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Design Development and Performance Evaluation of Phase Change Material (PCM) based Chiller for Raw Milk Cooling

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Abstract: The phase change material (PCM) based milk chiller was designed and developed at ICAR-Central Arid Zone Research Institute (CAZRI), Jodhpur, India. The performance evaluation of the developed box type well insulated chiller made of stainless steel 304 (SS 304) was carried out experimentally for different eutectic solutions and salt hydrate *viz.* potable water (PW), propylene glycol, diethylene glycol, triethylene glycol, and ammonium chloride (NH_4Cl) at different concentrations (5-30%) are used for cooling energy storage. The initial temperatures of PW and propylene glycol at different concentrations were 25.8°C. The final temperatures of PW and propylene glycol at various concentration (5-30%) varies from -4.2°C to -14.9°C. The initial temperatures of PW and diethylene glycol at different concentrations were 25.9°C. After freezing for 12 hrs the final temperatures at various concentration (5-30%) varies from -4.1°C to -17.8°C. The initial temperatures of PW and triethylene glycol at different concentrations were 25.8°C. After freezing for 12 hrs the final temperatures at various concentration (5-30%) varies from -3.9°C to -17.2°C. Similarly, the initial temperatures of PW and NH_4Cl at different concentrations were 25.8°C. After freezing for 12 hrs the final temperatures at various concentration (5-30%) varies from -3.7°C to -16.0°C. The chiller reduced milk temperature from 32.7°C to 11.4°C in about 120 minutes in case of PCM as potable water, 32.6°C to 9.1°C in case of PW with 10% propylene glycol, 32.5°C to 8.5°C in case of PW with 10% diethylene glycol, 32.6 to 8.8°C in case of PW with 10% triethylene glycol and 32.5 to 9.3°C in case of PW with 10% NH_4Cl concentration. The highest drop for PCM (PW+10% diethylene glycol) came to 9.9°C in 100 min followed by 8.7°C in the next 40 min. The final temperature 10°C varied for about 2.5 hrs.

Key words: Phase change material (PCM), milk cooling, energy saving, rural areas.

Dairy sector role is very important in boosting the rural economy. Livestock rearing is a major production activity which adds to income of farmers in arid Rajasthan. India is the world leader in milk production with an annual output of 210 million tones which is 23% of milk production (Anonymous, 2022). The fundamental purpose of cooling milk is to retard the growth of bacteria. The growth of bacteria is rapid at high temperatures and there is practically no growth at 4.4°C (Roberts and Larson, 1941). The milk production in India is mainly concentrated in rural area, so it has to be transported to long distances which may lead to spoilage of milk. This necessities cooling during transit period. In arid region of Rajasthan, milk production of marginal farmers varies widely from 3 to 10 litres, but the major problem of the rural areas is the milking collection centre or diary plants situated far away from production areas. Milk chilling and cooling is most crucial and key operations of milk processing as quality, safety and shelf-life of milk and milk products are concerned. Over the years numerous methods and systems *viz.*, hydro-vac cooler, surface cooler, mechanical cooler, and electric energy-based refrigerated tank cooling have been developed to cool/ chill fresh raw milk. All these methods need much energy and the initial investment is very high. The grid power supply in the rural areas is very poor with respect to its quantity and quality. Phase change material (PCM) is the one of best solutions for operating small cold storage systems in rural areas for raw milk cooling (Poonia *et al.*, 2022; Sharma *et al.*, 2009; Taylor *et al.*, 2016; Kong *et al.*, 2017). The most common phase change materials for cold thermal energy storage applications are inorganic salt hydrates, organic paraffin waxes and mixtures of these as well as eutectics module and nano-particle-based nanofluids are commonly utilized as phase change materials for cold storage. Toledo *et al.*, (2018) designed

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and built an on-farm milk cooling solution based on insulated cans with an integrated ice compartment. The experimental study concluded the ability of the system to cool down 30 L milk to 17°C in less than 90 min with 6 kg ice. By using the same milk can with 20 L and 8 kg ice, milk remains below 13°C over 12 h at 35°C ambient temperature. Kasaeian *et al.* (2017) reviewed the applications of PCMs and nano-PCMs in buildings for cooling, heating and air-conditioning/ventilation at a relatively low temperature ranging from 10°C to 40°C. The PCM of -20°C to 5°C saved upto 12% energy (Oró *et al*., 2012a, b). Liu *et al*. (2012) developed a novel design of refrigerated trucks consisting of an off-vehicle refrigeration unit with an on-vehicle PCM storage unit (melting point of -26.7°C), which brought down energy consumption by 86.4% in comparision to without PCM. Azzouz *et al*. (2009) was placed the PCM slab in the back side of the evaporator inside a household refrigerator to improve its efficiency and to provide a storage capacity allowing several hours of cold storage without a power supply. It is also demonstrated that a refrigeration system with eutectic PCM achieves better COP than water, due to a low melting temperature (-5°C) (Khan and Afroz, 2013). Wu *et al*. (2010a, b) tested the potential of Al_2O_3 nanofluids and Cu/parrafina nanofluids as a new phase change material for the thermal energy storage of a cooling system. Drasan (2015) developed a eutectic module for raw milk cooling and found that cooling raw milk temperatures 35°C to reduce to 20°C. The minimum temperature of raw milk achieved 8.4°C when it was cooled from 37°C in 68 min. using nano-particle-based nano-fluids under field conditions (Prakash, 2015). Prakash *et al.* (2018) studied the sub-zero temperature behaviour, super-cooling degree, and cooling energy storage capabilities of aqua-glycol eutectics for milk cold chain at various concentrations (5-30%) in distilled water as well as for potable water. Therefore, an attempt has been made to develop a phase change material (PCM) based system for raw milk cooling for rural areas of arid Rajasthan without access to reliable grid electricity.

Materials and Methods

Design of PCM-based milk cooling module

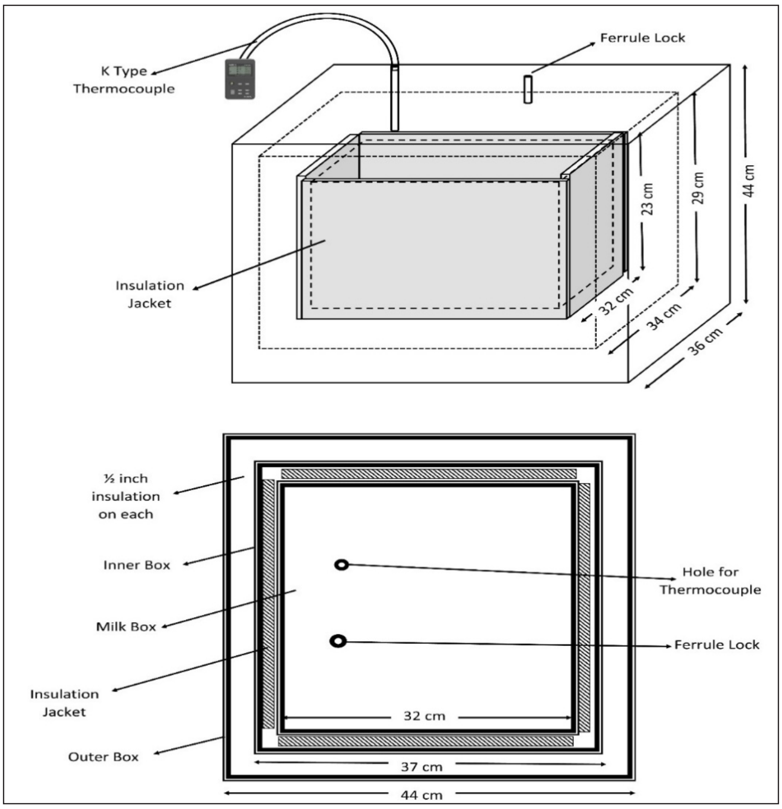

Fig. 1. Schematic diagram of PCM based cooling system for raw milk.

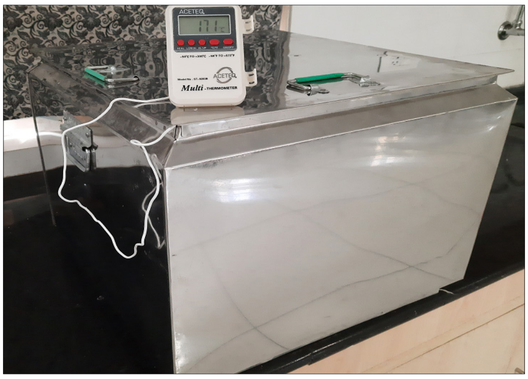

Fig. 2. Phase change material based cooling module for raw milk.

The phase change material-based suitable cooling module for raw milk cooling was designed and fabricated. A square-shaped insulated milk cooling module made of stainless steel 304 (SS 304) series was developed, and the cooling performance of different phase change material-based modules was evaluated. The dimension of the insulated outer box was 440 mm × 360 mm and the dimension of the inner box was 370 mm × 290 mm. The diameter of the milk can was 320 mm × 230 mm and the dimension of the four jackets containing PCM-based frozen cooling fluid were 290 mm × 190 mm (Fig. 1). The total surface area of the milk can is 0.07 m^2 (Fig. 2).

Table 1. Properties of different eutectic solutions (base fluids) used for milk cooling

Phase change material	Concentration in potable water (%)	Melting temperature (°C)	Heat of fusion (kJ kg^{-1})
Potable water	-	0	333
Eutectic solution (95% H_2O + 5% Propylene glycol) (%wt)	5	-4.2	246
Eutectic solution (90% H_2O + 10% Propylene glycol) (%wt)	10	-7.0	246
Eutectic solution (85% H_2O + 15% Propylene glycol) (%wt)	15	-9.3	246
Eutectic solution (80% H_2O + 20% Propylene glycol) (%wt)	20	-11.5	246
Eutectic solution (75% H_2O + 25% Propylene glycol) (%wt)	25	-13.9	246
Eutectic solution (70% H_2O + 30% Propylene glycol) (%wt)	30	-14.9	246
Eutectic solution (95% H_2O + 5% diethylene glycol) (%wt)	5	-4.1	247
Eutectic solution (90% H_2O + 10% diethylene glycol) (%wt)	10	-7.4	247
Eutectic solution (85% H_2O + 15% diethylene glycol) (%wt)	15	-10.7	247
Eutectic solution (80% H_2O + 20% diethylene glycol) (%wt)	20	-12.4	247
Eutectic solution (75% H_2O + 25% diethylene glycol) (%wt)	25	-15.4	247
Eutectic solution (70% H_2O + 30% diethylene glycol) (%wt)	30	-17.8	247
Eutectic solution (95% H_2O + 5% triethylene glycol) (%wt)	5	-3.9	246
Eutectic solution (90% H_2O + 10% triethylene glycol) (%wt)	10	-7.1	246
Eutectic solution (85% H_2O + 15% triethylene glycol) (%wt)	15	-10.2	246
Eutectic solution (80% H_2O + 20% triethylene glycol) (%wt)	20	-11.9	246
Eutectic solution (75% H_2O + 25% triethylene glycol) (%wt)	25	-15.0	246
Eutectic solution (70% H_2O + 30% triethylene glycol) (%wt)	30	-17.2	246
Inorganic (salt hydrate) (95% H_2O + 5% NH_4Cl) (%wt)	5	-3.7	289
Inorganic (salt hydrate) (90% H_2O + 10% NH_4Cl) (%wt)	10	-6.7	289
Inorganic (salt hydrate) (85% H_2O + 15% NH_4Cl) (%wt)	15	-9.5	289
Inorganic (salt hydrate) (80% H_2O + 20% NH_4Cl) (%wt)	20	-11.2	289
Inorganic (salt hydrate) (75% H_2O + 25% NH_4Cl) (%wt)	25	-14.4	289
Inorganic (salt hydrate) (70% H_2O + 30% NH_4Cl) (%wt)	30	-16.0	289

Freezing behavior and cooling energy storage capabilities of PCM

Different eutectic solutions (phase change material) *viz.* potable water, propylene glycol, diethylene glycol, triethylene glycol, and ammonium chloride (NH_4Cl) at different concentrations (5-30%) were used for cooling energy storage (Table 1). Cooling eutectic fluid (base fluid) was prepared by weighing appropriately and mixing properly. These eutectic solutions at different concentrations were filled separately in four cooling jackets and kept for freezing for 12 hrs in the deep freezer. The temperature of the deep freezer was at -20°C for the entire duration of the trials. After freezing the PCM fluids, the jackets were immersed in all container sidewalls containing fresh raw milk. The K-type thermocouple measured the cooling fluid temperature inside jackets during the cooling module's freezing and cooling performance evaluation. The data logger continuously recorded the temperature changes of the milk and cooling fluid.

Results and Discussion

Different aqua-glycol as cooling base fluids *viz,* Potable water (PW), propylene glycol, diethylene glycol, triethylene glycol, and ammonium chloride (NH_4Cl) at different concentrations (5-30%) were tried in the experimental trials to evaluate the freezing and super-cooling behavior in terms of cooling thermal energy storage. The results of freezing and super-cooling behavior of the cooling fluids as recorded by the data logger and presented in Fig. 3-6. The temperature of the deep freezer was at -20°C for entire duration of trials. The quantity of each eutectic solution taken for freezing and related studies was 2.0 L. Fig. 3-6 shows that the temperature dropped rapidly for all the glycol-based base fluids at different concentrations during the first 2 h cooling period, as evidenced by the steep slopes of the curves. Thereafter, the curves decreased gradually and a significant difference in temperature drop was observed with all the cooling base fluids at their respective concentrations as cooling and afterward freezing progressed further. The potable water (PW) freezing point curve loop started freezing at around 0°C in 240 min. The initial temperature of PW was 25.6°C. After freezing for 12 h, the final temperature of PW was -0.7°C. As indicated by the dip in the cooling curve between 0 and -5°C, the freezing point curve loop of PW was caused by super-cooling until ice crystals were formed. Then, a sudden temperature rise was observed which could be due to the release of latent heat upon cooling associated with the onset of freezing.

The rate of temperature drop of propylene glycol+PW with different concentrations showed faster drop as indicated by the steep slope of curves. The initial temperatures of PW and propylene glycol at different concentrations

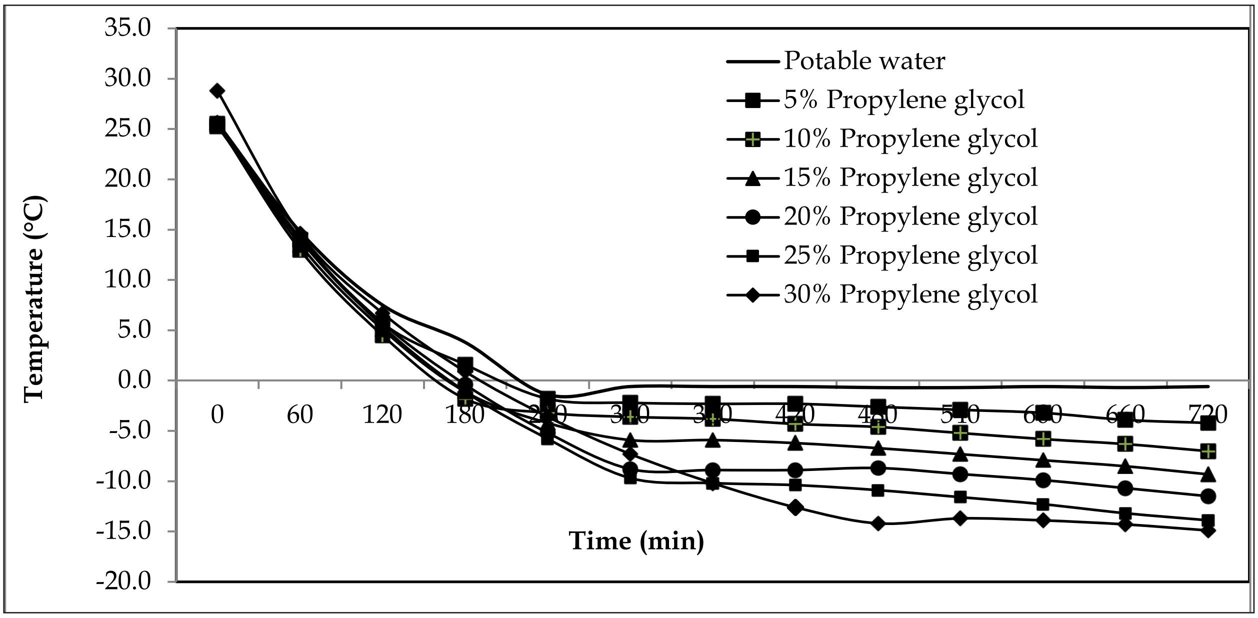

Fig. 3. The temperature profile of PW and propylene glycol at different concentrations upon freezing.

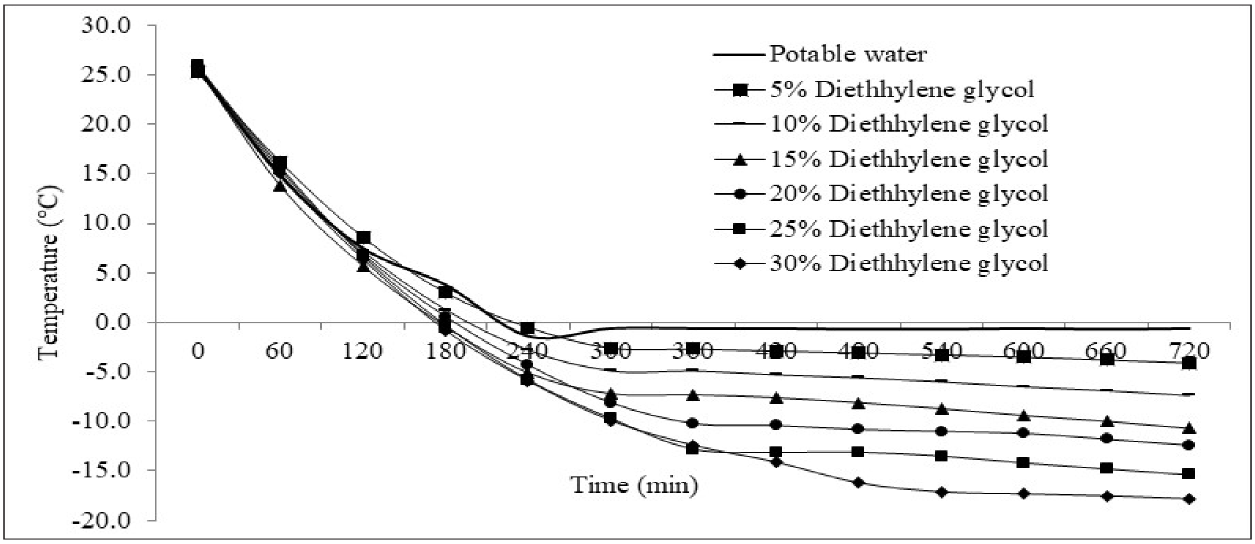

Fig. 4. The temperature profile of PW and diethyleneglycol at different concentrations upon freezing.

were 25.8°C. The final temperatures of PW and propylene glycol at 5% concentration is -4.2°C, at 10% is -7.0°C, at 15% is -9.3°C, at 20% is -11.5°C, at 25% is -13.9°C and finally at 30% is -14.9°C (Fig. 3). The initial temperatures of PW and diethylene glycol at different concentrations were 25.9°C. After freezing for 12 hrs, the final temperatures at 5% concentration is -4.1°C, at 10% is -7.4°C, at 15% is -10.7°C, at 20% is -12.4°C, at 25% is -15.4°C and finally at 30% is -17.8°C (**Fig. 4**). The initial temperatures of PW and triethylene glycol at different concentrations were 25.8°C. After freezing for 12 hrs, the final temperatures at 5% concentration is -3.9°C, at 10% is -7.1°C, at 15% is -10.2°C, at 20% is -11.9°C, at 25% is -15.0°C and finally at 30% is -17.2°C (**Fig. 5**). Similarly, the initial temperatures of PW and NH_4Cl at different concentrations were 25.8°C. After freezing for 12 hrs the final temperatures at 5% concentration is -3.7°C, at 10% is -6.7°C, at 15% is -9.5°C, at 20% is -11.2°C, at 25% is -14.4°C and finally at 30% is -16.0°C (Fig .6)

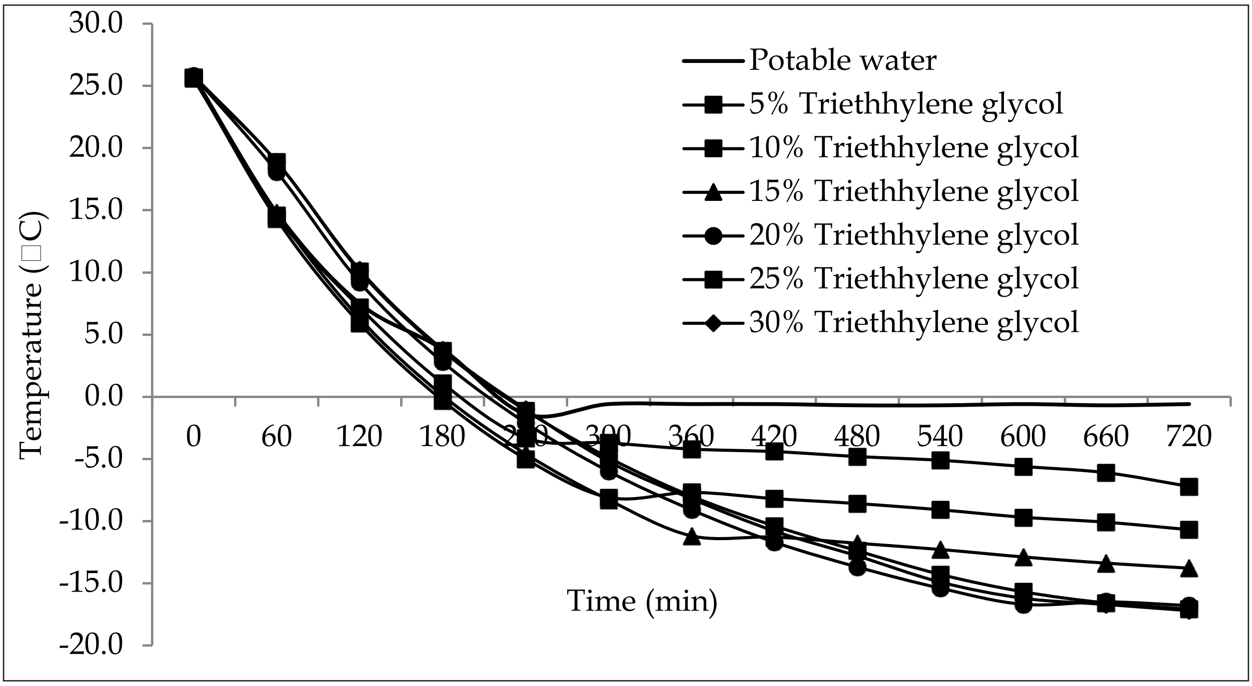

Fig. 5. The temperature profile of PW and triethyleneglycol at different concentrations upon freezing.

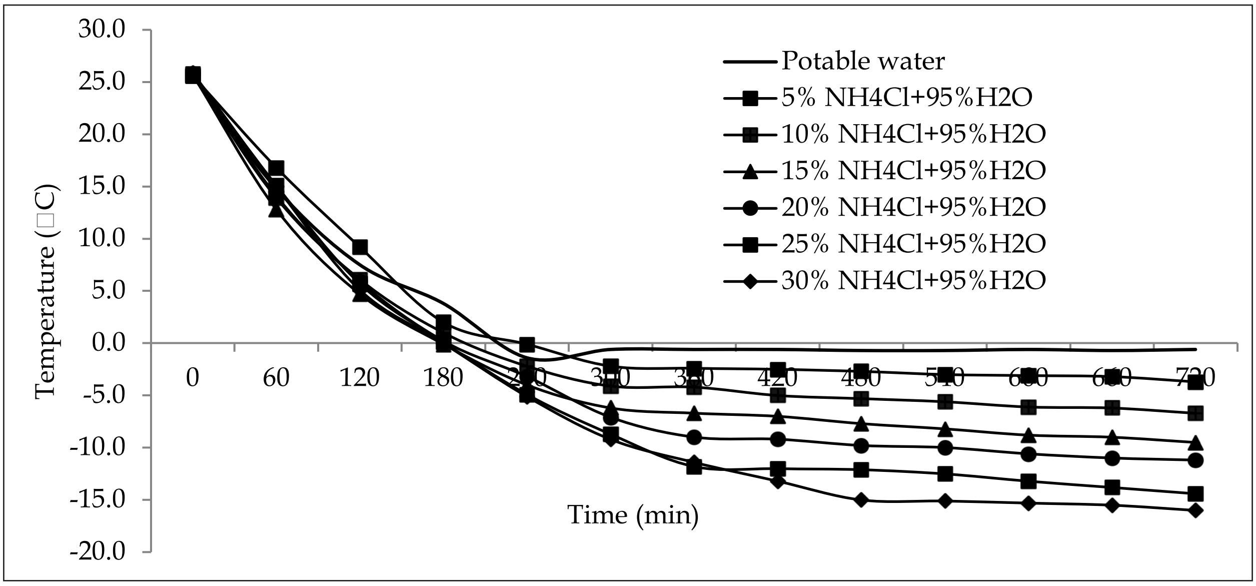

Fig. 6. The temperature profile of PW and NH_4Cl at different concentrations upon freezing.

Performance evaluation of a phase change material-based milk cooling module

The developed phase change material-based milk cooling module was tested during 2021-22. The variation in milk temperature with respect to time for selected freeze PCM at 10 percent concentration has been shown in Fig. 7. It has been observed that temperature dropped rapidly in the initial stage, i.e., up to 90 min of cooling, and later the change was gradual till the temperature became constant (**Fig. 8**). The developed cooling module cooled raw milk from 32.7 to 11.4°C in about 120 minutes in case of PCM as potable water, 32.6 to 9.1°C in case of PW with 10% propylene glycol, 32.5 to 8.5°C in case of PW with 10% diethylene glycol, 32.6 to 8.8°C in case of PW with 10% triethylene glycol and 32.5 to 9.3°C in case of PW with 10% NH_4Cl concentration. The maximum temperature drop of raw milk cooled by the jackets containing PCM (PW with 10% Diethylene glycol concentration) was found to be 9.8°C in 90 min and reached 8.5°C in the next 30 min. The temperature of cooled milk was maintained below the critical limit (10°C) for another 2.5 hrs. The cooling jacket filled

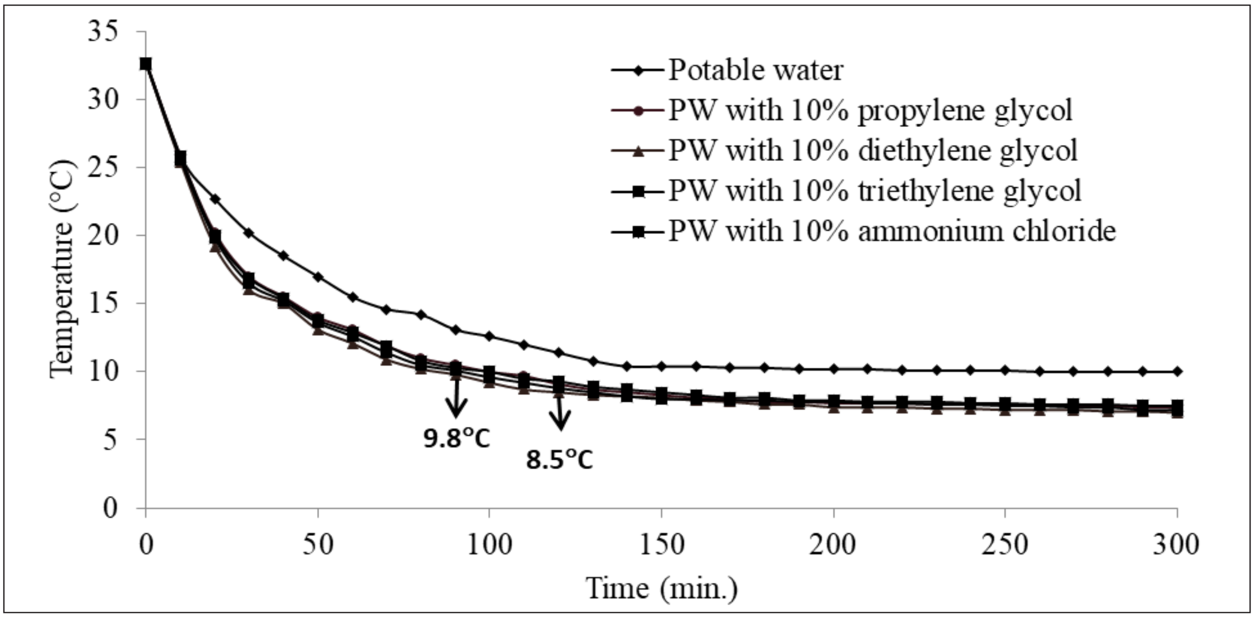

Fig. 7. Milk temperature variation for selected PCM at different concentration under milk can.

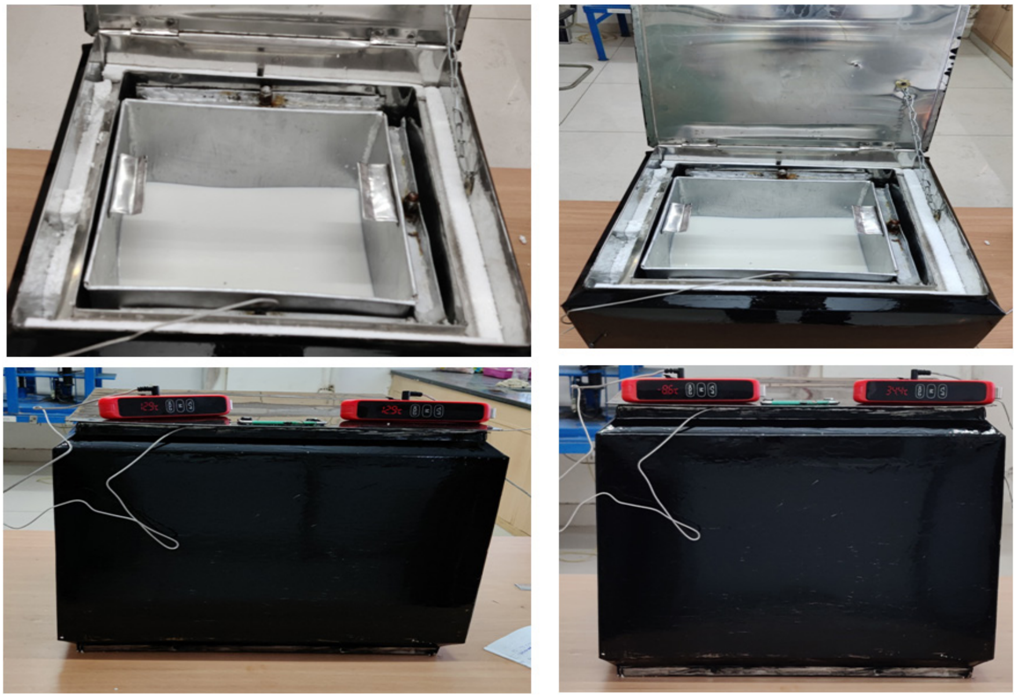

Fig. 8. Phase change material based cooling module for raw milk.

with PW with 10% diethylene glycol provided the maximum cooling effect, i.e., it colled seven liters of raw milk from 32.5 to 8.5°C in 120 minutes, followed by PW with 10% triethylene glycol. The maximum rate of heat transfer was found with a 10% diethylene glycol solution. The potable water had the highest latent heat of fusion, providing a cooling effect than other refrigerants. The degree of super-cooling was more pronounced in the case of ethylene glycol solution, followed by propylene glycol solutions. At higher concentrations of glycols, the degree of super-cooling was while cooling energy storage capabilities were less. The highest temperature drop (ΔT) for potable water and all aqua-glycol solutions was observed in the first hour of freezing. Therefore, the developed aqua-glycol-based eutectics can be successfully recommended for cooling milk and milk products for hasty and energy-efficient cooling, chilling, and refrigeration applications.

Conclusion

A box type well insulated milk chiller made of stainless steel 304 (SS 304) was developed by ICAR-CAZRI, Jodhpur, India, and evaluated for the cooling performance of different phase change material-based modules. The study used aqua-glycol eutectics as the PCM, and studied the sub-zero temperature behaviour and cooling energy storage capabilities of the eutectic solutions, using potable water, propylene glycol, diethylene glycol, triethylene glycol, and ammonium chloride (NH_4Cl) at different concentrations (5-30%) for cooling energy storage. Results showed that the maximum temperature drop of raw milk cooled by the jackets containing PCM (PW with 10% diethylene glycol concentration) was 9.8°C in 90 min and reached 8.5°C in the next 30 min.

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