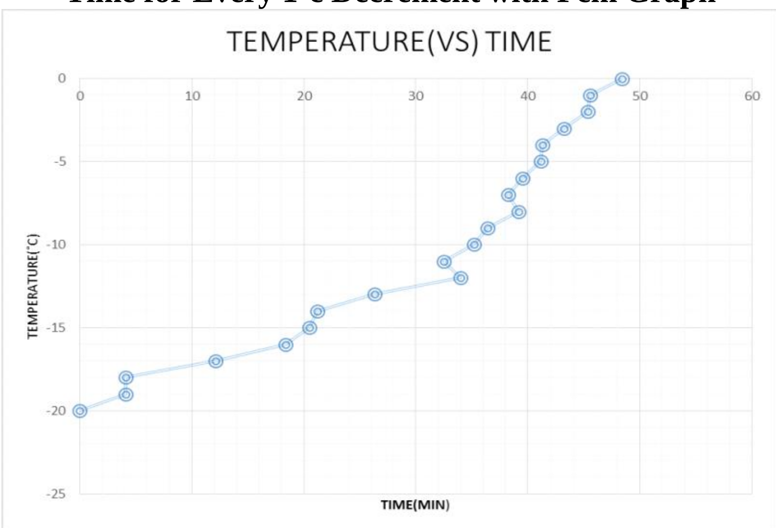

Fig.7 Time for Every 1°c Decrement with Pcm Graph

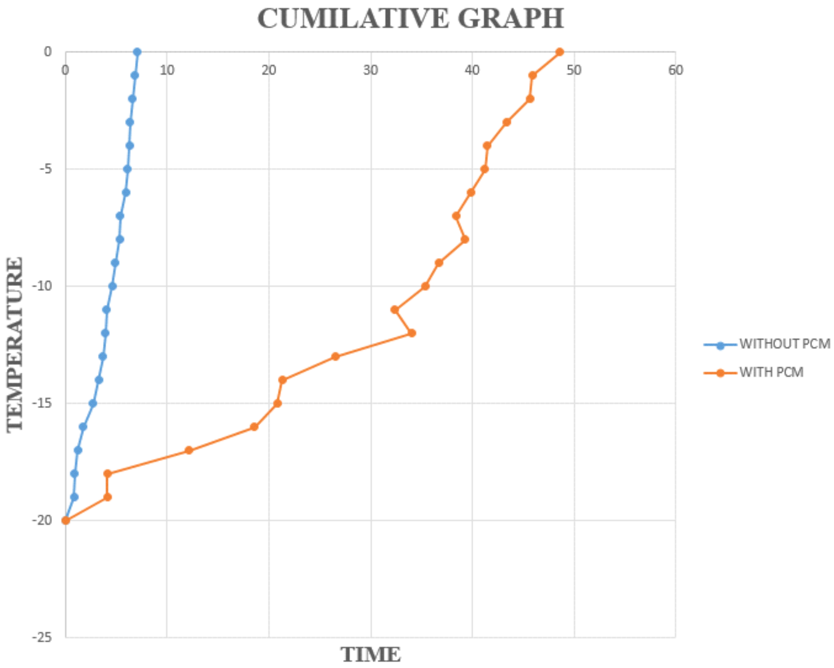

Fig.8 cumulative graph

The above graphs 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 fast with respect to time. It takes a time of 1 hour 27 minutes. 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 10 hours 30 minutes. With this by using PCM panel we retain the cooling effect for a long period of time. The retained time using PCM is 9 hours 3 minutes than that the retained time without using PCM.

VIII. CONCLUSIONS

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

1. From the experimentation it is observed that in Cascade (Binary) refrigeration system with pcm the cop can be increased by 12.05% as compared to cascade system without pcm for producing -20˚C in the cold storage

2. Experimental results shows that for fall of temperature from -20˚Cto 0˚Cwithout phase change material, takes 1 hours 27 min time whereas the same by using phase change material it takes 10 hours 30 min time. So with phase change material (PCM) panels at the walls of a cold storage, temperature can be retained for long period of time.

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.

REFERENCES

[1] Cabeza, L.F., Mehling, H., Hiebler, S., Ziegler, F. (2002). Heat transfer enhancement in water when used as PCM in thermal energy storage. Applied Thermal Engineering, vol. 22, p. 1141-1151.
[2] Butala, V., Stritih, U. (2009). Experimental investigation of PCM cold storage. Energy and Buildings, vol. 41, no. 3, p. 354-359.
[3] Vakilaltojjar, S.M., and Saman, W. (2001). Analysis and modelling of a phase change storage system for air conditioning applications. Appl. Thermal Eng., 21, 249-263.
[4] Omer, S.A., Riffat, S.B., and Ma, X. (2001). Experimental investigation of a thermoelectric refrigeration

system employing a phase change material integrated with thermal diode (thermosyphons). Appl. Thermal Eng., 21, 1265-1271.
[5] Riffat, S.B., Omer, S.A., and Ma, X. (2001). A novel thermoelectric refrigeration system employing heat pipes and a phase change material: an experimental investigation, Renew. Energy, 23, 313-323.
[6] Energy efficiency and Managing in hotel and commercial building. Ten Publications. 2000 Edition.65.
[7]Eckhard, A Groll Jianyi Zhang., "Energy Saving in Refrigerated Warehouse using PCM ethylene, Air Conditioning and Refrigeration Journal, China, April-June 2001.
[8] Gupta, P., "Cooling Tower Impact Blade Modification on Energy Consumption", A Conditioning and Refrigeration Journal, New Delhi, October-December 2001.
[9] Stulz Gmb, H., "Comfort Air Precision or Conditioning", Air Conditioning and Refrigeration Journal, Germany, January-March 2002.
[10] GeorgeSze, Lek Siang Hwa., " HVAC hospital Design: A Challenge for Energy Recovery and Reliability System ", Air Conditioning and Refrigeration Journal. Singapore, July-September 2002.
[11] Effect of phase change material on performance of a house hold refrigerator, MD Imran Hossaen Khan & Hassan M.M Afroz
[12] B. Zalba, J.M. Marı´n, L.F. Cabeza, H. Mehling, Freecooling of buildings with phase change materials, International Journal of Refrigeration 27 (8) (2004) 839–849
[13] B. He, F. Setterwall, Technical grade paraffin waxes as phase change materials for cool thermal storage and cool storage systems capital cost, Energy Conversion and Management 43 (2002) 1709–1723.
[14] S. Shibutani, PCM micro-capsule slurry thermal storage system.

AUTHORS

N.Ganesh babu, presently pursuing M. Tech in G. Pulla Reddy Engineering College (Autonomous), Kurnool, A.P, India. My Research interest on Refrigeration and air coditioing and fluid dynamics.

M.Lava Kumar, presently working as Assistant Professor in G. Pulla Reddy Engineering College (Autonomous), Kurnool, A.P, India. His Research interest on Refrigeration and Air-Conditioning.