**Fundamentals and application of phase change material in the food industry**

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1. **Introduction**

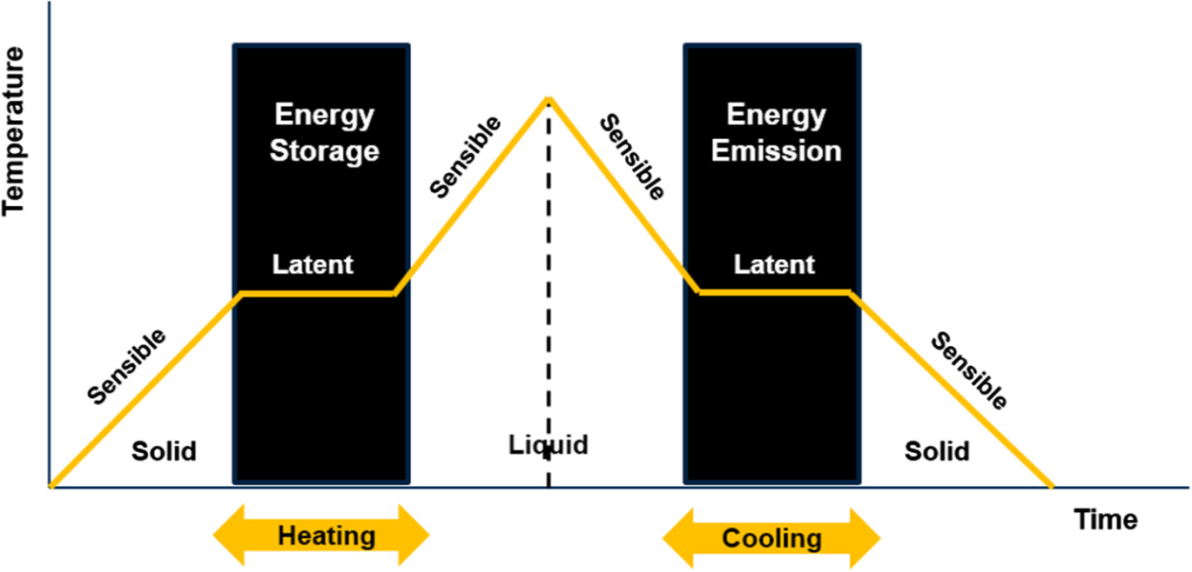
Refrigeration and air conditioning system are the most energy consuming system due to their widespread use and continuous operation. Improving the energy efficiency of refrigeration system is thus an important issue regarding energy savings and better performance. Most of the ideas applied to improve refrigeration systems lie in four major categories i.e. development of energy-efficient compressors, enhancement of thermal insulation, enhancement of heat transfer in heat exchangers (condenser and evaporator ) and development of different multi-stage refrigeration cycles. Heat transfer enhancement of heat exchangers (condensers and evaporators) in refrigeration systems can increase by application of micro-fins in condenser and evaporator and application of phase change materials (PCM) (Khan and Afroz, 2013).

Phase Change Materials (PCMs) are substances that have the ability to change their state, typically from solid to liquid or vice versa, within a certain temperature range. This phase change is accompanied by a significant amount of energy absorption or release, known as latent heat, without a large change in temperature. PCMs have been studied and utilized extensively due to their energy storage and temperature regulation capabilities. Thermal energy storage with PCM is a promising technology based on the principle of latent heat thermal energy storage (LHTES) (Oro *et al,* 2012). Using PCM as LHTES system will be a new option for performance improvement by enhancing heat transfer of the evaporator and reducing efficiency losses of compressor. The most important requirements in subzero temperature cooling applications for PCM are suitable phase change temperature and larger fusion heat.

PCMs are classified based on their phase change temperatures and can include organic materials (paraffins and non-paraffins), inorganic materials (salt hydrates, metals), and eutectics. Each type of PCM has unique properties, such as melting point, heat storage density, thermal conductivity, and cost, which determine their suitability for different applications. Despite the promising potential of PCMs in the food industry, challenges such as material compatibility, encapsulation, and thermal cycling stability must be addressed. Additionally, the selection of the appropriate PCM is crucial and must consider factors such as the desired operating temperature, PCM thermal properties, cost, and environmental impact. With ongoing research and development, the use of PCMs in the food industry is expected to grow, contributing to energy efficiency, food quality, and safety.

**2.0 Phase Change Materials (PCM)**

Phase Change Materials (PCM) is used as a latent heat storage material. According to Lane (1983), latent heat storage is coined by Telkes in the 1940s and it is new area of study. The chemical bonds within the phase change material break up when the source temperature is increased and result in the phase change from solid to liquid.



**Fig. 1: Schematic diagram of the phase change transition of PCM**

The phase change material absorbs heat so phase change is the endothermic process. At the phase change temperature, the material is started to melt and the temperature is remaining constant until the process is completed. The amount of heat that is consumed by the material during the melting process is known as the latent heat.

It is possible within a small temperature change a large amount of heat is stored and therefore it has a high storage density. The phase change process occurred at a constant temperature so that the temperature will be changed at a smooth rate. The store heat per unit volume of Latent storage materials such as water, masonry, or rock compare to sensible storage material is more around 5 to 14 times (Heine and Abhat,1978).

**Phase Change Material**

**Paraffin Compounds**

**Non-Paraffin Compounds**

**Salt Hydrate**

**Metallic**

**Organic**

**Inorganic**

**Eutectic**

**Organic-Organic**

**Inorganic-Inorganic**

**Inorganic-organic**

**Fig. 2: Classification of PCM**

**3.0 Requirements of a suitable PCM**

**3.1Physical and thermal requirements of PCM according to the storage and release of heat:**

1) The temperature must be suitable.

2) Large phase change enthalpy.

3) Reproducible phase change also called cycling stability.

4) High thermal conductivity and low super cooling

**3.2Technical requirements according to the construction of storage:**

1) Low vapor pressure

2) Small volume change

3) Chemical stability of the PCM

4) Compatibility of the PCM with other materials

5) Safety constraints

**3.3 Economic requirements:**

1. Low price 2) Excellent cycling stability

**4.0 The working mechanism of phase change material (PCM) in a refrigeration system**

The compressor is working in on-off mode in conventional refrigerator. Heat is released from the food during the off mode of compressor and the temperature inside the evaporator cabinet will increase. When the compressor is on, the refrigerant of the evaporator coil absorbs heat from cabinet. If PCM is used in the cabinet, then by changing its phase from solid to liquid it will take most of the heat. The temperature will remain same until the melting process is finished. Therefore, the required temperature of the product will obtained during the off mode of compressor until the phase change of material phase change properly.

Due to the latent heat of ice crystal ice is used as an efficient heat carrier. Ice slurry is an excellent option as a coolants in the conventional refrigeration system because it has low operating temperature and also high heat transportation capacity. Nowadays, due to the regulation of synthetic refrigerants use and also for thermal energy storage indirect cooling systems are more beneficial.

The cooling rate of milk is depends on the rate at which coolant can absorb heat from raw milk. The heat is absorbed by the air is very slow for example if the can of warm milk is placed in room at where the temperature of air is at freezing point then it will take around 12 h for cooling the milk to 10°C. On the other hand the cooling rate of water is higher 20 times comparing to air. Davies (2005) observed that the sensible heat of water to increase its temperature from 0°C to 80°C is equal to the latent heat of fusion for 454 g of ice. For increasing the cooling rate the volume of surrounding is ice must be high and lower temperature will require. These method of ice slurry are making interest which has been employed successfully in many milk cooling system by Sharma et al., (2014).

In developing countries like India, no method is currently applied at farm level for the chilling of milk; the risen is that for refrigeration process the compressor is used which needs much energy and initial investment. Therefore, it is necessary that the suitable material is easily available at lowest cost. Several researchers were mentioned earlier about cold water and ice as a cooling medium in their patented designs since water is one of the phases changing material having desirable properties.

**5.0 PCM application at evaporator**

In refrigeration system, the purpose of PCM is the enhancement of system performance and reduction of temperature fluctuation. Thus, even small performance enhancement of these appliances gives huge benefits in energy saving. Most of the new ideas applied to refrigeration systems for performance enhancement lie in three major categories: enhancement of thermal insulation, development of energy-efficient compressors and enhancement of heat transfer process from heat exchangers, i.e., evaporator and condenser (Cheng *et al.,* 2011), Due to the high latent heat of phase change material, integration of it at evaporator of a refrigerator could prolong the OFF time of compressor. This creates two new important options for refrigerators; to work off-peak and to maintain the compartment cold even during power outages for longer periods of time.

As a result of application of energy storage by PCM at evaporator, the on time period of compressor is decreased. Hence, the advantages are lower overall energy consumption, good quality of food, and preventing destructive effect of frequent compressor start/stop. Phase change material can be needful in case of power outages since it affects both air temperatures and product and their rate of increase during power outage (Gin and Farid, 2010). In addition, more uniform temperature of compartment can be achieved by phase change material presence (Osterman et al., 2012).

The direct application of PCM with a naturally-cooled evaporator is more advantageous because it will enhance heat transfer from the evaporator and also it can store excess cooling capacity of the system in the phase change material (Visek et al., 2014). Where evaporator coils were immersed in phase change material, faster heat transfer is obtained which is due to the faster nature of convection/conduction in phase change materials than natural convection of air. In the following sections, the effect of each parameter such as the PCM thickness, phase change temperature, its orientation and geometry, and also the effect of thermal load are discussed separately.

**5.1 Phase change temperature**

Appropriate choice of phase change temperatures is of high importance in cooling system as it actually affects not just to performance of the system but rather the consistency of the food material. The primary objective of domestic refrigeration systems is to preserve food; furthermore, change in temperature in phase should be appropriate with this main objective. Remember that phase selection changes temp is an important specification parameter for the effective utilization of phase change material and the melting point must fall within the operating temperature range of the thermostat if added within the compartment.

The application of phase change material around evaporator coils, it was observed that heat transfer enhancement of the system by PCM was higher if its melting point was not less than the compartment set-point temperature (Chen *et al*., 2020). This is due to higher evaporation temperature during phase change causes reduction of compressor start/stop frequency and higher system COP. Otherwise, PCM does not work well due to its low phase change temperature which prevents it from fully participating in the phase change process.

The most important factor that should be considered to find out a proper phase change temperature is the super cooling effect (Akeiber *et al*., 2016). Super cooling reduces system efficiency because it both prolongs phase change period and reduces temperature difference between the phase change material and evaporator (Wang et al., 2002). Therefore, it reduces the rate of heat transfer and prolongs the compressor ON time which consequently increases the energy consumption. Addition of nucleating agents can inhibit the super cooling effect (Sharma et al., 2009).

The selection of the PCM is based on the proper phase change temperature with appropriate thermo physical properties. Water has unique characteristics for consideration because of its large latent heat value, easily availability and sharp phase change point (Marques et al., 2014). For subzero temperature application it is not used because it’s higher freezing point. Therefore water-salt eutectic solution is normally used because of desirable melting point and high latent heat (Li et al., 2013).

**5.2 Volume of PCM**

According to Onyejekwe in 1989, the minimum volume of phase change material for required energy storage can be calculated by the following equation:

Where, Q is the total energy storage in PCM, h and ρ are the latent heatand density of vaporization of PCM and V is volume of phase change material.

The total energy stored in phase change material, Q, can be estimated from the following equation:

Where, K is the coefficient of exchange, S is the surface fusion; t is the PCM working time (compressor of time), Tamb is the ambient temperature and Tcold is the cold compartment temperature.

Therefore, the volume of PCM required for a system can be determined from above equations.

The efficiency of heat exchange system depends on the geometric characteristics, parameters which could influence the thermal resistance and also the temperature of storage.

Therefore, the volume of PCM should be more than the calculated volume from equation to balance heat gain through the walls during OFF time of compressor. The thickness of PCM should not be more than the required otherwise not all the thickness has the chance to undergo phase change (Azzouz *et al*., 2009). In such type of case, phase change material is partially frozen/melted which decreases its effectiveness and thicker phase change material is more costly and also requires longer work of compressor for cold storage; thus the thickness of PCM should be optimized based on the thermal load.

**5.3 Evaporation temperature**

Phase change material integration and evaporation temperature have mutual effects. At a higher latent heat of a PCM giving it a high thermal capacity and corresponding evaporation temperature is also high during phase change (Castell *et al*., 2009). Besides, higher evaporation temperature means higher evaporation pressure as compared to without PCM in cooling system (Khan and Afroz, 2013) which results in higher COP. Lower evaporating temperature requires longer PCM freezing time (Waqas and Din, 2013).

**5.4 Power outage**

In developing countries like India, the performance of refrigeration system is highly affected due to power shortage problem (Hua *et al*., 2021). During the power outage in conventional refrigeration system, the compartment does not cold for the longer period of time due to rapid heat gain from the walls. It will affect the food quality, energy consumption and durability of compressor. For solving the problem, Phase change materials can store energy whenever the system is working and release it in case of power outage. It was observed that after two weeks with frequent power loss, PCM worked as the promising results during power outage to maintain food quality of frozen meat and ice cream against drip loss and ice recrystallization, respectively (Krishna *et al*., 2017).

In this way, PCMs can also act as an emergency backup in case of blackouts. The period that phase change material can keep the compartment cold depends mainly on the thermo physical properties, thickness, and thermal load of the system. It is considered that only cold storage in PCMs at evaporator side is helpful for power outage.

**6.0 Analysis of PCM at evaporator**

The application of PCM increases the compressor OFF time and increases the system COP. The enhancement of COP can be obtained to 2-74% by the integration of PCM at evaporator. The amount of enhancement is mainly depends on the PCM type, thermal loadand ambient temperature.

Phase change material at the evaporator has a promising solution because it helps the refrigeration system by cold storage. It was also reported that phase change material at the evaporator increases evaporation temperature which in turn increases compressor inlet temperature. Thus, the temperature at the condenser side is increased and the performance enhancement of system equipped by phase change material at evaporator side is limited. However, compressor efficiency is more sensitive to evaporation temperature (Behi et al., 2017).

PCM is the promising solution in refrigeration cycle because it is cheaper as compared to the insulation or compressor change which requires manufacturing line upgrading. Furthermore, it is also applicable to the existing refrigeration system. PCM not only enhanced the performance of the system but also used as the backup in power outage.

**7.0 Advantages of PCM**

**Table 1: Advantages of phase change material (PCM)**

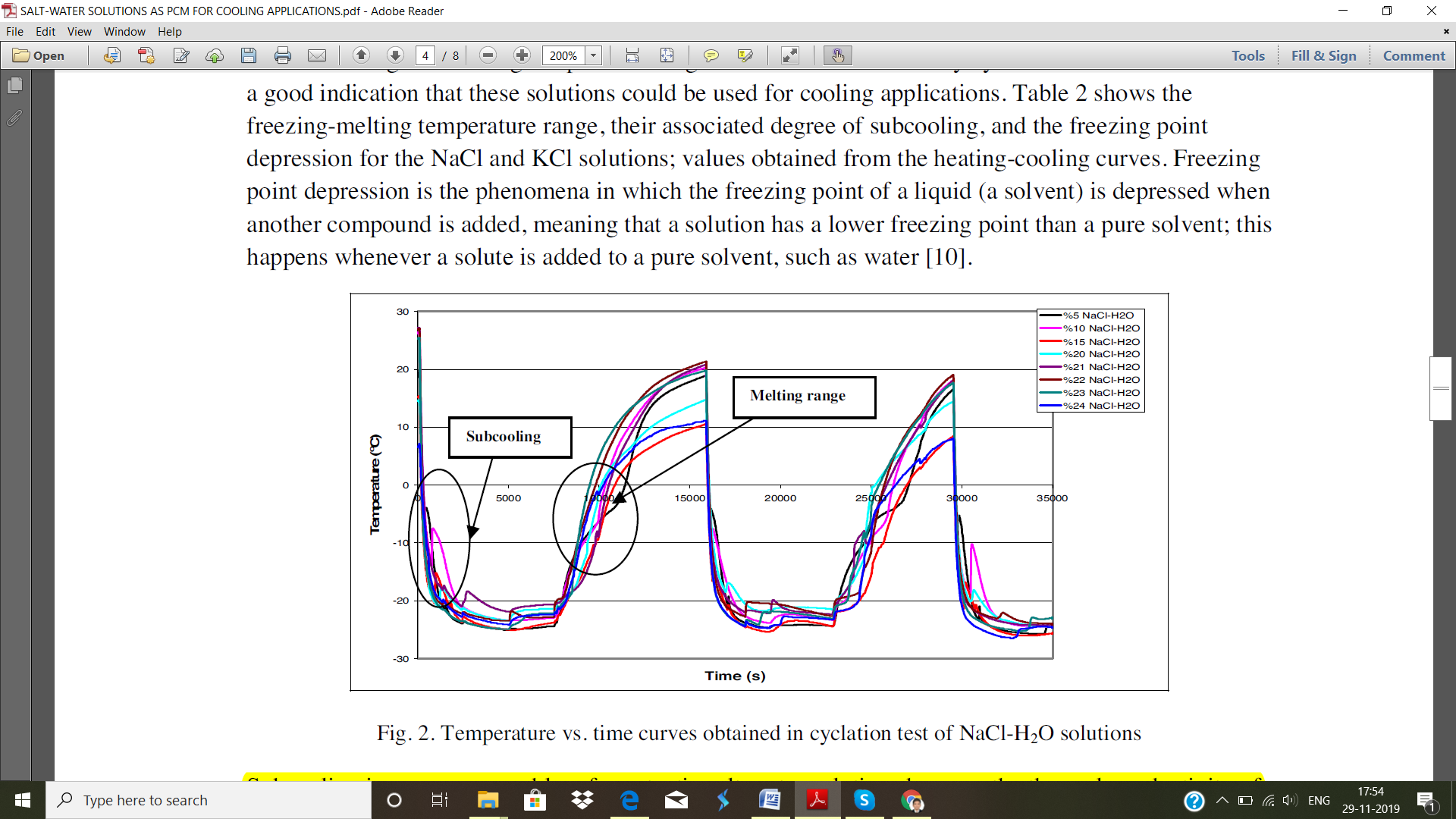
|  |  |  |
| --- | --- | --- |
| **Advantage** | **Details** | **Reference** |
| More controlled temp at compressor inlet | Less compressor work  Uniform temperature distribution | Wang et al.,2007 |
| More stable against thermal load variations | Better system performance  Lower sensitivity against Changes in ambient temperature | Khan et al.,2013 |
| Higher refrigerant density at compressor inlet | Higher refrigeration capacity | Rahman et al.,2014 |
| Assistance in case of power outage | Acting as an emergency backup  Kept stored food cold for longer periods with no power supply | Oró et al.,2012 |
| Higher COP | Better cooling performance of the system | Khan et al.,2013 |
| Slower storage temperature changes | Better food quality | Visek et al.,2014 |

**8.0 Eutectic salt-water solutions as PCM**

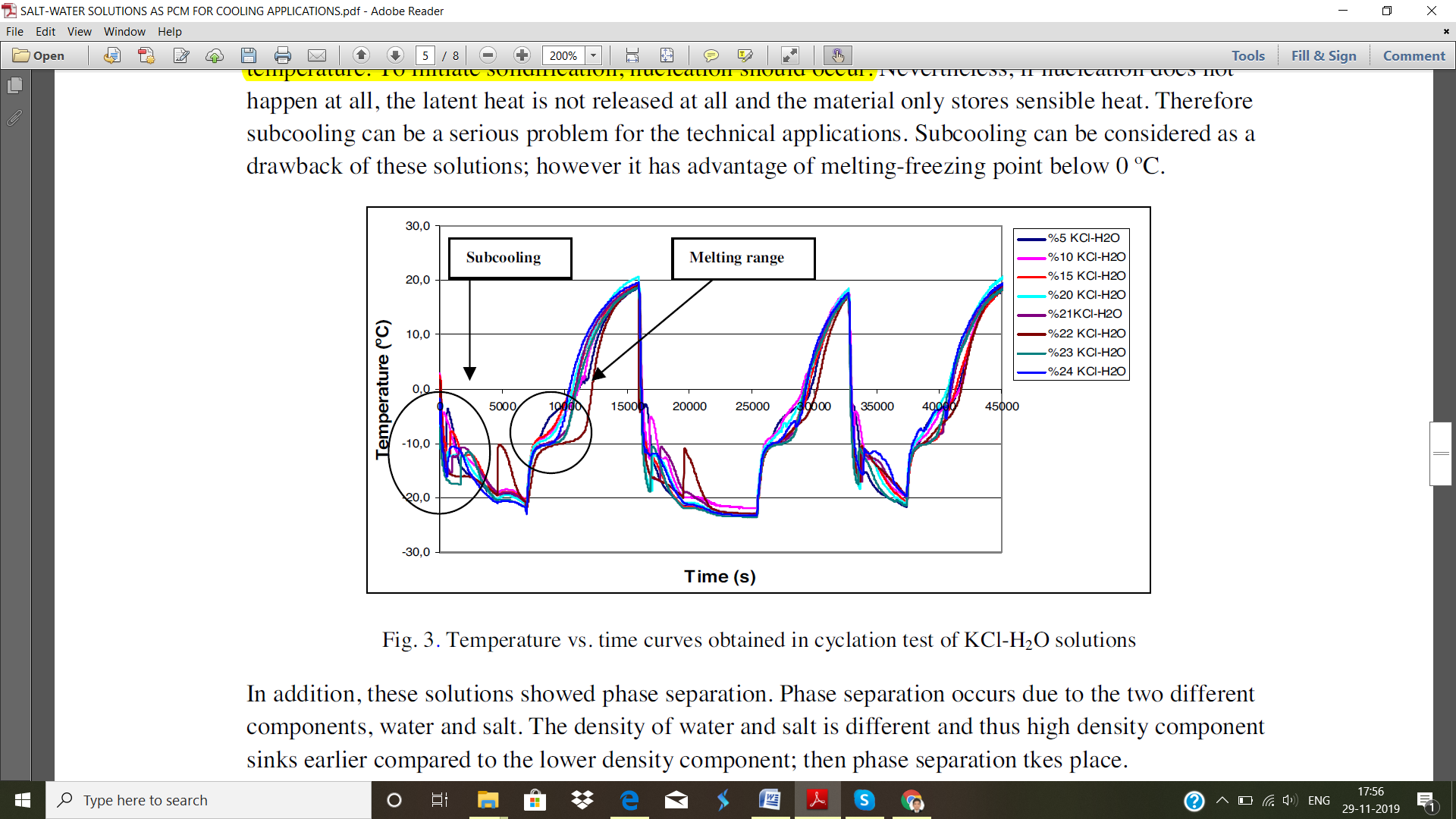
**When one or more substances acting as solutes are mixed with one or more solvents in such proportions as to obtain the lowest possible freezing for thecombination, the resulting solution is called as eutectic solution. The lowest possible freezing temperature is called as eutectic point (Hussain *et al*., 2017).**

Energy demand has been increased during the last few times. Due to the limited sources of nonrenewable energy, it is in great demand to develop other sources of energy using renewable energy sources. Thermal energy storage (TES) technique could be proven as a new technique by which energy could be stored and that can be extracted later (Mehling and Cabeza, 2008).TES using latent heat of the phase change material (PCM) utilizes a renewable energy source. PCM has high energy storage density per unit volume therefore it has more potential efficiency for heat and cold storage; phase change materials also allow isothermal operation at a constant temperature (Ge et al., 2013). Use of PCM for cooling applications such as protection of temperature-sensitive products like food, beverages, pharmaceutical products, blood derivatives, air-conditioning, and many more is proved very beneficial (Pichandi *et al*., 2020).Water, ice, eutectic mixtures, aqueous solutions of organic salts, and mixtures of salts are used as PCM for cold storage but salt-water eutectic mixtures are easily available and cheap compared to alkane mixtures (Yilmaz et al., 2010). Eutectic salt-water solutions are PCM which is melted below 0 ºC, usually have good storage density, and are available at low cost. For the subzero cooling application, PCM should have a phase change temperature range from -24 ºC to -10 ºC. Gawron and Schöder (1977) reported that the eutectic mixture of 22.4% NaCl-H2O showed a melting point at -21.2 ºC.

The heating-cooling test of NaCl-H2O and KCl-H2O solutions are shown in figures 2.5 and 2.6. The sub cooling effect can be detected in both figures 2.5 and 2.6. It can be noticed that sub cooling and melting temperature range remains similar for every cycle of all solutions. This is a good indication that these solutions could be used for cooling applications. Table 2.17 shows the freezing-melting temperature range, their associated degree of sub cooling, and the freezing point depression for the NaCl and KCl solutions; values obtained from the heating-cooling curves. Freezing point depression is defined as the decreasing the freezing point of the solvent when another compound is added meaning that a



**Fig. 3: Heating and cooling process of NaCl-H2O solution**



**Fig. 4: Heating and cooling process of KCl-H2O solution**

solution has a lower freezing point than a pure solvent like water.

Sub cooling of eutectic salt-water solutions is a common problem because the thermal conductivity of these liquid is similar to water and it can sub cool like water by several kelvin or more. Sub cooling is the phenomenon in which many PCM does not solidify immediately upon cooling below the melting temperature, but start crystallization only after a temperature well below the melting temperature is reached. During the heat storage, there is no significant effect of sub cooling, but during the heat extraction, the latent heat is not released when the melting temperature is reached due to sub cooling. To avoid the sub cooling it is necessary to decrease the temperature well below the phase change temperature. To initiate solidification, nucleation should occur. Nevertheless, if nucleation does not occur at all, the latent heat is not released at all and the material only stores sensible heat. Therefore sub cooling can be a serious problem for technical applications. Sub cooling can be considered as a disadvantage of these solutions however, it has the advantage of a melting-freezing point below 0 ºC. Thus, ice and salt slurries are being used as sub**-**zero temperature applications but there is a need to determine the freezing behavior and to record their cooling storage capabilities at different concentrations as a function of temperature to establish the appropriate eutectic behavior of a particular salt**-**slurry for a specific milk**-**cold chain application (Yilmaz *et al*., 2010).

**Table 2: Freezing Point depression of eutectic salt-water solutions**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Solutions** | **Subcooling**  **[ºC]** | **Freezing**  **temperature [ºC]** | **Melting**  **temperature [ºC]** | **(Freezing point**  **depression)** |
| 5% NaCl | 3.87 | -3.87/-4.27 | -4.8/-3.18 | 3.04 |
| 10% NaCl | 6.28 | -7.60/-7.70 | -7.80/6.10 | 6.56 |
| 15% NaCl | 5.30 | -15.19/-15.29 | -10.40/-9.20 | 10.88 |
| 20% NaCl | 2.79 | -18.22/-17.92 | -18.92/-14.62 | 16.45 |
| 21% NaCl | 2.20 | -18.46/-18.26 | -18.86/-14.62 | 17.77 |
| 22% NaCl | 1.60 | -21.95/-21.39 | -20.15/-19.65 | 19.17 |
| 23% NaCl | 0.20 | -20.89/-21.85 | -22.15/-19.65 | 20.66 |
| 24% NaCl | 0.30 | -20.19/-19.9 | -3.28/-2.08 | - |
| 5% KCl | 1.59 | -3.38/-3.58 | -11.79/-6.00 | 2.32 |
| 10% KCl | 7.48 | -6.60/-7.10 | -11.40/-9.60 | 4.80 |
| 15% KCl | 4.40 | -12.80/-13.20 | -10.23/-9.43 | - |
| 20% KCl | 5.59 | -12.93/-13.13 | -10.15/-9.15 | - |
| 21% KCl | 4.80 | -10.35/-10.65 | -10.15/-9.65 | - |
| 22% KCl | 6.90 | -10.45/-11.25 | -10.95/-9.15 | - |
| 23% KCl | 7.48 | -12.12/-12.82 | -12.32/-9.83 | - |
| 24% KCl | 5.10 | -10.80/-11.10 | -11.10/-9.10 | - |

When one or more compounds acting as solutes are mixed with one or more solvents in such proportions as to archive the lowest possible freezing point for the combination, the resulting solution is called a eutectic solution. The lowest possible freezing temperature is called a eutectic point. Granryd and Melinder (2005) reported that the aqueous solutions do not usually solidify to ice when ice crystals begin to form and mix with the liquid. Total freezing starts when the temperature reached to the eutectic point for the mixture. This process is known as the super**-**cooling of water as a solvent in the aqua**-**salt solution.

In general, a reduction of about 2.5% in heat transfer value takes place by each 1% increase in CaCl2 concentration. This happens because of a reduction in the specific heat value of the eutectic solution upon increasing the concentrations of salts.

Hillerns presented a review of the thermo physical properties and corrosion behavior of secondary coolants. It was suggested that brines consisting of calcium chloride or potassium carbonate possess favorable thermo physical properties, inexpensive, non**-**toxic and provide efficient freezing**-**point depression (29.9% w/w CaCl2 lowers the freezing point to **-**55 °C). However, corrosion at temperatures below 0 °C is a drawback of using their application to cooling systems.

Latent heat is defined as the energy absorbed or released during a thawing or freezing process. It is observed that latent heat could be correlated with the amount of water participated in the phase change process rather than the amount of water content which is present.

**9.0 Conclusion**

In the food industry, phase change materials (PCMs) have become a promising solution for a variety of temperature regulation problems. They are especially useful for thermal management and energy storage because they can collect and release large amounts of energy during phase transitions with little change in their own temperature. The properties of various PCM types, including organic, inorganic, and eutectic or bio-based PCMs, can be tuned to particular purposes. These uses demonstrate the adaptability and promise of these materials and cover every aspect of the food supply chain, from temperature-controlled packaging and food processing to cold chain logistics and refrigeration systems. Although the basics of PCMs are widely established, the field of their actual application in the food business is still in its infancy. It is important to carefully analyze aspects including cost-effectiveness, environmental impact, stability through numerous heat cycles, and containment or encapsulation solutions. To fully realize their potential and overcome current obstacles, additional research and development are required. Despite these difficulties, PCMs have enormous potential for boosting energy efficiency, ensuring food safety, and raising the quality of food items.

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