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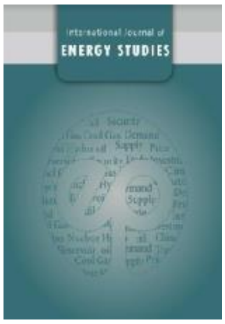

Review Article

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Investigation and Comparision of Thermal Energy Storage Methods Used in Food Production

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Highlights

- Presentation of significant criterias for ice storage
- Comparison of thermal energy storage systems for cooling systems
- Investigation of energy storage systems used in food cooling
- Energy efficient cooling with successfull energy-storage methods
- Explain of energy storage methods for cooling demands

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ABSTRACT

In this study, Thermal energy storage methods for food production have been investigated and compared. Food products must be cooled to maintain product quality in the food industry and to extend shelf life by slowing or stopping the enzymatic activities of food products. Different refrigerants are used in cooling systems to meet cooling loads. The refrigerants in the Hydrofloroclorocarbon (HCFC and clorofluorocarbon (CFC) group used in the cooling system can be caused significant damage to the environment. However, cooling systems which need to work long hours for the preservation of food products cause high energy costs. Efficient use of energy reduces environmental problems and its effects on energy costs are also important.When the cooling loads in food production are high, thermal energy storage is very important in energy systems to meet instantaneous energy loads. , Thermal energy storage methods in cooling processes used in food production were presented. The technologys used in thermal energy storage models were compared in terms of efficiency, environmental effects, coefficient of performance and risks. By investigating the effects of thermal energy storage methods for cooling purposes in food production costs, appropriate thermal energy storage technologies-systems have been proposed. The informations which are presented in this article are going to shed light on researchers in both energy efficency and environmental perspective.

Keywords: *Food production, Ice storage, Thermal energy storage, Cooling*

1. INTRODUCTION

Nowadays, the increasing energy demand is getting harder to compensate day by day. Alternative energy sources become more important due to the insufficient fossil fuels and their environmental damages. Although renewable energy sources are the most suitable energy sources in order to prevent environmental impacts, continuity cannot be achieved due to the daily, seasonal and annual change of the energy source. The mismatch between energy demand and energy supply will be eliminated by combining energy storage systems with renewable energy sources. Thermal energy storage method is the most convenient method in which waste or excess heat can be evaluated. With this method, heat energy is stored in applications as sensible or latent form [1]. Sensible heat energy storage technique has disadvantages such as corrosion and leakage, high pressure, insulation requirement and overcosting due to high heat storage dimensions. While in latent heat storage, becomes prominentas the most suitable thermal storage method since it has more heat storage capacity in smaller temperature ranges and smaller volumes [2].

In the food industry, cooling needs arise to stop or slow down microbial and enzymatic processes of food products. In addition, the cooling requirement is important in terms of maintaining the quality of the products and extending the shelf life. None the less, the high energy costs resulting from the use of the cooling systems used to compensate this cooling have led to the research of energy storage methods. In his study, Dinçer [3], stated that using the chiller cooling system and the thermal energy storage system together with the energy storing on ice during the hours when electricity usage is not intense will save energy and decrease operating costs. Besides, when compared with thermal heat storage method and single chiller system, it was stated that will be 44% decrease in energy consumption and 43% CO_2 emissions. According to the Massachusetts Institute of Technology Technology Review [4], the thermal energy storage method has proven to be a very effective alternative for reducing fossil fuel usage. It noted a milk collection plant using a thermal energy storage system saves more than 40,000 rupees (about 622,42 USD) per month on diesel fuel and increases the plant's daily milk production by several hundred liters. Kauffeld et. al.[5] examined the system integrated into the cooling system of the tank with 5000 kWh thermal energy storage capacity to improve the energy costs of the direct expansion ammonia refrigeration system used extensively in beer enterprises. As a result of their analysis, they found that whereby the thermal energy storage, the cooling load decreased from 1350 kW to 670 kW and the amount of ammonia refrigerant charge decreased from 3000 kg to 500 kg. Kumar et. al. [6] analyzed an ice storage ammonia refrigeration system used for cooling 320000 liters of milk after pasteurization. He stated that as a result of their work, the heat transfer decreased and the ice formed thermal resistance as the ice thickness formed on the evaporator coil exceeded 50 mm. He observed that 37439,8 kg of ice was stored at the end of the week by working 16 hours a day and 1466 kWh of electricity was saved per week.

This study explained the methods for applications of energy storage systems to food cooling technologies and examined the critical point. The advantages and disadvantages of energy storage technologies for cooling systems in food production were discussed and practical information were presented to researchers.

2. THERMAL ENERGY STORAGE SYSTEMS

Continuous operation of compressors in vapour-compression refrigeration systems which are widely used to compensate cooling requirements increase peak electric charge. Therefore, by operating a cooling system integrated with the thermal storage system at night when the electricity unit price is low, a significant reduction in energy costs will be achieved by storing thermal energy. Unit price of electricity during day and unit price of electricity during night is 0,103 $/kWh and 0,064 $/kWh in Turkey [7]. Therefore , electricity cost savings 40% will be achieved by using thermal energy storage system at night. Storage of thermal energy during the night hours enables the cooling system to work more efficiently due to lower outdoor temperatures at night [8]. The cold storage medium can be chilled water in the sensible heat storage system or ice or phase change material in latent heat storage system. Thermal energy storage systems are widely used in the food and pharmaceutical industries.For food producers and researchers, it is aimed to investigate the important points of the methods used in cooling proceses in production. These methods are chilled water, on pipe coil, in encapsulated phase change material and ice slurry. The explanation of both methods in term of energy efficiency and environmental effects by explaining and comparing the properties of these methods is the focus of this study.

2.1. Thermal energy storage system in chilled water

Thermocline water storage system is sensible heat storage system with operating temperature range between 4-6°C. The water which is the storage medium in this type of system is circulated for charge and discharge. Chilled water is pumped into the cooling coil of the building air-conditioning system at the lower level of the thermocline tank through out the day, and the water absorbed from the building air-conditioning system is returned to the top of the tank. Overnight, the water is pumped from the top layer into the chiller for cold charging, then chilled water is pumped back to the bottom of the tank. Nelson et al. [9] made a parametric study of the stratified chilled water storage tank. According to the results obtained, degree of thermal stratification is an important performance factor and the aspect ratio (height to diameter ratio) of the tank has improved up to 3, and there has been no significant improvement. The causes of the deterioration of the thermoclines are the heat transfer from the environment, thermal diffusion in the storage tank, axial wall conduction and mixing due to the ingress of liquid in the storage tank during charging and discharging . Thermal energy storage system with single tank is given in Fig.1.

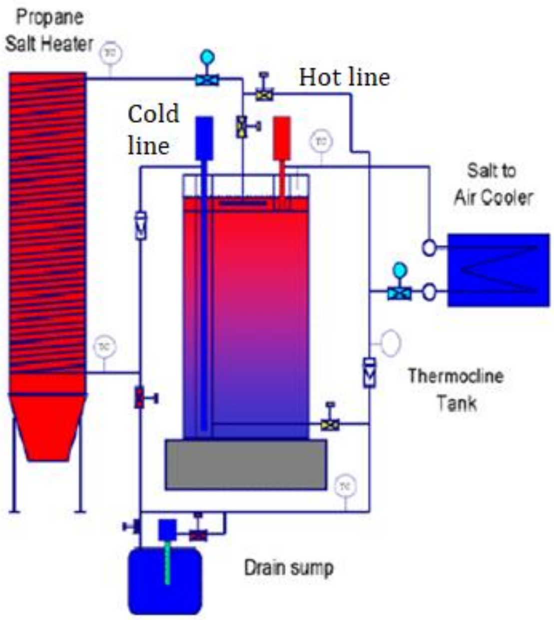

Figure 1. Thermal energy storage system with single tank. [10]

2.2. Ice energy storage system on pipe coil

The heat is stored in the form of latent heat using phase-change materials (ice, paraffin, etc.) İn these systems. In the phase change material in a heat insulated tank, heat energy is stored with heat transfer fluid (ethylene glycol, etc.) circulated for cooling purposes in an indirect heat exchanger such as a spiral coil or shell and tube heat exchanger [9]. The storage medium is heat insulated and the phase change material is static in this system. Only heat transfer fluid (HTF) is circulated in the coil for charge and discharge. HTF, which comes from the evaporator of the cooling system during the charging process, is sent through the coil approximately 3°C below the freezing point of the latent heat storage medium [11]. The hot heat transfer fluid, which is sent to the thermal storage tank during discharge, absorbs heat from the phase-changing material and is sent to the coil in the region where cooling is needed. Kumar et al. [6] investigated an ice-storage ammonia refrigeration system which used for cooling 320000 liters of milk after pasteurization. It is found that to subsequently maintain a 50 mm ice layer over the coil, the compressor has to run for 39 minutes. The amount of heat to be removed to maintain the 50 mm ice layer is found to be 70.48 W. It was observed that 149759,2 kg of ice was stored by operating the energy storage system for a month, thus saving 5864 kWh of electricity per month. Ammonia (NH3) is used as refrigerant in the cooling system (Fig.2).

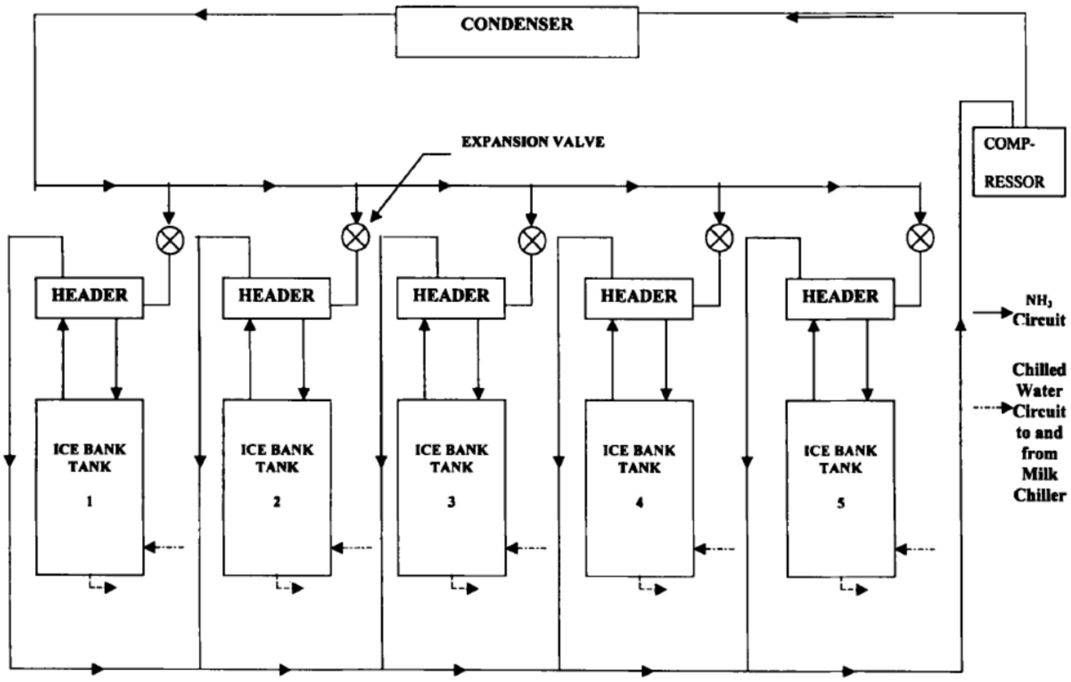

Figure 2. Scheme of thermal energy storage system in milk processing plant [6]

Navarro et al. [12] investigated the effect of the heat transfer fluid flow rate and inlet temperature in case of ice formation on the coil. They found that HTF needs an inlet temperature between -2.5 ° C and -5.2 ° C to charge the energy storage system on ice, as well as the lowest energy consumption for low mass flows and cold inlet temperatures [12]. The flow chart of the thermal storage system is given in Figure 3.

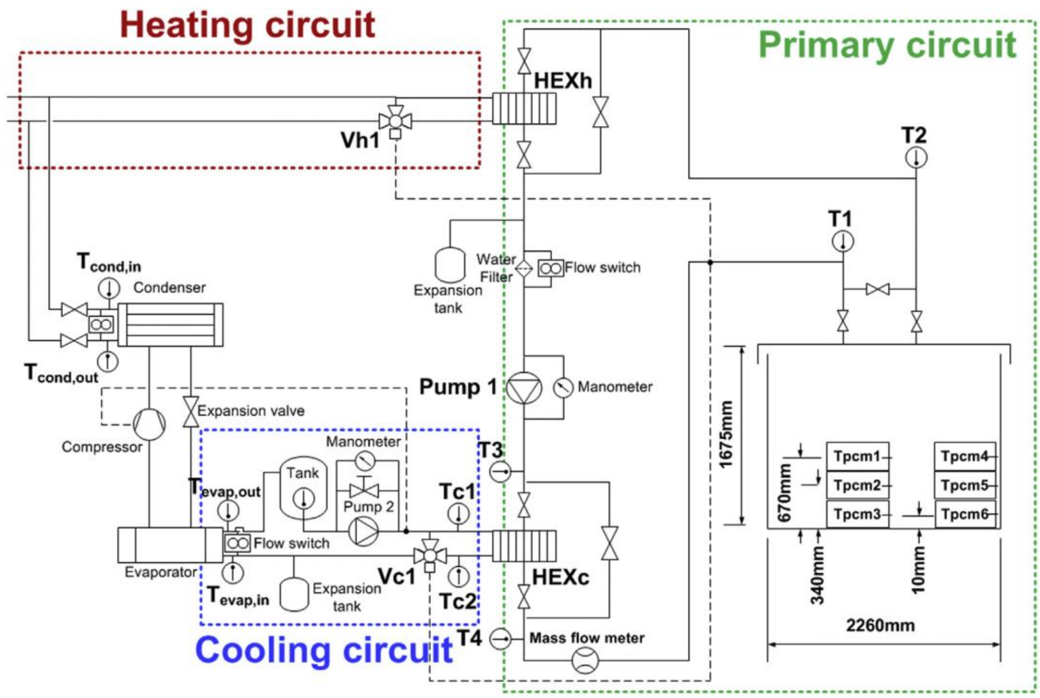

Figure 3. Schema of thermal storage system [12]

2.3. Thermal energy storage system in encapsulated phase change material

The thermal energy storage medium consists of many multi-layered spherical capsules or other forms of capsules which placed in an insulated storage tank in thermal energy storage system with encapsulated phase-change material. Typical capsule materials are stainless steel, polyolefin etc. The capsules remain stable in the thermal storage tank and heat is stored or used with heat transfer fluid**.** HTF is in direct contact with the outer surface of the capsules and therefore requires a large contact surface area for heat transfer mechanism [13]. During charging, the cooled HTF, which is supercooled below the freezing point of the phase-change material (PCM), absorbs heat from the encapsulated phase-change material. During the discharge process, the hot HTF at a temperature above the melting point of the encapsulated PCM is cooled by absorbing heat from the PCM inside the capsules and sent to the area where it needs cooling. Erek et al. [13] carried out a numerical analysis on the encapsulated thermal energy storage system. They determined important effect parameters on heat transfer coefficient and solidification time during the charging process. During the charging process, the heat transfer coefficient increased with higher mass flow rate, lower inlet temperature of cold HTF. They made an anaylsis in 4 different diameters (40,50,60 and 80 mm) for 1 mm thick spherical capsule in their study and found that the solidification process depends on the growth of the global capsule diameter and the Stefan number. Bedecarrats et al. [14] experimentally analyzed the effects of parameters such as the inlet temperature and flow rate of the heat transfer fluid, the kinetics of cooling on the charge and discharge processes with the encapsulated phase-change material in the energy storage system. They stated that subcooling is an important factor during the charging process, and thermal energy storage is much faster due to the high flow rate of HFT and low inlet temperature. They investigated the situation of supercooling in charge mode and remarked that at the end of 16 hours at -11°C, very few nodules crystallized, latent heat storage was low, and -6° C was sufficient to store all energy at the end of the 8 hours. The scheme of the encapsulated thermal energy storage system is shown in Figure 4 and the global encapsulated heat storage system is shown in Figure 5.

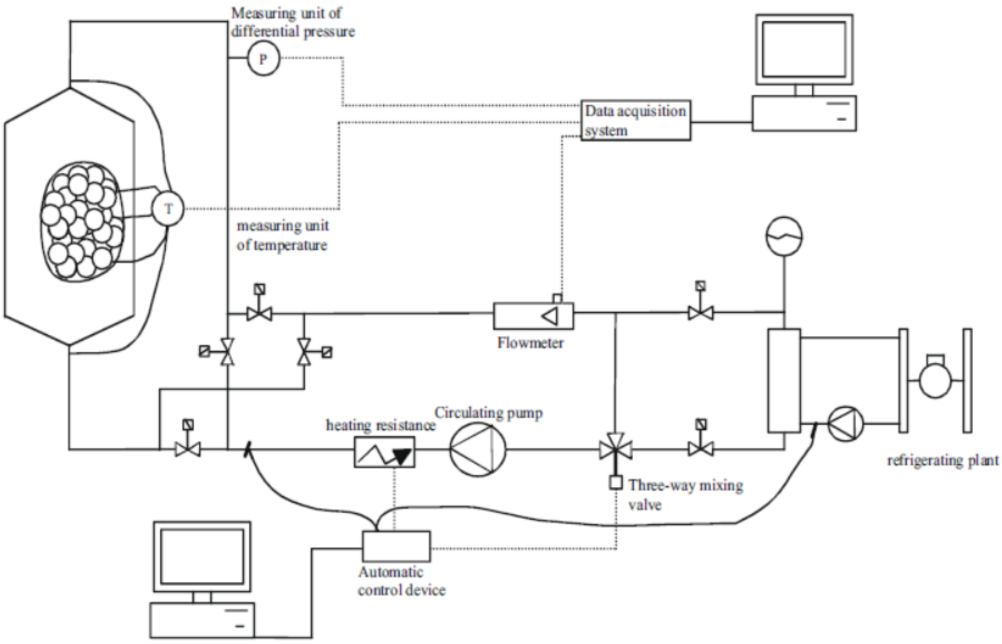

Figure 4. Encapsulated thermal energy storage system [14]

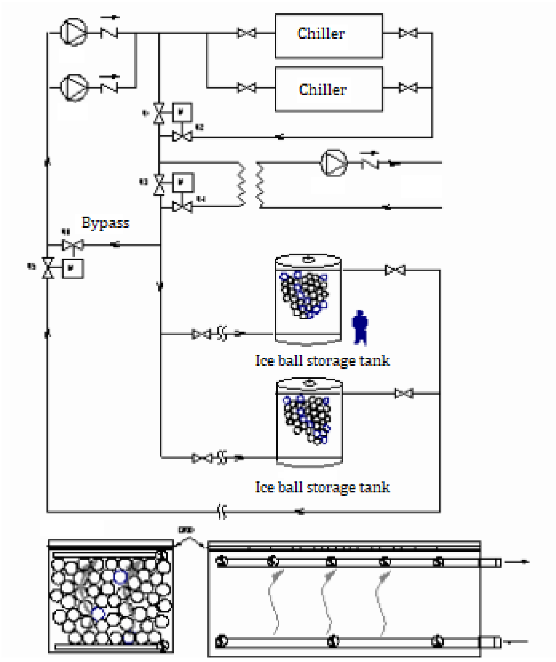

Figure 5. Spheral encapsulated thermal energy storage system (Iceball, [15])

2.4. Ice slurry thermal energy storage system

The ice slurry acts as both storage medium and HTF with dispersed two-phase flow characteristics in the thermal energy storage system. In a slurry, the liquid carrier fluid acts as the continuous phase and the solid phase change material (PCM) acts as the dispersed phase. The slurry with dispersed solid latent heat environment has a much better heat transfer coefficient compared to a single-phase liquid HTF. Therefore, it helps to charge or discharge more efficiently in the cooling system [11]. The ice slurry thermal energy storage system can provide adequate temperature drop over the conventional chilled water system and is a remarkable system for achieving a high degree of cooling. Continuous formation of ice slurry is an important technical problem here. Matsumoto et al. [16] used a functional liquid consisting of 10% silicone oil and 90% water by volume with a small amount of silane-coupler additive for continuous ice slurry production. This method has shown that it clears problems such as ice sticking to the cooling chamber and that all the water in the functional mixture can be kept dispersed for a long time. Gladis [17] proposed the ice slurry energy storage system to ensure the continuity of the cooling loads which needed in stages such as ensuring continuity in a cheese production facility, initial cooling and whey protein concentration system. Laboratory scale ice slurry thermal energy storage system can be seen in Figure 6.

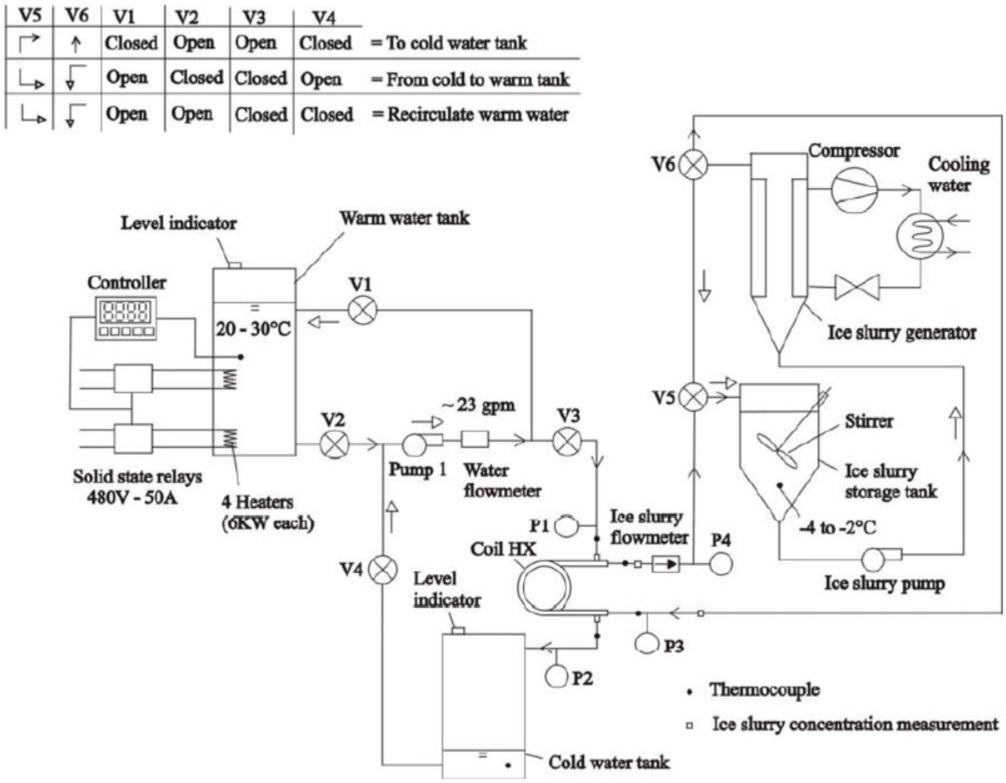

Figure 6. Laboratory scale ice slurry thermal energy storage system [18]

Lin et al. [18] experimentally investigated the laboratory scale ice slurry thermal energy storage system. The system which was the cooling capacity of 35 kW was primary circuit water flow rate1.44-1.65 kg / s, ice slurry flow rate 0.41-1.19 kg/s, water inlet temperature 20.5-30°C, ice slurry inlet temperature -4/-2.9°C under conditions, more than 2 MJ of heat was stored. R404a refrigerant was used in the cooling system.

3. COMPARISON OF SYSTEMS

Cooling systems and thermal energy storage systems are used together to afford the cooling needs of food products and ensure continuity. In Table 1, the thermal storage systems are compared in terms of environmental impacts, operational difficulties and the use of heat delivered in condenser.

Table 1. Comparison of thermal energy storage systems

Thermal energy storage systems	**Environmental Effects**	**Operational difficulties**	**Coefficient of Performance (COP)**	**Refrigerant**	**Waste heat usage**
System of thermal energy storage on chilled water		Very large volume of thermal storage tank [9]	-	-	No waste heat
Ice energy storage system on pipe coil	High global warming potential (GWP) and ozone depletion potential (ODP) value of refrigerant R22	Creating an insulating effect of the ice thickness formed on the pipe coil [6]	2,1 -	R22 NH_3	Waste heat used Waste heat used
Thermal energy storage system in encapsulated phase change material	GWP and ODP value of Refrigerant in cooling system	Low heat transfer coefficient of capsule material [14]	-	-	Waste heat not used
Ice slurry thermal energy storage system	R404a refrigerant high GWP	Ice sticking to the cold room [16]	-	R404a	Waste heat not used

Cooling system with thermal energy storage presents these advantages:

- Energy costs which spent for the cooling process required to maintain the quality and structure of food products are saved.
- Cooling continuity needed for food products is provided against negative factors such as power cuts and etc.
- It helps to meet the heat loads which will increase in food products.

- Production capacity is expected to increase in food production due to reduced energy costs.

When the obtain results,

Thermal energy storage systems need a vapour-compression cooling system to store the cold energy needed. The cooling system can be worked with various refrigerant. Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) value of the refrigerant is very important in the cooling system. It reacts with ozone as result of atmospheric release of the refrigerant containing chlorine in its structure and causes the ozone layer to break down.

- The release of refrigerants with high GWP into the atmosphere causes the greenhouse effect. Global warming will increase as the greenhouse effect increases.
- Therefore, the negative environmental effects of HCFC and CFC refrigerants should be eliminated by using natural refrigerants such as R290, R600 and NH_3. Another important factor is the coefficient of performance in the selection of refrigerants.
- Coefficient of performance (COP) should be calculated and compared under suitable operating conditions for each refrigerant. Energy savings can be achieved by choosing the refrigerant with the highest coefficient of performance.
- Due to the sensible heat storage in the thermal energy storage on chilled water system, large tank volumes are required. It should not be used in industrial applications in terms of energy efficient and effective use.
- Ice energy storage systems on pipe coil occur an insulating effect of the ice thickness formed on the pipe coil . Because of this insulating effect the cooling systems consume electricity of high amount.
- Using of R22 refrigerant was forbidden in industrial applications according to F-gas regulation and instead of R22 can be used alternative refrigerants R134a, R407c and R410a.
- Thermal energy storage system in encapsulated phase change material is an innovative system. When it compares with ice energy storage system on pipe coil, insulating effect does not occur without ice layer on the coil. Therefore, there is no unnecessary energy consumption. The uniform distribution of heat transfer fluid directly affects the thermal storage quality.
- Coefficient of heat transfer of capsul material must be high in thermal energy storage system in encapsulated phase change material. The heat transfer fluid and heat storage

medium are combined in the ice slurry thermal energy storage system and the pump requirement was reduced.

- However, instead of R404a refrigerant with high GWP, R407a or R290 can be used as an alternative refrigerant. Silicon oil can be added to the heat transfer fluid to prevent ice sticking problem.

4. CONCLUSION AND RECOMMENDATIONS

As a result of the studies and researches conducted in this study, the thermal energy storage systems used in the food industry were examined. For these methods, practical informations were presented by examining the environmental impacts, operational difficulties, the refrigerants used and the use of waste heat in the condenser.

It has been concluded as follows:

- Due to the sensible heat storage in the chilled water storage system, it requires very large tank volumes. But, with the use of ice or other phase changing materials, large amounts of latent heat can be stored in smaller volumes.

- It should be taken into consideration that the ice acting as a thermal insulation material creates a thermal resistance with increasing continously the thickness of the ice in the energy storage system on the pipe coil and therefore the electricity consumption of the cooling compressor increases. Chilled water thermal energy storage systems are more economical than other systems. But, it requires a high capacity water tank due to the sensible heat storage.

- With storing thermal energy in encapsulated phase change materials, a high amount of heat can be stored in smaller volume tanks. The thermal storage rate increases when the heat transfer fluid interacts with the encapsulated phase-change material at high flow and low temperature.

- The most important feature that distinguishes the ice slurry thermal energy storage system from other systems is that the slurry with two-phase flow properties dispersed in the thermal energy storage system serves both as storage environment and ITA. It can afford huge amounts of heat loads in a short time. Ice slurry systems have a lower design weight, it provides greater equipment flexibility because ıce slurry is pumpable and it provides lower water temperatures to the load compared to other thermal energy storage systems.

- Thermal energy storage methods should be used to prevent the cooling process in food products from being adversely affected by power cuts, failures or other factors and to ensure continuity in the cooling process. The electricity costs of the cooling system can be reduced by storing thermal energy at the night unit price of electricity is cheap. In addition, due to the low outdoor temperature at night, the efficiency of the cooling system increases. Also, renewable energy system and thermal energy storage method is an effective model that can provide continuity in the use of renewable energy systems.

- Waste heat discharged from the condenser is not evaluated in many cooling systems in the processes.

- For future works, in terms of active and efficient use of energy, this waste heat can be stored with the help of phase-change materials or used for heating domestic water in operations.

- Considering the environmental effects of thermal energy storage systems in cooling, the use of refrigerants with low global warming potential (GWP) and ozone depletion potential (ODP) values is very important in terms of environmental effects. In addition, the use of systems in future with a high coefficient of performance (COP) value will reduce energy consumption, accordingly reducing energy costs.

Acknowledgment

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Declaration of Ethical Standards

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

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