IMPROVING ENERGY EFFICIENCY OF A VAPOR COMPRESSION REFRIGERATION SYSTEM USING A PHASE CHANGE MATERIAL

[1] Mallikarjuna Rao Dandu, [2] Dr. P. Vijaya Kumar, [3] J. Venkata Somi Reddy
[1]Assistant Professor, [2] Professor, [3] Assistant Professor
Mechanical Engineering Department,
Lakireddy Balireddy College of Engineering, Mylavaram, India.

Abstract: Latent heat storage is especially suited to the storage of energy to prolong the food preservation time and use the excessive stored energy to improve the freezer cooling cycle by its release at appropriate time. The principle of latent heat storage using phase change materials (PCMs) can be incorporated into a thermal storage system suitable for use in deep freezers. The objective of this work is to prolong compressor off time, to prolong the food preservation time and to save energy by storing thermal energy during low demand and release of this Energy during peak loads with potential by adding a few centimeter-thick slabs to the outer surface of the evaporator.

In this work deep freezer with a storage capacity of 80lit is fabricated with a PCM integrated evaporator. The eutectic salt solutions NaCl+H2O and Al (NO3)3+H2O used as PCMs. By conducting all the test, it was observed that the compressor off time is 6hrs more compared to system without PCM, food preservation time is prolonged from 7 to 15hrs and annual energy savings as Rs. 3,203 with NaCl+H2O and Rs. 3,006 with Al (NO3)3+H2O.

***Index Terms* - Energy storage, Energy storage, Cool thermal energy storage systems, The Plus ICE Range, Passive Cooling.**

I. INTRODUCTION

Phase Change Materials: Phases Change Materials (PCM) are also called as latent heat storage materials. Phase change materials (PCMs) have a strong ability to store energy and have an excellent characteristic of constant temperature during absorbing or releasing energy. The phase change is a heat-seeking (endothermic) process and therefore, the PCM absorbs heat. Upon storing heat in the storage material during low load condition, it releases energy in the high load condition.

The temperature then stays constant until the melting process is finished. The comparison between latent and sensible heat storage shows that using latent heat storage, storage densities typically 5 to 10 times higher can be reached. Latent heat storage can be used in a wide temperature range. Many PCMs are known to melt with a heat of fusion in any required range.

Classification of Phase Change Materials: There are large number of PCMs (organic, inorganic and eutectic), which can be identified as PCMs from the point of view melting temperature and latent heat of fusion. However, except for the melting point in the operating range, a majority of PCMs do not satisfy the criteria required for an adequate storage media. As no single material can have all the required properties for an ideal thermal storage media, one must use the available materials and try to make up for the poor physical properties by an adequate system design. For example, metallic fins can be used to increase the thermal conductivity of PCMs, super-cooling may be suppressed by introducing a nucleating agent in the storage material, and incongruent melting can be inhibited using a PCM of suitable thickness.

Phase change materials suitable for Cool Thermal Storage Systems: The phase change materials suitable for cool thermal storage are shown in below table with their properties.

commercially available phase change materials

MATERIALS	MELTING POINT (°C)	LATENT HEAT (kJ/kg)
SN-33	-33	245
TH-31	-31	131
SN-29	-29	233
TH-21	-21	222
SN-21	-21	240
STL-21	-21	289
STLN-10	-11	271
STL-6	-6	284
TH-4	-4	286
SNO3	-3	328
CLIMSEL-7	7	130
RT5	9	205
CLIMSEL-15	15	130
CLIMSEL-23	23	148

Thermal Energy Storage TES:

Thermal Energy Storage TES is the temporary storage of high or low temperature energy for later use, bridging the gap between requirement and energy use. The storage cycle might be daily, weekly or seasonal depending on the system design requirements, and whilst the output will always be thermal, the input may be thermal or electrical.

Advantages of TES:

Reduced running cost -load shifting provides reliable operation and lower annual electricity/energy running costs.

Reduced machinery -shifting some of the peak load may enable designers to reduce the main machine size.

Increased capacity -as a retrofit application, the additional TES load may increase the system output without any additional Machinery.

Green solution -reduced machine size means reduced energy consumption, giving lower direct and indirect CO2 emissions.

Flexible system -the overall machinery capacity and TES capacity can be exactly matched to system loads.

Stand-by capacity -incase the main machinery fails, the stored energy can be utilized to handle the system loads, thereby providing a degree of back-up facility.

II. EXPERIMENTATION

Selection of Phase Change Material:

Selection of latent heat storage material plays an important role in cool thermal storage systems. It mainly depends on the minimum temperature to be maintained in evaporator section. The temperature limit that should be maintained in deep freezers for maintaining the better food quality is -190C and -230C.Hence the PCM phase transition temperature should not be less than -190C.Two phase change materials are selected for cool thermal energy storage in the above temperature region, and their properties are listed below table.

MATERIALS	Melting Point (0C)	Thermal Conductivity (W/m K)	Melting enthalpy (kJ/kg)	Density (kg/m3)
NaCl (22.4wt. %) +H2O	-21.2	1.8 W / m K (solid) 0.6 W / m K (liquid)	222	1165 (liquid) 1108 (solid)
Al (NO3)3(25.4wt. %) + H2O	-25.1	-	131	1283 (liquid) 1251 (solid)

The performance of the vapor compression machine is tested with PCMs NaCl+H2O and Al (NO3)3+H2O as latent heat storage materials one at a time. The conventional vapor compression refrigeration machine incorporated with temperature and energy measuring devices is made ready for conducting the experiments with the different phase change materials.

Experimental Setup: The experimental setup consists of the conventional vapor-compression refrigerating machine which has the four main components compressor, condenser, capillary tube and evaporator coil. The experimental setup consists of the conventional vapor-compression refrigerating machine with proper instrumentation to measure temperature at evaporator section and to measure energy required by the system. An energy meter is used to measure the energy input to the compressor motor and temperature indicator is used to measure the temperature inside the evaporator. The schematic diagram of the experimental setup. The PCMs are bonded to the evaporator on the outer surface in order not to reduce storage capacity and not to pay any extra material for placing the PCMs

Here a measured quantity of 10 lit. solution with proportions of NaCl (22.4wt. %)+ H2O (77.6wt. %) and Al(NO3)3(30.5wt.%) + H2O (69.5wt. %) is encapsulated in polythene pouches and bonded to the outer surface of the evaporator to prolong the compressor off time and to analyze the energy efficiency of the conventional system. These PCMs are bonded to the evaporator on the outer surface in order not to reduce storage capacity and not to pay any extra material for placing the PCMs. Evaporator is insulated by puff material.

Specifications of the Refrigerating Machine:

A hermetically sealed reciprocating compressor is of 186.4W power and an air-cooled Al-fin and Cu tube condenser is used. The lubrication oil used in the compressor is mineral oil. The expansion device is a capillary tube of 0.036-inch diameter and 13 feet length. An evaporator tank with storage capacity of 80lit made of G. I. sheet of gauge (22).an evaporator coil of Cu material with dimensions (Diameter = 3/8inch, Length = 50feet) is aligned on the outer side of evaporator tank. Suction and discharge lines of sizes 3/8 inch, 1/4inch respectively are used. Phase change materials namely NaCl+H2O and Al (NO3)3+H2O are used. These PCMs are bonded to the evaporator on the outer surface in order not to reduce storage capacity and not to pay any extra material for placing the PCMs.

Test Procedure: The thermocouple is placed near all the sides of the cabinet to know temperature maintained inside the cabinet such as air center. The energy meter is connected between the compressor and the main supply in order to measure the amount of energy required by the compressor to run the system. The readings are noted according to the test performed.

No Load Test:

It is one of the fundamental tests to be performed. In this test, the compressor will be running continuously bypassing the thermostat. The thermocouples are placed at different locations as specified above. For every half an hour the temperatures are noted till steady state is reached. Significance of this test is to find out how much time is required to attain specified temperature at the air center. This test helps us to know how the system is running.

No load cycling test:

The system is run keeping the thermostat in cycling mode in the refrigeration system. As the temperature reaches specified highest set freezing temperature, the compressor stops which is called the cut-off time, and as the temperature inside the cabinet reaches lowest set freezing temperature, the compressor starts which is called the cut-in time, taking the power and maintaining the temperature inside the cabinet at stabilized condition. The compressor on/off can be noted down directly from the digital temperature control unit, which records the temperatures. Significance made through this is to find the time required to attain the specified temperature near the air center when freezer is in unloaded condition. And other is the compressor run percentage should be equal to or less than 80%.

Load Test:

In this test, the freezer is fully loaded, and the thermostat is by-passed. The thermocouples are placed at different locations as specified before excepting at the air Center and some thermocouples are noted till steady state is reached by the digital temperature control unit. Significance of this test is to find out how much time is required by the loaded product to attain the specified temperature. The system performance is tested according to center temperature of cabinet and time, which shows how the system runs at full load condition and how much time is required to pull down the load.

Load cycling test:

In this test, the thermostat is connected to the circuit at full load condition. As The temperature reaches highest set freezing temperature the compressor stops which is called the cut-off time, and as the temperature inside the cabinet reaches the lowest set freezing temperature, the compressor starts which is called the cut-in- time, taking the power maintaining the temperature inside the cabinet at stabilized condition. The compressor on/off can be noted down directly from the digital temperature control unit, which records the temperatures. Significance of this test is to find out how much time is required by the loaded product to attain the specified temperature at full load condition also shows how power is required by the compressor at cut-in and cut-off positions.

Energy Consumption:

Consumption by an appliance over a period of 24 hr when loaded with simulated frozen food storage test packagers, running under stable operating temperature.

Significance of this test is done for efficient energy consumption at full load condition, which indicates the running cost of the freezer. At full load condition the energy meter reading is noted down for every one hour till the system reaches the steady state temperature.

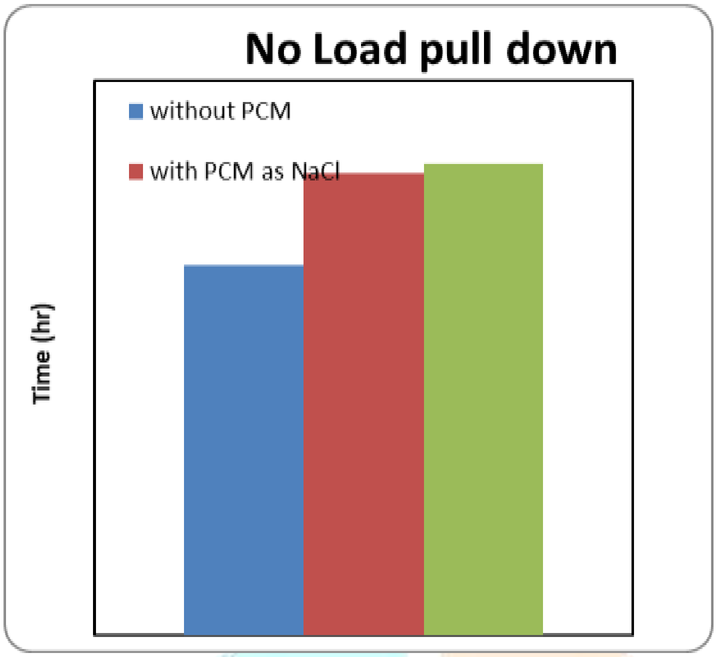
Load Pull Up Test:

Significance of this test is carried to find out the time required to store the product without any spoilage inside the freezer at power off conditions.

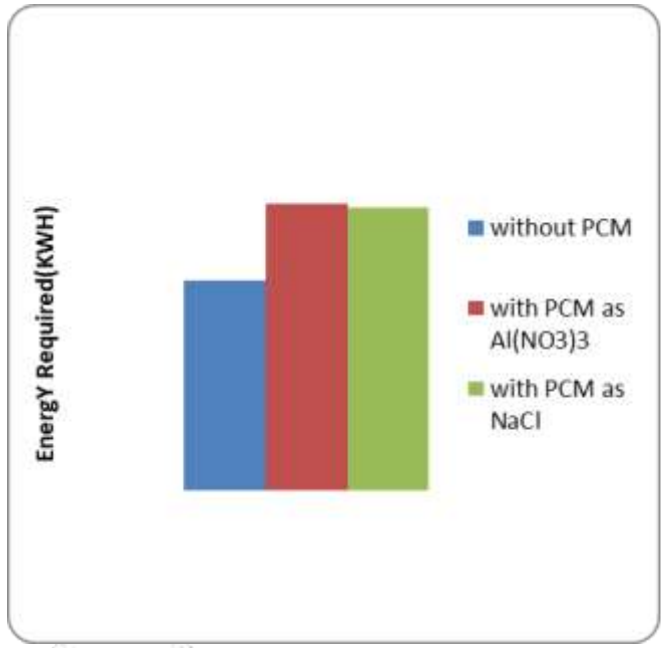
III. RESULTS AND DISCUSSIONS

No Load Pull Down Test:

The system without PCM is run for about 4hrs without load. After the steady state (-270C) reached the performance is analyzed by drawing graph between evaporator temperature and time at an input power of .92kWh.



Above figure represents time taken by systems with /without PCMs to reach the temperature -27^{0}C



Above figure represents energy consumed by the systems with/without PCMs to reach the temperature -27^{0}C.

Similarly, system with PCM material as NaCl+H2O is run for about 5hrs for acquiring steady state temperature -270C and analyzed by drawing graph between evaporator temperature and time at an input power of 1.24KWH. Now system with PCM material as Al(NO3)3+H2O is run for about 5hrs 10min for acquiring steady state temperature -270C and analyzed by drawing graph between evaporator temperature and time at an input power of 1.31KWH.

No Load Cycling Test:

With Out PCM:

As the temperature reaches -23.10C the compressor stops which is called cut-off time, and as the temperature inside reaches -190C the compressor starts which is called the cut-in time, taking the power and maintaining the temperature inside evaporator at stabilized condition. The system is run for 4 hrs 34 min. the performance is analyzed with the help of graphs.

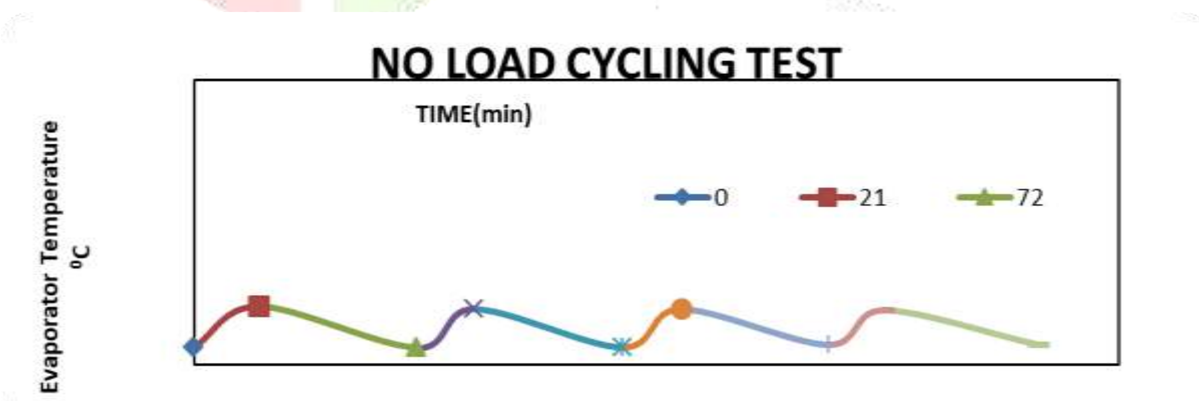
The energy required for one cycle (time period between two successive starts) to run the compressor is noted as 0.12KWH.

Cut-off time = 1hr 20min.

Cut-in time (run time) = 3hr 14min.

Total time= cut-off time + cut-in time = 274min.

Run percentage time= (run time/total time) * 100% = (194/274) * 100% = 71%



Above figure represents cot-off,cut-in time of compressor with corresponding evaporator temperatures for the system without PCM.

With PCM NaCl+H2O:

The system is run for 7 hrs. the performance is analyzed with the help of graphs.

The energy required for one cycle (time between two successive starts) to run the compressor is noted as 0.28KWH.

Cut-off time = 5hr 45min.

Cut-in time (run time) = 1hr 20min.

Total time= cut-off time + cut-in time = 6hrs 59min.
Run percentage time= (run time/total time) * 100% = (1.34/7) * 100% = 19.14%

With PCM Al (NO3)3+H2O:

The system is run for 7 hrs. the performance is analyzed with the help of graphs.
The energy required for one cycle (time between two successive starts) to run the compressor is noted as 0.30KWH.
Cut-off time = 5hr 55min.
Cut-in time (run time) = 1hr 21min.
Total time= cut-off time + cut-in time = 7hrs 16min.
Run percentage time= (run time/total time) * 100%= (1.32/7.2) * 100% = 18.33%
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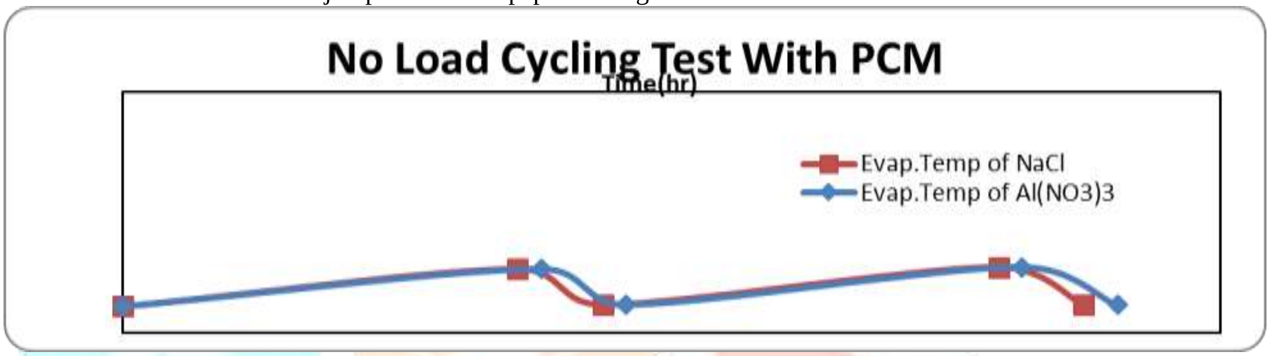
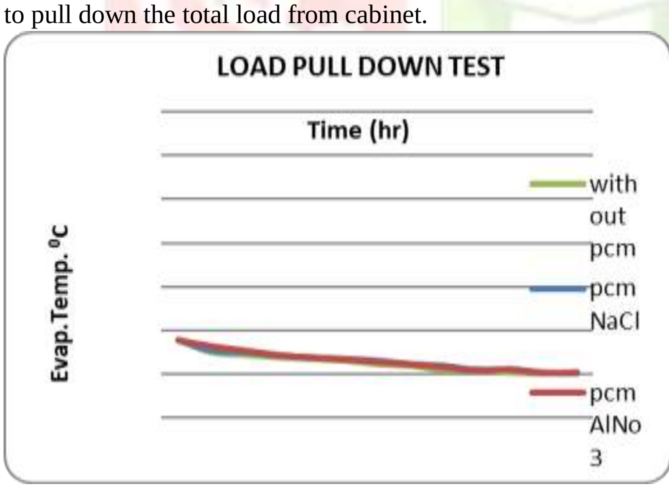


Above figure represents cot-off,cut-in time of compressor with corresponding evaporator temperatures for the system with PCM.

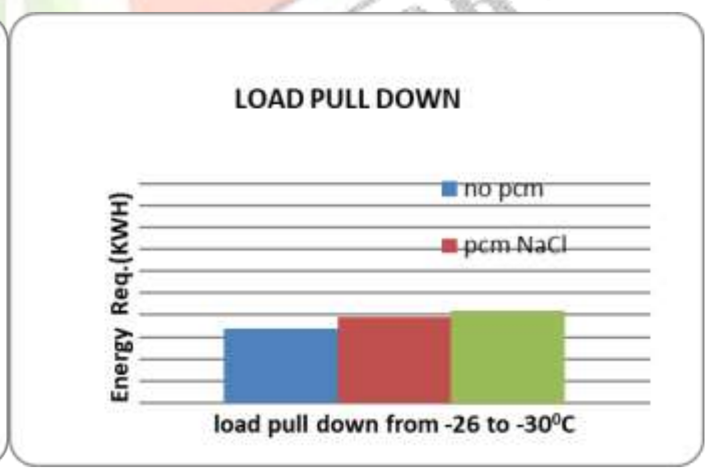
Load Pull Down Test:

The system is made to run at full load condition, the evaporator temperature comes to steady state condition in 11 hrs 30min time. The energy taken by the system is 2.17KWH. This would be the maximum power required to pull down the total load from cabinet. The system with PCM material NaCl+H2O is made to run at full load condition, the evaporator temperature comes to steady state condition in 12hrs time. The energy taken by the system is 2.19KWH. This would be the maximum power required to pull down the total load from cabinet.

The system with PCM material Al (NO3)3+H2O is made to run at full load condition, the evaporator temperature comes to steady state condition in 12hrs 25min time. The energy taken by the system is 2.21KWH. This would be the maximum power required to pull down the total load from cabinet.



Above figure represents time taken by the systems with/ without PCMs to pull the temperature from -26.10C to -30.10C at full load condition.



Above figure represents energy consumed by the systems with/ without PCMs to to pull the temperature from -26.10C to -30.10C at full load condition.

Load cycling test:
For load 50 liters:
(i)Without PCM:

As the temperature reaches -230C the compressor stops which is called cut-off time, and as the temperature inside reaches -190C the compressor starts which is called the cut-in time, taking the power and maintaining the temperature inside evaporator at stabilized condition.

Cut-off time = 2hrs 2min.
Cut-in time (run time) = 7hrs 19min.
Total time= cut-off time + cut-in time = 9hrs 20min.
Run percentage time= (run time/total time) * 100% = (7.31/9.33) * 100% = 78.34%

(ii)With PCM NaCl+H2O:

Cut-off time = 8hr 9min.
Cut-in time (run time) = 7hr 44min.
Total time= cut-off time + cut-in time = 15hrs 52min.
Run percentage time= (run time/total time) * 100% = (7.9/15.86) * 100% = 49%

(iii)With PCM Al (NO3)3+H2O:

Cut-off time = 8hr.
Cut-in time (run time) = 7hr 53min.
Total time= cut-off time + cut-in time = 15hrs 53min.
Run percentage time = (run time/total time) * 100% = (7.89/15.9) * 100% = 49.6%

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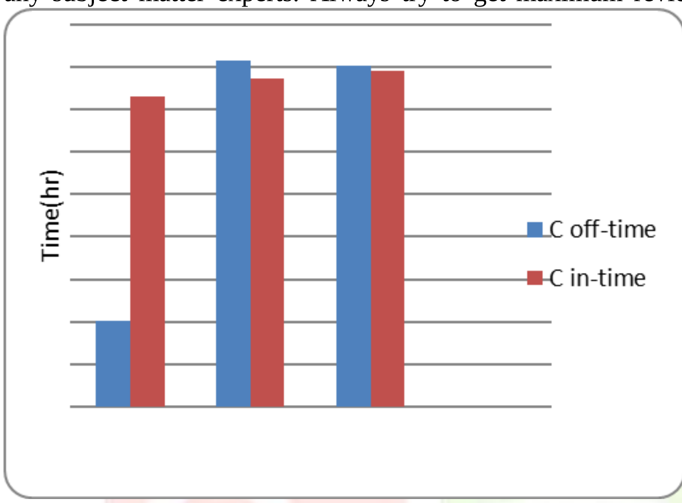
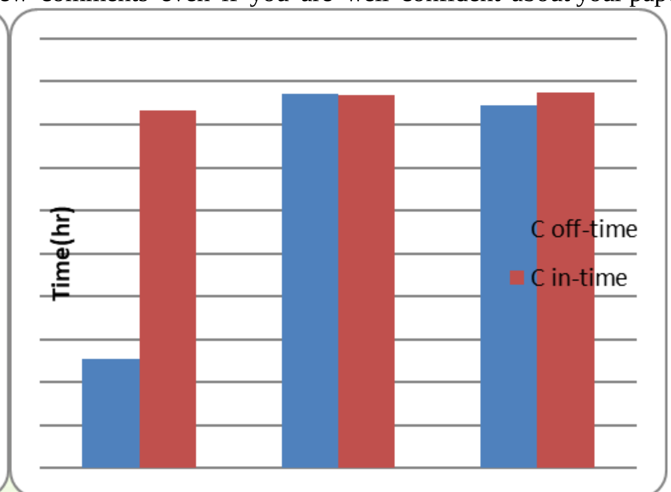


Above graph it is observed that cutt-off time is increased With PCM NaCl+H2O about 6hrs 8min and With PCM Al (NO3)3+H2O is about 5hrs 59min.



The above graph it is observed that cutt-off time is increased With PCM NaCl+H2O about 6hrs 10min and With PCM Al (NO3)3+H2O is about 5hrs 55min.

For load 60 liters:

Run percentage time Without PCM= (run time/total time) * 100% = 79.5%
Run percentage time With PCM NaCl+H2O = (run time/total time) * 100% = 50%
Run percentage time With PCM Al (NO3)3+H2O = (run time/total time) * 100% = 51%

Cost Analysis:

At no load:

By Considering the cut-in, cut-off time of compressor to maintain the temperature range -190C to -230C in evaporator as one cycle.

i. System without PCM:

The energy required for one cycle (time between two successive starts) to run the compressor = 0.12KWH.
Compressor off time = 25min.

ii. System with PCM (NaCl+H2O):

The energy required for one cycle (time between two successive starts) to run the compressor = 0.28KWH.
Compressor off time = 5hrs 45min.
Difference = (0.28 KWh - 0.12KWh) = 0.16 KWh
Time gaining per cycle = 5hrs 30min.
Capacity of compressor = 186.4 W
Energy saving of NaCl+H2O per cycle = (.1864*5.5 kW-h) – (0.16KWh) = 0.865 KW-h
Cost of 1 unit power (kW-h) = 6 Rs
Energy saving of NaCl+H2O per day in kW-h = (0.865*3.2) kW-h = 2.81 KWh. = 2.81*6 Rs. = 16.86 Rs.
Annual energy saving of NaCl+H2O = 6,154Rs

iii. System with PCM (Al (NO3)3+H2O):

The energy required for one cycle (time between two successive starts) to run the compressor = 0.27KWH.
Compressor off time = 6hrs 5min.

Difference = (0.27 KWh - 0.12KWh) = 0.17 KWh
Time gaining per cycle = 5hrs 40min.
Capacity of compressor = 186.4 W
Energy saving of **Al (NO3)3+H2O** per cycle = (.1864*5.67 kW-h) – (0.17KWh) = 0.886 KW-h
Cost of 1 unit power (kW-h) = 6 Rs
Energy saving of **Al (NO3)3+H2O** per day in kW-h = (.886*3.25) kW-h = 2.88*6 Rs. = 17.27 Rs.
Annual energy saving of Al (NO3)3+H2O = 6,306 Rs.

At 50lit load: By Considering the cut-in, cut-off time of compressor to maintain the temperature range -190C to -230C in evaporator as one cycle

i. System without PCM:
The energy required for one cycle (time between two successive starts) to run the compressor = 1.47 KWh.
Compressor off time = 2hr

ii. System with PCM (NaCl+H2O):
The energy required for one cycle (time between two successive starts) to run the compressor = 1.63KWH.
Compressor off time = 8 hrs 9min.
Difference = (1.63 KWh – 1.47KWh) = 0.16 KWh
Time gaining per cycle = 6hrs 8min.
Capacity of compressor = 186.4 W
Energy saving of NaCl+H2O per cycle = (.1864*6.133 kW-h) – (0.16KWh)= 0.983KW-h
No of cycles per 48 hrs = 3
Cost of 1 unit power (kW-h) = 6 Rs
Energy saving of NaCl+H2O per 48 hrs in kW-h = (.983*3) kW-h = 2.94 KWh.
Energy saving of NaCl+H2O per day = 1.47 kWh = Rs. 8.84
Annual energy saving of NaCl+H2O = 536.55 kWh = 3,230/-

iii. System with PCM (Al (NO3)3+H2O):
The energy required for one cycle (time between two successive starts) to run the compressor = 1.8KWH.
Compressor off time = 8 hrs
Difference = (1.8 KWh – 1.47KWh) = 0.33 KWh
Time gaining per cycle = 6hrs.
Capacity of compressor = 186.4 W
Energy saving of Al (NO3)3+H2O per cycle = (.1864*6 kW-h) – (0.33KWh) = 0.788 KW-h
No of cycles per 48 hrs = 3
Cost of 1 unit power (kW-h) = 6 Rs
Energy saving of Al (NO3)3+H2O per 48 hrs in kW-h = (0.788*3) kW-h = 2.37 KWh.
Energy saving of Al (NO3)3+H2O per day = 1.185 kWh = Rs 7.11
Annual energy saving of Al (NO3)3+H2O = 432.5 kWh = Rs 2,595

By doing all calculations it is concluded that using PCM for a conventional deep freezer which is working with a load 62 to 75% can save a sum of rupees tabulated below by taking average.

Load Pull Up Test:
After switching off the system the time is noted to reach the temperature inside the evaporator from-230C to -90C. This is the time required to store the product without spoiling inside the freezer at power off conditions is noted as 15hr

Energy savings with PCM

PCM	Annual energy saving(Rs)
NaCl+H2O	3,200
Al (NO3)3+H2O	2,563

Comparison of systems with PCM and without PCM

	system without PCM	system with PCM NaCl+H2O	System with PCM Al(NO3)3+H2O
Compressor off time (per cycle)	2 hrs	8hrs 9min.	7 hrs 55min.
Run percentage time(per cycle)	79%	49%	49.6%
energy savings (per day)	-	1.47 kWh	1.18 kWh
		Rs 8.80	Rs 7.11

IV. CONCLUSIONS

The vapor compression system was tested with R134a in the presence of latent heat storage materials. Considering the cut-in, cut-off time of compressor to maintain the temperature range -190C to -230C in evaporator as one cycle,

- The compressor off time of the system without PCM is about 2hrs.
- The compressor off time of the system with PCM NaCl+H2O is increased about 6hrs 8min.

- The compressor off time of the system by using PCM Al (NO3)3+H2O is increased about 5hrs 55min With PCM Al (NO3)3+H2O.
- Compressor Run percentage time With PCM NaCl+H2O is reduced from 79% to 49%.
- Compressor Run percentage time With PCM Al (NO3)3+H2O is reduced to 49.6%
- Annual energy savings:
- By increasing compressor off time to 6hrs 45 min Using PCM NaCl+H2O for a deep freezer can save annually Rs 3,200 and by increasing compressor off time to 6hrs 31 min using PCM Al (NO3)3+H2O can save Rs 2,563 compared to the system without PCM.
- After switching off the system the time to reach the temperature inside the evaporator from-230C to -90C is noted as 15hrs. This is the time required to store the product without spoiling inside the freezer at power off conditions.
- The extra amount we need to invest for providing the PCM (NaCl+H2O) is about 300/- and for providing PCM (Al (NO3)3+H2O) the extra amount we need to invest is 800/-.
- Comparing all the experimental results a vapor compression system with phase change material as NaCl+H2O is suitable economically than a system without PCM.

Considering the cut-in, cut-off time of compressor to maintain the temperature range -190C to -230C in evaporator as one cycle.

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