Experimental Investigation on Thermal Performance of Evaporator using PCM

S Panneerselvam*1 and V Mathanraj1

Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, India.

* Corresponding author: panneers@srmist.edu.in

Abstract: The project is mainly focused on improving the performance of evaporator using the phase change materials (PCM) associated with the evaporator in a refrigeration system. The usage of phase change material (PCM) to improve the withstand time of the evaporator temperature and also enhances the heat transfer rate thus improve the COP (Coefficient of performance) of refrigeration. Using Sodium chloride, Magnesium Chloride and Diethylene glycol as PCM and for a certain thermal load it is found that with stand time of evaporator increased by 48 minutes and the COP (Coefficient of performance) of the conventional refrigerator increased up to 35 per cent. Here the phase change material (PCM) used in a chamber built manually and which surrounds the Evaporator chamber of a refrigeration system. On considering the PCMs with remarkable properties such as low freezing point, increases with stand time remarkably and also improves the COP (Coefficient of performance) the refrigeration system. Also, performance range of the refrigerant R407c And R134a has been studied along with the effects of the PCM named above in the both systems.

1. Introduction

Wenlong Cheng in his paper talks about units in the household refrigerators that directly affect the efficiency namely evaporating units and condensing units. To improve performance of these units, energy storage refrigerator is proposed providing storage facilities near both evaporating and condensing unit. With these incorporation and the best observation showed 32 per cent conservation of the usage of electrical sources. The ratio of the time the compressor was switched off to that of it being switched on was 4.3. Schalbart and D. Leducq in their paper they explained that energy optimization of an ice cream warehouse refrigeration was required and for that a model predictive controller was developed connected to a PCM tank. The steady state refrigeration cycle model was taken as the base to model the controller internal part. This study showed that when the model predictive controller was used the energy consumption was
reduced and the quality of food was sustained.

Ahmed A. Altohamy and M.F. Abd Rabbo experimentally studied about a nanofluid 50nm Al2O3 PCM in a spherical capsule and the nanofluid was water based. Aqua ethylene glycol was the heat transfer fluid (HTF) used. The capsule wall temperature was maintained at minus 4 to minus 10 NACL. Pure water was used to conduct the experiment and the nanoparticles in the used PCM were of volume fractions 0.5, 1, 1.5, and 2(per cent). Complete charging time for all HTF volume flow rates reduces when there is a significant increase in the nanoparticles concentration in the PCM. At the flow rates of 12, 10, 8, 6 lpm at HTF inlet temperature 12C, a decrease in time it took to charge completely was observed which was approximately 32, 28, 18 and 12(per cent) respectively. Imran Hussain and R. Dinesh in their article study both thermal and physical properties of materials that are capable of storing energy for the purpose of cold storage. These material are eutectic based that store latent energy (Oleic and Capric acid).

Nucleators are used to enhance thermophysical properties. Nanosheets made from highly porous activate carbon were synthesized to use as nucleators. The interaction of Activated carbon was only physical and no exothermic or endothermic reactions.

Vikul Vasudev and Raja Sekhar Dondapati talks about using absorption refrigeration systems for cooling applications as there is an increasing demand for electricity. The Hermetic compressors are used to raise the pressure in compression system, but it requires a lot of power input to work. Absorption systems uses much lesser energy input and it does not harm the environment, but it can work at the same level. In the Evaporator of an Ammonia/Water absorption system, ethylene glycol is installed as a latent heat storage substance to study its transient effects on temperature. Temperature inside the Evaporator began to rise at a very fast rate due to heat generation and infiltration when the system was unexpectedly shutdown. It is proved experimentally in this paper that Ethylene Glycol reduces this rate significantly and protects the quality of the products stored inside. Chetan Tulapurkar and Pradip Radhakrishnan Subramaniam had come up with an idea to facilitate thermal storage in refrigeration systems by designing a domestic refrigerator with a novel dual evaporator with explanations and calculations. In that, the thermal storage could be achieved with help of PCM and also it had the potential to improve COP by sub cooling. This idea could be incorporated in both single and dual evaporator systems in commonly used refrigerators which have both refrigerator and freezer. M.Surendra Reddy, G.Venkatesh, K.Jayasimha Reddy and B.Suresh talk about thermal energy and their storage through phase change material has been used for wide applications in the field of air conditioning and refrigeration. The principle of latent heat storage using phase change materials (PCM) can be incorporated into a thermal storage system suitable for using deep freezers. The evaporator is covered with another box which has storage capacity or passage through phase change material.

2. Objective and pcmselection
The motive of this project is to improve the Thermal performance of the evaporator using Phase change materials (PCM). The objectives are as follows

1. To improve the withstand time of the Evaporator in the Refrigeration Setup.
2. To improve the COP (coefficient of performance) of the refrigeration system using the PCM.
3. To improve the Energy Conservation.
4. To reduce the Global warming.

5. Study the refrigerant R407c.

By using R134a and R407c as refrigerants, we conducted the experiment. We are trying to improve the withstand time of the evaporator by using the PCM and also improve the Coefficient of Performance (COP) of the refrigeration system if possible. As the properties of PCM are in such a way that their freezing point of their PCM are less than the freezing point of water. Also, additionally we investigate R407c as a refrigerant compared to the existing R134a which is widely used.

3. Refrigerant selection

Our experiment setup being a Vapor Compression cycle model required a refrigerant that is well established and common in use at the same time environment friendly. As it is well established, it is safe to expect it to satisfy all required thermal properties at least in this level. For this purpose we choose R134a which is well established. The series of experiments were also performed on R407c to study the refrigerant or to say the least, compare with that of R134a. With popularity of R407c growing due to its ODP and GWP values which are very low, it is to be seen whether the performance is satisfactory. R134a has Ozone Depletion Potential (ODP) = 0. Global Warming Potential (GWP) = 1430. PROPERTIES OF REFRIGERANT R407c. Ozone Depletion Potential (ODP) = 0. Global Warming Potential (GWP) = GWP = 3. It is highly flammable but in toxic

| CHEMICAL FORMULA     | CH₂FCF₃       |
|----------------------|---------------|
| MOLAR MASS           | 102.03 g/mol  |
| APPEARANCE           | COLORLESS GAS |
| DENSITY              | 0.00425 g/cm³ |
| MELTING POINT        | -103.3°C      |
| BOILING POINT        | -26.3°C       |
| SOLUBILITY IN WATER  | 0.15 wt%      |

Table 1. Properties of R134a

| CHEMICAL FORMULA     | C₃H₈          |
|----------------------|---------------|
| MOLAR MASS           | 44.1 g/mol    |
| APPEARANCE           | COLORLESS GAS |
| DENSITY              | 0.0493 g/cm³  |
| MELTING POINT        | -190°C        |
| BOILING POINT        | -41°C         |
| SOLUBILITY IN WATER  | 0.0244 g/L    |

Table 2. Properties of R407c

Our study is based on finding the optimal material that serves best the purpose of both the refrigerator and mitigating the effect it has. One fundamental factor to be considered is human comfort and the material needs to be in that range. So, if there is one thing that need to be checked, it is the Phase Change Materials (PCM). The above factors narrow our range of temperature to 1725 NAACL celsius. The critical factors that directly contribute to the
performance of PCM are latent heat of fusion and thermal conductivity. To be able to have an efficient storage, it is required for the density to be high. Another desirable character is the stability which calls for a high value of latent heat of fusion. For us to determine the performance, we require values of factors like specific heat, melting point etc. Hence these parameters have been selected to help in the evaluation process of the candidate materials. Here we selected Sodium Chloride (NaCl) and Magnesium Chloride (MgCl2) and Ethylene glycol (CH2OH)2.

Sodium Chloride is a very capable PCM with high latent heat of vaporization. Having described PCM earlier, it is pretty self-explanatory the intended use of Sodium Chloride. It has the ability to retain cooling after cutting the supply off. In our setup it is 50 percent ethylene glycol and 50 percent water that a very effective temperature withstanding effect.

**Table 3. Properties of NaCl**

| PROPERTIES         | SCIENTIFIC VALUES |
|--------------------|-------------------|
| Normal Boiling Point | 245.3°C           |
| Normal Freezing Point | -9.0°C            |
| Specific Gravity    | 1.1182            |
| Viscosity          | 35.7 mPa          |
| Molecular Weight   | 106.12 g/mol      |
| Solubility in Water | 100.0 wt%         |

We had discussed inorganic salt hydrate when we classified PCM. Magnesium Chloride falls in this category. The characteristics that make it desirable are its high volumetric energy density, high thermal conductivity and a noncorrosive nature. It is also nontoxic and of low cost. It exists as 2MgCl2·6H2O water of crystallization.

**Table 4. Properties of MgCl2**

| PROPERTIES         | SCIENTIFIC VALUES |
|--------------------|-------------------|
| Normal Boiling Point | 1412°C            |
| Normal Melting Point | 714°C             |
| Latent heat        | 168.6 KJ/kg       |
| Molecular Weight   | 95.21 g/mol       |
| Solubility in Water | 0.23 wt%          |

This organic compound is highly toxic. It is also known as Ethane-1,2-diol or Mono ethylene glycol. It has no smell and is viscous. It is colorless and has a sweet taste. It appears as a clear, colorless, liquid. It is widely used as an antifreeze and a raw material in the plastic industry. Ethylene Glycol is produced when ethylene oxide reacts with water. Ethylene glycol has been the most abundantly produced diol because it is one of the monomers of polyethylene terephthalate. Ethylene glycol has been synthesized by the oxidation of ethylene with O2 to ethylene oxide and the subsequent hydration of ethylene.
oxide to ethylene glycol.

Table 5. Properties of \((\text{CH}_2\text{OH})_2\)

| PROPERTIES               | SCIENTIFIC VALUE |
|--------------------------|------------------|
| \(\text{C}_2\text{H}_6\text{O}_2\) | Ethylene Glycol  |
| Molecular Weight/ Molar Mass | 62.07 g/mol     |
| Density                  | 1.11 g/cm³      |
| Boiling Point            | 197.3 °C        |
| Melting Point            | -12.9 °C        |

4. Experimental setup and procedure

The working setup of our experiment consists of the following components which represent each process of the refrigeration process separately. The automobile engine and the compressor are similar to each other. Inside the cylinder there is a piston which is driven by a motor. During the downward motion of piston in the cylinder, the space in the cylinder increases thus increasing the volume of the combustion space where the refrigerant exiting the evaporating unit is pulled into. The inlet valve is closed when there is a pressure balance between refrigerant and evaporating unit. The compression process takes place on the upstroke. During this the temperature and pressure increases making the refrigerant into a superheated state. After this, the refrigerant moves is expanded and channeled with an expanding unit into the condenser. The flow of refrigerant is unidirectional, and the valves are designed in sucha way.

![Figure 1. Experimental Setup](image)

The superheated vapor from the compressor outlet passes into the condenser inlet. During condensation when the liquefaction of the refrigerant that has been vaporized takes place, heat is released for which the condenser is responsible. At constant pressure the temperature drops gradually, and the superheated vapor first gets converted into saturated vapor and on further condensation it achieves saturated liquid state. There are two variants of condenser namely aircooled and watercooled. After compression, the flow of refrigerant gas through the condenser
is forced. The arrangement of tubes is in such a way the surface area is maximum which will result in maximum possible amount of heat removed. For this purpose, we use evaporating coils in our system which is wound along the inner wall of the container in which the load (water) is kept. The actual process of the refrigerant absorbing heat from the load happens in this process with the sole source of heat transfer being conduction. In our experiments, the PCM boxes are also placed in contact with evaporating coils immersed in water which is the load to be cooled. There are two basic types of expansion valve used in refrigeration system namely Capillary tubes and Thermostatic expansion valve. It is here where the throttling effect takes place. The valve is like a small orifice. So when the refrigerant passes through it, it moves from a lower area to a higher area, so the pressure and temperature decreases, and the enthalpy remains constant. Therefore, the refrigerant will be in a partially liquid partially gaseous state as it moves into the evaporator.

Energy meter is basically an indicator or power. There is a metallic disc that rotates in relation with power passing through the meter. So, this helps in indicating the power. So, it can be operated by recording the count of number of revolutions of the metallic disc which is nonmagnetic but at the same time a conductor. The energy usage is calculated be the time taken for n number of revolutions. Generally, Time taken is noted for five revolutions of the disc for calculation purposes. In this setup, pressure gauges are used for the indication of pressure at the outlets of the evaporating, compressing, condensing units and capillary tube exits. It helps us keep track and check if the system is functioning properly. The box which is used to store PCM in the evaporator is called as PCM box. Here we considered two PCM boxes. Inside each of these boxes the PCM that had to be used were filled. The properties of PCM box are: Material of Construction Copper

| Table 6. PCM Box Dimension |
|-----------------------------|
| **Height** | **Width** | **Thickness** | **Internal Volume** |
| 0.1 m | 0.05 m | 0.00053 m | 0.0003 m³ |

**Figure 2. PCM Box**

Thermocouples are instruments which are used to measure temperature. By using thermocouples, we can measure the temperature inside the system. We can also measure the temperature variance at two different places in certain area. In this setup we used 6
thermocouples to measure the Temperature at the exit of evaporating unit, compressing unit, condensing unit, capillary tubes and two PCM boxes.

The instrument which is used to indicate the temperature by using thermocouples is known as Temperature indicator. The thermocouples are connected to the temperature indicator through a varying switch. All the six temperatures are displayed in the indicator.

WATER TANK
A water tank consists of the water to be cooled. It has a capacity of nearly 10 litres (mass of water = 10 kg). The refrigerant is made to pass through the water through the capillary tube. The tube is coiled with windings.

Here we considered Sodium Chloride and Magnesium chloride as PCMs and conducted the experiment and calculated the COP. We also used two different refrigerants namely R134a and R407c. The experiment was performed using R134a as refrigerant and without PCM, then with Sodium Chloride PCM , with Magnesium Chloride PCM and lastly with Ethylene Glycol PCM. Similarly, it was done for R407c refrigerant also.

The above experiment setup is made to run with a load of 10Kg water with different combinations as follows.

1. With R134a as refrigerant without PCM
2. With R134a as refrigerant and NACL as PCM
3. With R134a as refrigerant and MgCl2 as PCM
4. With R407c as refrigerant without PCM
5. With R407c as refrigerant and NACL as PCM
6. With R407c as refrigerant and MgCl2 as PCM
7. With R407c as refrigerant and (CH2OH)2 as PCM

After all these are run it is further analysed for improvement in COP or savings of energy. After a certain cooling is achieved, the compressor is switched off and the system is observed for another 23 minutes to study the temperature withstanding capability of the system in presence of PCM and without one.

Experiment was performed for two hours. Following is the procedure of the experiment:

1. Switch on the main switch.
2. Let the stable conditions of the refrigerator be achieved.
3. Then for every 5 minutes take the temperature and pressure readings from the pressure gauges and temperature indicator.
4. Then calculate the COP of the system and note down the energy meter reading and do the power consumption calculations without PCM materials.
5. Total we were having 300ml of PCM material. So we have divided it into 2 parts.
6. n carry out the same procedure with Sodium Chloride PCM and Magnesium chloride PCM.
7. Then change the refrigerant to R407c and follow the same procedure.

Coefficient of Performance of the system is given by the formula,
Coefficient Of Performance (COP) = (ACTUAL REFRIGERATION EFFECT Q) / (WORK DONE BY COMPRESSOR Wc)

Further,
Q = (M * Cp * T) / t
Wc = (1/Ec)*(N/t)*3600
Where,
M = mass of the water = 10kgs
Cp = Specific heat of water = 4.187 KJ/Kgk
T = Temperature difference
T = time duration
N = number of revolutions of energy meter = 5
t = time taken for 5 revolution of the energy meter

5. Results and discussion

The performance of the refrigeration system in the presence and absence of PCM is studied. It can be observed that the COP decreases with time to provide cooling effect at relatively lower temperatures. In the presence of PCM, COP at those stages are better slightly. With NACL as PCM, COP has improved variably with a maximum improvement of 35 percent. With MgCl2 as PCM, the same effect is observed but it does not better NACL and has a maximum improvement of 15 percent. The above chart was observed after desired cooling was done with the compressor switched off to observe the retaining capacity in the presence and absence of PCM.
Figure 4: Comparison Refrigeration Effect with R134a as refrigerant

Setting the temperature to be maintained as 15 NACL, we observe how long does it naturally take to restart the compressor. With, MgCl₂ as PCM, it took 17 minutes to reach that temperature whereas it took 21 minutes in the case of NACL. Thus, it can be concluded that MgCl₂ saved 4 minutes of energy and NACL saved 8 mins.

Figure 5. Refrigerant R407c Performance
In case of R407c, the performance is not in the level of R134a. The difference in OP is clearly visible. Even in that regard, the effect of PCM is visible with NaCl showing an improvement up to 15 per cent and MgCl2 realizing improvement up to 3 per cent which is not very significant and calls for further studies on R407c.

![Figure 6. Comparison of refrigeration effect with R407c as refrigerant](image)

Just like in the case of R134a, R407c was analyzed in the same fashion and the ability to retain temperature is studied. In the case of MgCl₂, there is no significant effect as there is no difference in duration temperature retention which is set at NaCl. It is also observed that R407c does not achieve as much cooling as R134a in the given duration which is evident from the initial temperatures of this gap. However, NaCl shows a (relatively) better retention capability in this case too. Refrigeration (R407c) have to conducted performance improvement of a refrigeration system using PCM, COP has better than comparing R134a. Use of (MgCl₂) as PCM imposes a slightly increase on COP improvement at certain thermal loads. Use of (CH₂OH)₂ as PCM imposes a more than great impact on COP improvement at certain thermal loads.

6. Conclusions

By conducting the experimental analysis, it is understood R134a has a normal COP, which is substantial. R407c which is an upcoming refrigerant whose ecofriendly traits are known has a lower range of COP compared to R134a which needs further investigation. Incorporation of PCM has a significant effect in case of R134a whereas in case of R407c it is variable. It can be concluded that NaCl is the better PCM of the two as it realized COP improvement up to 35 per cent in R134a refrigeration system and up to 15 per cent in R407c system. The temperature retaining was also observed to be better in the presence of NaCl saving 8 minutes of compressor effort in R134a system and saving 4 minutes in R407c system. In case of MgCl₂, there was a significant improvement of 15 per cent in R134a system and failed to produce any improvement of significance in R407c system. MgCl₂ saved 4 minutes of compressor effort in R134a system and failed to save any in R407c system. All of the above variations can be attributed to R407c refrigerant which needs to be studied further. Thus, use of NaCl as PCM has a significant effect.
in COP and energy saving. Use of (CH$_2$.OH)$_2$ as PCM imposes a more impact on COP improvement at certain thermal load. Depending on the PCM and the thermal load, around 20-30% COP improvement has been achieved in respect to the PCM usage in the evaporator coil.

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