LONG-TERM PERFORMANCE ANALYSIS OF ICE THERMAL COLD STORAGE WITH PHOTOVOLTAIC-POWERED DC REFRIGERATION SYSTEM FOR MILK COOLING THROUGH COMPUTATIONAL MODEL

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Abstract

Pastoral communities in Africa depend on animal husbandry and milk production for their subsistence. Even though large quantities of milk are produced by pastoralists and small-scale dairy farms, the milk is either left to be spoilt or excessively consumed due to the absence of power for refrigeration. To address the problem, standalone PV-powered milk refrigeration system with ice thermal storage is proposed. The ice thermal storage replaces the battery for nighttime cooling. Sizing cold thermal storage for milking cooling using charging and discharging techniques with computational models is rarely investigated. Hence, this work focuses on the development of a transient computational model for performance analysis and prediction of the annual performance of a milk cooling system with DC refrigeration integrated with ice thermal storage powered by PV system. The simulations conducted using the MATLAB computational model were used to determine the thickness and mass of ice thermal storage to cool 50 liters of milk between 2-4 ºC for more than a day. A minimum of 0.061m ice thickness and 31kg mass of ice is required.

Keywords: Milk cooling, PV, Cold thermal storage, Charging, and discharging

1. Introduction

Since nearly one-third of the world's food production is spoilt, food preservation has become crucial for tackling world hunger (Hu et al., 2021). This issue is more prevalent in low-income nations, particularly those in East Africa. Dairy remains to be the most easily spoilt food product. Moreover, utilizing raw milk is causing a health crisis in developing countries as refrigerating milk with power from the grid is not a viable option mainly because of inaccessibility and limited infrastructure. Dairy production relies heavily on refrigeration, which reduces losses due to the deterioration of milk and improves milk quality (Sidney et al., 2021). Several developing countries are researching effective ways to keep milk preserved for at least 24 hours (De Blas et al., 2003).

Better and more affordable chilling technologies can help rural and pastoral communities in tropical regions grow economically by making milk reach the market without perishing. Hence, it is necessary to look into alternative energy sources that have the right cooling technology to preserve milk. One suitable solution is the use of PV-based solar power system. Although solar energy from the sun is sporadic, a solar energy system can be used to address the issue from the bottom up. Solar PV systems with rechargeable batteries were initially proposed as a substitute. (Kasera et al., 2021) investigated the performance of a vapor-compression-based milk refrigerator powered by solar photovoltaic modules. The system comprised of a variable-speed R290 DC compressor, solar PV panels, and batteries. (El-Bahloul et al., 2015) examined the operation of a 50-liter portable refrigerator, a solar-driven DC motor vapor compression refrigerator with a PV module, and a battery with or without PCM thermal energy storage. The results showed that this technology can be utilized to transport post-harvest crops in hot, arid environments.

10.18086/swc.2023.04.01 Available at http://proceedings.ises.org

Even though a lot of different researchers worked on utilizing solar batteries as one alternative energy storage for agricultural products and milk storage, the operational expenses of such systems are high and the energy conversion efficiency is low. Therefore, looking for other storage alternatives for use in rural and pastoral communities, where there is high milk production and located far away from the grid, is substantial. A cost-effective method for preserving milk and ensuring its safety for longer than a day is replacing the batteries with ice thermal energy storage. Ice thermal storage is a thermal latent heat storage system that potentially reduces cost and environmental pollution by shifting power demand from on- to off-peak hours. In comparison to sensible heat thermal energy storage, latent heat thermal storage systems provide substantial energy storage density and give the advantage of energy release or absorption with steady temperature control (Ezan et al., 2011). Water is the preferred phase change material (PCM) in this study due to its high latent heat of fusion and low cost. Producing and utilizing ice in static or dynamic modes are two alternatives (Ghaith & Onur Dag, 2022). In static mode, ice is produced and used in the same location during charge and discharge, while in dynamic mode, ice is produced during charging and transferred to another space for discharge (Asgharian & Baniasadi, 2019). In this study, latent thermal storage and static modes of ice utilization for milk cooling were used to reduce cooling costs and ensure good energy density. Regarding ice thermal storage, research has been conducted in this area for use as a replacement for solar batteries for a variety of applications. Some that are relevant researches are highlighted in this study. (Xu et al., 2018) found that all solar energy converted by the panels can be preserved in ice. The outcomes of the experimental studies show that it is feasible to store components utilizing ice thermal storage instead of battery banks. (Asgharian & Baniasadi, 2019) uses numerical models and spherical capsules to optimize an ice reserve system. Analysis indicates that utilizing two heat transfer fluid inlets minimizes charging time and improves efficiency by 37%. (Xie & Yuan, 2014) study focuses on a novel thin-layer ring structure and allows a numerical model to foresee ice formation in a thermal storage system. Following this, increasing ring thickness could improve the accumulation of ice rate. (Abhishek et al., 2019) conducted experimental and numerical modeling to look at the charging and discharging performance of an ice-on-coil latent thermal energy storage tank (LTES). The study found that thermal stratification in molten phase change materials significantly impacts charging and discharging performance.

(Xu & Li, 2022) investigated the feasibility of low-cost ice thermal storage as part of replacing battery banks for energy storage. Solar irradiance and compressor fluctuations were looked at under four different operating scenarios with a 3 HP residential air conditioning system. (Ghaith & Onur Dag, 2022) explored the possible use of ice storage and solar-powered cooling systems for space cooling in residential and commercial structures. With peak cooling loads of 70 kW and 366 kW, respectively, and PV panel installation areas of 240 m^2 and 400 m^2, the system was tested on two Abu Dhabi office towers and a residence in Dubai, which significantly decreased annual energy usage in the office building by 38%, with savings of around 140,160 kWh and a 40% reduction in CO_2 emissions.

(Kahraman, 2002) explored the energy-saving draft beverage coolers by applying numerical simulation and experimental validation of an ice bank and adopting a glycol solution as an alternative refrigerant to sustain stable inner pipe temperatures.
The development of PV-powered cold storage with a vapor compression refrigeration system (VCR) promotes the rapidly growing cold chain logistics industry, particularly fueled by the demand for agricultural fresh products (Hu et al., 2021). An experimental investigation of the ice thermal storage employed in milk refrigeration from rapid pasteurization-induced milk chilling has been carried out using an external ice-on-coil producing and ice melting increased rapidly, as the cooling load was higher, with outlet water temperature below 0.8°C in all discharging experiments (Grozdek et al.,

2010). (Han et al., 2021) proposed a photovoltaic direct-driven DC compressor ice storage air-conditioning system, improving refrigeration efficiency. In the investigation, as the thickness of the ice layer rises, the evaporator's thermal conductivity declines. (Hu et al., 2021) developed a PV-driven cold storage system with ice thermal storage, with PV capacity of 5.4 kW at a maximum cumulative solar insolation of 20.41 MJ/m^2, with a maximum daily cumulative ice mass of 144.10 kg, thereby providing a competitive alternative for chain logistics services and can be eased with the ice thermal storage system, which can maintain ice storage temperatures within 5°C for 11 hours. (Marques et al., 2014) look at the development and performance of a thermal storage refrigerator, emphasizing the numerical modeling and validation through experimentation carried out with the guidance of a working prototype refrigerator fitted with a PCM. The findings prove that embedding a 5mm PCM slab allows for 3-5 hours of uninterrupted use without an additional power supply.

To determine the precise quantity of ice needed for cooling the milk for more than a day and the quantity of energy necessary, the system should be sized using the proper technique. An ice thermal energy storage system's yearly electricity consumption and overheads can be reduced by 25% to 32% by optimal design (Sanaye & Khakpaay, 2022). Although there are several studies on ice thermal storage, a handful of them trace sizing through proper techniques that determine the amount of ice needed for charging and discharging, helping to avoid over- and under-sizing of the necessary amount of ice that is needed for milk chilling at night.
This study investigates the sizing of cold thermal storage for milk cooling, employing charging and discharging techniques using computational models and predicting the performance of the system.

2. Methodology

The ice thermal storage that is going to be traced and obtained through the refrigeration cycle mainly harvests power from a PV array and is driven by a DC compressor, as indicated in Fig.1. During the day, PV arrays transform solar energy into DC electricity, which is used to drive the DC compressor. The refrigeration effect is obtained through the use of R134a refrigerant in the vapor compression refrigeration(VCR) system, and as the temperature of the refrigerant in the evaporator is low, the heat is absorbed from the water, and ice begins to form in the ice storage tank when the water temperature of the thermal storage reaches 0°C.

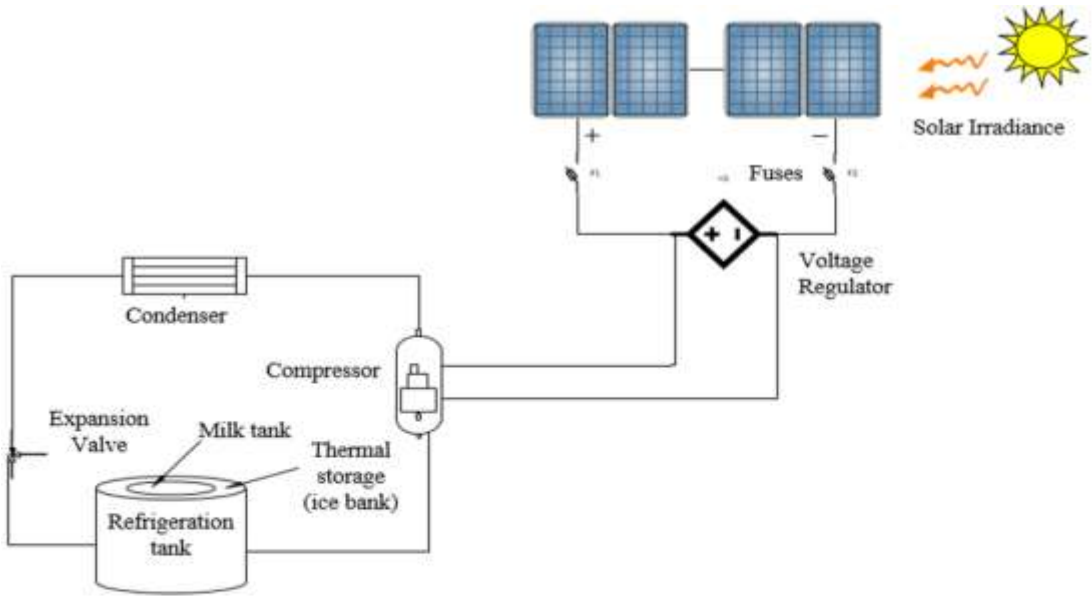

Fig. 1: overall description of ice thermal storage

The system consists of a concentric cylinder, where milk is placed in the inner cylinder, surrounded by a water jacket in the annular space. The evaporator helical coils are placed in the inner wall of the outer cylinder as shown in Fig. 2. During the day, an ice layer forms around the evaporator copper tube, and from the outer cylinder inward, ice slurries are used for night cooling.

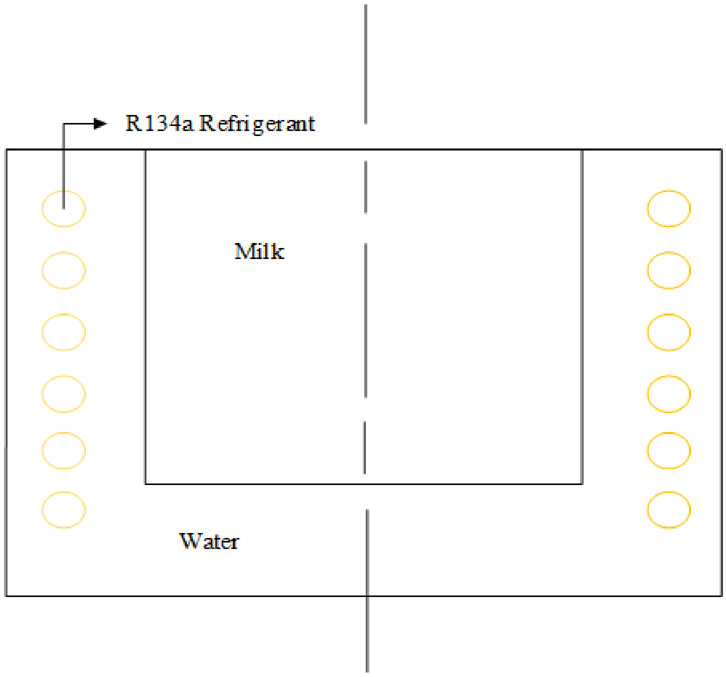

Fig. 2: Concentric ice thermal storage and milk tank

To determine the optimal mass of ice needed, temperature distribution in the water jacket and phase change with increase or decrease of ice thickness due to solidification or melting as a function of the cooling rate of the evaporator obtained from power input to DC variable speed compressor based on power generated by PV panel as per incident solar radiation is required. Such types of problems are usually solved by finite methods using moving boundaries and mesh (solid-liquid interface) or the enthalpy method with a fixed mesh. In this study, the fixed mesh technique and the enthalpy method are used.

The assumptions in the formulation of the computational model are the following:

- The heat transfer from the evaporator through ice/water to the milk tank is considered substantially one-dimensional in the radial direction.

- The charging process for ice is performed by heat transfer from the water to the evaporator in the concentric tank.
- As the water is cooled by the refrigerant in the evaporator coils, the ice thickness increases radially from the evaporator inward during charging as long as the cooling rate of the evaporator is greater than the cooling rate of the milk.
- When the cooling supplied by the evaporator decreases or becomes null in the evening and night, the ice melts, absorbing heat to overcome heat losses and maintain the milk temperature at 2-4 ^{O}C, as shown in Fig.3.

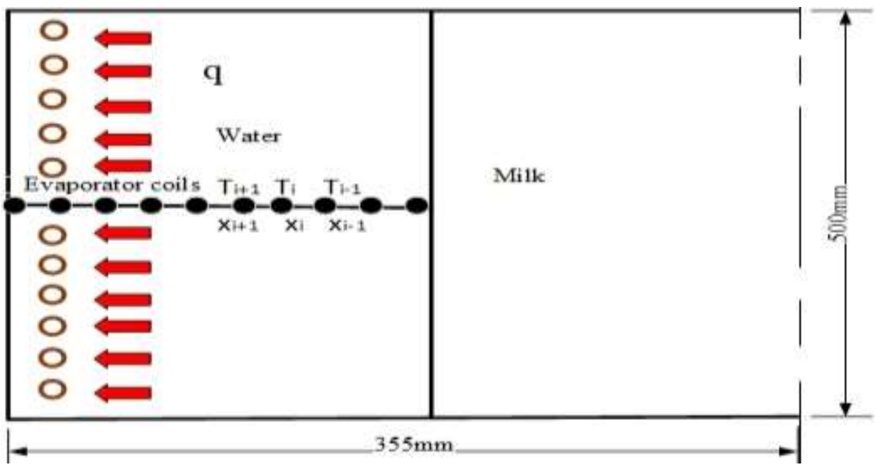

Fig. 3: Charging of ice with the nodal distribution and discharging of ice with the heat transferred from milk.

3. Numerical modeling of ice thermal storage

Ice thermal storage used in this study for milk cooling was modeled using the one-dimensional (1D) enthalpy method. As the heat transfer is predominantly in the radial direction, one-dimensional transient heat conduction equation is used to describe heat transfer during solidification and melting.

$$\rho c \frac{\partial T}{\partial t} = \frac{k}{r}\frac{\partial T}{\partial r} + k\frac{\partial^2 T}{\partial r^2} \qquad \text{(Eq.1)}$$

Where ρ and c are density and heat capacity

The ice thickness is computed from the solid-liquid interface condition balance at the interface (Marques et al., 2014).

$$\rho_s L_f \frac{dr_i}{dt} = k_s \frac{\partial T_s(r_i,t)}{\partial r} - k_L \frac{\partial T_L(r_i,t)}{\partial r} \qquad \text{(Eq. 2)}$$

Where k_s is solid thermal conductivity, k_L is liquid thermal conductivity, T_s and T_L are solid and liquid temperature.

For the water node at the milk tank boundary during charging as well as discharging, the following boundary condition is applied.

$$-k\frac{\partial T}{\partial r} = h(\ T - T_m) \qquad \text{(Eq. 3)}$$

Where T_m is milk temperature.

The explicit finite difference method is used to discretize the above equation in the ice slab for solving the nodal temperature in the liquid and solid domain at the new time step by taking three adjacent nodes. The interior node temperature for the ice/water region is obtained as follows using the appropriate thermophysical properties.

$$T_i^{\,n+1} = \frac{\alpha\Delta t}{2\,r\,\Delta r}\left(T_{i+1}{}^{n} - T_{i-1}{}^{n}\right) + \frac{\alpha\Delta t}{\Delta r^2}\left(T_{i+1}{}^{n} + T_{i-1}{}^{n}\right) + \left(1 - 2\frac{\alpha\Delta t}{\Delta r^2}\right)T_i^{\,n} \qquad \text{(Eq. 4)}$$

For the boundary node at the side of the evaporator, the heat flux of cooling from the evaporator has to be considered.

$$T_i^{\,n+1} = \frac{2\alpha\Delta t}{\Delta r^2}\left(T_{i+1}{}^{n} - \frac{\Delta r\, q}{k}\right) + \left(1 - 2\frac{\alpha\Delta t}{\Delta r^2}\right)T_i^{\,n} \qquad \text{(Eq.5)}$$

Where q is the heat flux supplied by the evaporator on the outer cylinder surface.

$$q = \frac{\dot{Q}_{evap}}{\pi D\ H} \qquad \text{(Eq.6)}$$

Where D and H are the diameter and height of thermal storage.

For the node of the water jacket at the milk tank side during charging without milk or in case of no heat transfer

$$T_{i,j}{}^{n+1} = \frac{2\alpha\Delta t}{\Delta r^2}\left(T_{i-1,j}{}^{n}\right) + \left(1 - 2\frac{\alpha\Delta t}{\Delta r^2}\right)T_i^{\,n} \qquad \text{(Eq. 7)}$$

For the water node at the milk boundary during charging as well as discharging

$$T_i^{n+1} = (T_{i-1}{}^n) + \left(\frac{h\Delta r}{k}\right)\,(T_m - T_{i,j}{}^n) \quad \text{(Eq. 8)}$$

Where $k = k_w$ $\rho = \rho_w$ $c = c_w$ for $T > 0.1^oC$ and $k= k_{ice}$ $\rho = \rho_{ice}$ $c = c_{ice}$ $T< -0.1^oC$

It is assumed that phase change will occur at $-0.1\ ^oC < T< 0.1^oC$, and the thermal conductivity and density are taken as an average of water and ice. However, the heat capacity is calculated from the latent heat of fusion as follows for the assumed phase transition interval, which is, in this case, 0.2 ^oC.

$$c = \frac{Q_L}{\Delta T} = h \quad \text{(Eq. 9)}$$

The thickness of ice is obtained by interpolation, finding the radial length from the outer radius location of 0^oC at every time step.

4. Result and discussion

The simulation was carried out by using the climate of Semera, Ethiopia, and PV panel of 600 W, and milk tank of 50 liters for representative average days of months of the year, and ice/ water temperatures during charging and discharging, ice thickness, and milk temperature drops after pasteurization were determined.

4.1. Charging and discharging temperature of ice thermal storage

In this study, the water and ice mixture are utilized to cool the milk to the required temperature. During the day, water is charged from an immersed copper coil evaporator that contains an R134a refrigerant that brings the water's temperature to the required level of -1°C. Charged ice thermal storage starts draining once the compressor is off, raising the temperature of the water inside of thermal storage by a maximum of 2°C in 24 hours. The charging and discharging temperature of the ice thermal storage as shown in Fig. 4 of the average months of the year indicated that the maximum temperature of water inside of thermal storage was 2^oC at the end of the 24-hour length for all representative months.

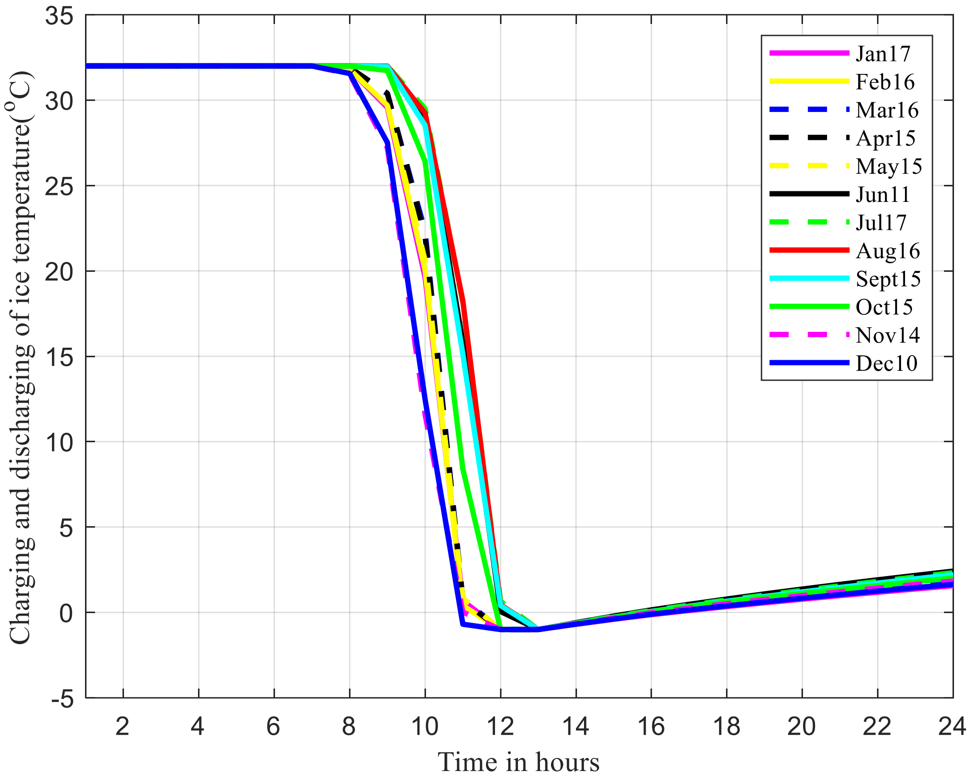

Fig. 4: charging and discharging ice water temperature in an average month of the year

4.2. Ice slab growth and melting in thermal storage

Whenever the solar PV harvests, the variable speed compressor runs, and as the temperature of the water reaches 0ºC around the immersed evaporative coil, the ice slab starts forming. The maximum ice slab thickness obtained from the simulation indicated about 0.074m and the minimum ice slab is about 0.061m in the average month of years during the charging as indicated in Fig.5 below.

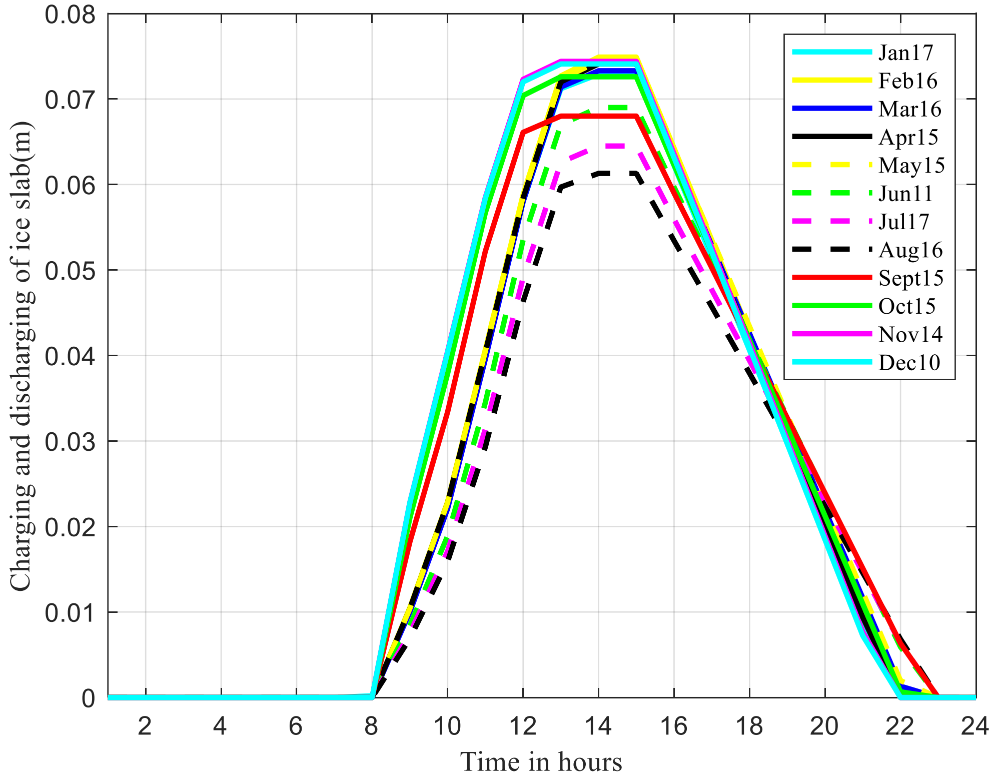

Fig. 5: Charging and discharging temperature and ice thickness of ice thermal storage for average months of a year.

4.3. Mass ice growth and melting

As the ice slab grew, the amount of ice mass required to cool the milk for the given 24 hours was identified. Similarly, as the ice slab started melting, the amount of mass of ice around the evaporative coil discharged. Fig.6 asserted that the maximum amount of ice was about 37 kg and the minimum amount was about 31kg in the average month of the year, respectively.

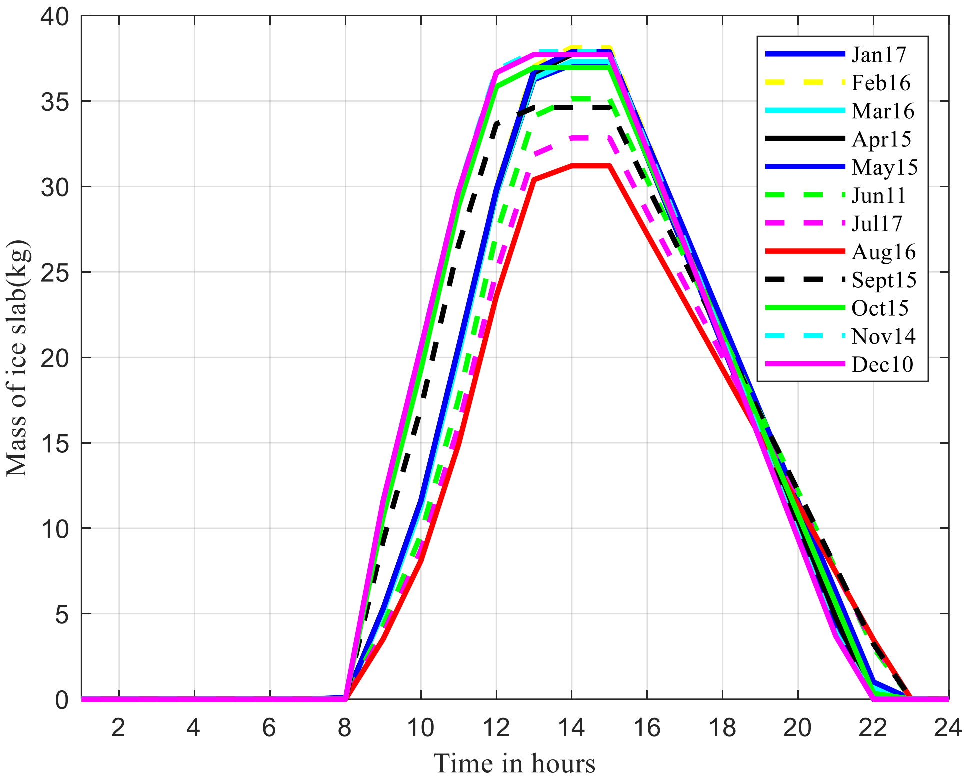

Fig. 6: Mass of ice charging and discharging in average months of the year

4.4. Milk Cooling Temperature

In this study, milk can be pasteurized using an evacuated-tube solar collector, an insulated storage tank, a circulation pump, and a control system. The method involves allowing hot water from a solar water heater to flow through a helical coil heat exchanger that is enclosed by milk in the pasteurization tank. This process ensures that the milk is heated to the required pasteurization temperature. The pasteurization tank has a capacity of 50 liters and requires a 1 m^2 area of evacuated tube solar collector to maintain the temperature of the pasteurized milk from 32°C to above 65°C. As indicated in Figure 7, the maximum temperature for milk pasteurization was 82°C in November and the minimum was 69°C in August. Once the milk reaches the required pasteurized temperature, it is transferred or flows to the milk-chilling tank and it can be cooled to temperatures of 2°C in less than 4 hours for all representative months of the year.

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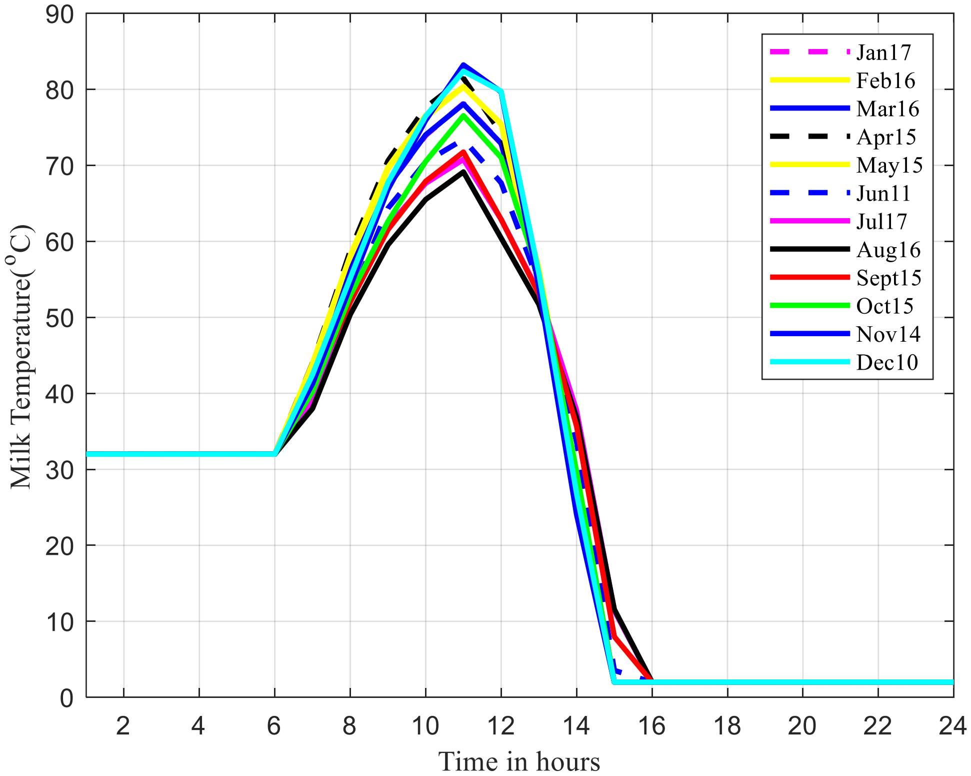

Fig. 7: Milk cooling temperature utilizing ice thermal storage for average months of a year.

5. Conclusion

Ice thickness and temperature during charging and discharging are computed using explicit transient heat conduction, and transient one-dimensional heat flow. Pasteurized milk is refrigerated to the required temperature in less than four hours utilizing ice as a backup. A minimum thickness of 0.061m and 31kg of ice is needed to keep 50 liters of pasteurized milk between 2 and 4°C for more than a day.

6. Acknowledgments

We sincerely thank the Norad Energy Net Project for funding this effort. The materials that are being presented here are a portion of the entire project and should not be viewed as a project output.

7. References

Abhishek, A., Kumar, B., Kim, M. H., Lee, Y. T., Chung, J. D., Kim, S. T., Kim, T., Lee, C., & Lee, K. 2019. Comparison of the performance of ice-on-coil LTES tanks with horizontal and vertical tubes. Energy and Buildings.183, 45–53.

Asgharian, H., & Baniasadi, E. 2019. Experimental and numerical analyses of a cooling energy storage system using spherical capsules. Applied Thermal Engineering. 149, 909–923.

De Blas, M., Appelbaum, J., Torres, J. L., García, A., Prieto, E., & Illanes, R. 2003. A Refrigeration Facility for Milk Cooling Powered by Photovoltaic Solar Energy. Progress in Photovoltaics: Research and Applications. 11(7), 467–479.

El-Bahloul, A. A. M., Ali, A. H. H., & Ookawara, S. 2015. Performance and Sizing of Solar Driven DC Motor Vapor Compression Refrigerator with Thermal Storage in Hot Arid Remote Areas. Energy Procedia.70, 634–643.

Ezan, M. A., Ozdogan, M., & Erek, A. 2011. Experimental study on charging and discharging periods of water in a latent heat storage unit. International Journal of Thermal Sciences. 50(11), 2205–2219.

Ghaith, F. A., & Onur Dag, R. 2022. Performance and feasibility of utilizing solar-powered ice storage system for space cooling applications. Energy Conversion and Management. 16, 100319.

Han, K., Ji, J., Cai, J., Gao, Y., Zhang, F., Uddin, M. M., & Song, Z. 2021. Experimental and numerical investigation on a novel photovoltaic direct-driven ice storage air-conditioning system. *Renewable Energy*.*172*, 514–528.

Hu, C., Li, M., Wang, Y., Li, G., Ma, X., Du, W., Zhou, X., & Zhang, Y. 2021. Preliminary investigation on pilot-scale photovoltaic-driven cold storage with ice thermal storage based on vapor compression refrigeration cycle. Sustainable Energy Technologies and Assessments. 45.

Kahraman, R. 2002. Numerical and experimental investigation of melting of ice involving natural convection. International Journal of Energy Research. 26(4), 347–354.

Kasera, S., Nayak, R., & Chandra Bhaduri, S. 2021. Performance analysis of solar milk refrigerator using energy efficient R290. Case Studies in Thermal Engineering. 24, 100855.

Marques, A. C., Davies, G. F., Maidment, G. G., Evans, J. A., & Wood, I. D. 2014. Novel design and performance enhancement of domestic refrigerators with thermal storage. Applied Thermal Engineering.63(2), 511–519.

Sanaye, S., & Khakpaay, N. 2022. Innovative combined optimization and modified maximum rectangle method for equipment sizing and operational strategy of an integrated system with cold thermal storage. Energy Reports. 8, 137–160.

Sidney, S., Kim, S. C., Dhasan, M. L., & Prabakaran, R. 2021. A novel solar-powered milk cooling refrigeration unit with cold thermal energy storage for rural applications. Environmental Science and Pollution Research. 29,16346–16370

Xie, J., & Yuan, C. 2014. Numerical study of thin layer ring on improving the ice formation of building thermal storage system. Applied Thermal Engineering. 69, 46–54.

Xu, Y., & Li, M. 2022. Impact of instantaneous solar irradiance on refrigeration characteristics of household PCM storage air conditioning directly driven by distributed photovoltaic energy. Energy Science and Engineering. 10(3), 752–771.

Xu, Y., Li, M., Luo, X., Ma, X., Wang, Y., Li, G., & Hassanien, R. H. E. 2018. Experimental investigation of solar photovoltaic operated ice thermal storage air-conditioning system. International Journal of Refrigeration. 86, 258–272.