JOURNAL OF CRITICAL REVIEWS

ISSN- 2394-5125 VOL 7, ISSUE 15, 2020

THERMAL PERFORMANCE EVALUATION OF A BULK MILK COOLER BUILT-IN COLD THERMAL STORAGE

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Received: 16 March 2020 Revised and Accepted: 17 June 2020

ABSTRACT: India and many other countries, the livestock sector has been arisen as an important area for ensuring a more comprehensive and sustainable agriculture growth. Dairying is an important source of income for millions of rural people and has taken a most important role in providing employment and income generating openings specifically for marginal farmers and rural women. About 40 % of the milk is handled by the organized sector and the 60 % by the unorganized sector, which is a major concern. However, to export the dairy products the infrastructure of handling of the milk in India should be at par with international standards. In this paper a milk cooler with cold thermal storage using PCM has been designed, fabricated and performance tested. If such systems are installed at collection centers it can increase the livelihood of villagers and export of dairy products due to meeting international standards.

KEYWORDS: Milk Cooler, Cold Thermal Storage, PCM, System Design, Dairy, Livelyhood

I. INTRODUCTION

India has the largest livestock population in the world and more than 70 million rural households are engaged in production of milk. The majority of these households are either small marginal farmers or people having no agriculture land. Indian dairy industry has a key role in the livelihood and economy of these people. India is the highest milk producing country in the world with total milk production of 187.7 million MT per annum in the year 2018-19. The economic value of milk is Rs. 6,500,000 million in 2018-19 [1,2]. The milk is collected through cooperative and non-organized sector. As major collection is through non-organized sector, therefore, it is leaving a wide scope for improving the milk collection, processing and production of dairy products for local utilization and export to other countries. There are many parts of the country which are not having the organized milk collection; the milk is collected once a day, if frequency increased, it can improve their financial condition [2].

Milk is a highly perishable commodity. The temperature of milk at the time of milking is about 37°C. To maintain its quality as per international standards, milk to be rapidly chilled to 4°C to control the growth of micro-organisms [4]. With most farmers having 2-3 milking animals, it is not possible for these small farmers to develop the infrastructure of storing the milk at required 4°C temperature before supplying to consumers or milk collection centers. These farmers had to sell his produce immediately which results in panic sale and the farmers suffered financial losses and had to remain at the mercy of milk purchasers [1-3]. Generally, the raw milk is transported to milk processing plants in a crude method like using plastic/aluminum milk cans. The time gap between milking and delivering to the milk processing plant are a few hours and is long enough to degrade the milk quality. At few places Bulk Milk Coolers (BMCs) at village level have been installed. A BMC is an insulated stainless steel tank, a refrigeration system and operated with a generator set, it does not have any integrated cold thermal storage system. The BMC is used to cool the milk 4- 8 °C within 2-3 hours after its collection. These BMCs are operated by diesel generator sets and operational costs are expensive & also not environment friendly, still it has provided a significant improvement in the quality of milk and income of the beneficiaries [2].

Under "Operation Flood" in 1970 and Technology Mission on Dairy Development (TMDD)-1989, it was planned to modernize the infrastructure dairy sector and to increase the rural income by using latest and efficient technology to increase the productivity, reduction in operation costs and to make ensure better accessibility of dairy and milk products. However, these missions were mainly focused on increase the quality of milk animals and processing of the milk to convert into product. Less efforts were made towards collection and raw quality of the milk. The more rapidly milk is cooled after milking, the better the quality. Therefore, the rate at which the milk is processed at the various control stages in the dairy supply chain is responsible for the quality. The

European Union aims to minimize the risks to human health from harmful bacteria and says that milk must be cooled to a temperature of 4-6 °C to reduce the chances of micro-organism growth. This also ensures that if collection is not done on daily basis then the temperature must not be more than 10ºC [3,4].
The objective of this paper is to design a bulk milk cooler with a backup of cold thermal storage based on latent heat storage system using phase change material (PCM) and to cool the milk in 3 hours and also to maintain the temperature at least for 24 hours with the help of storage system. Phase change materials have been widely used for various applications like refrigeration, air-conditioning, heating/cooling of space, solar cooking, transport, solar thermal power plants etc. due to its high energy density and isothermal nature [5-15]. Various types of heat exchangers have been used by researchers [16-24], in this paper finned plate and balls type heat exchanger has been used.

II. SYSTEM DESIGN

2.1 Coolness Energy Storage Required for 100 kg Milk

As the objective of the papert is to design a milk cooler of 100 kg capacity with a backup of coolness storage and to cool the milk within 3 hours and to maintain the desired temperature at least for 24 hours with the help of coolness storage system. The system would be requiring (i) PCM coolness storage tank, (ii) milk storage tank and (iii) refrigerating system. After receiving the milk from the farmer, it has to be cooled at a faster rate. Therefore, to calculate the heat load of milk, following assumptions were made:

(i) Thermo physical properties of milk are assumed nearly equal to water properties.
(ii) Initial temperature of milking 37 ºC
(iii) Final temperature of cooled milk is 5 ºC
(iv) Specific heat of milk is assumed equal to water i.e. 4.0 kJ/kg°C

To calculate the heat to be removed from the milk following data has been used:-
The heat to be removed from the milk is-

$$Q_1 = mC_p\Delta T \qquad \text{(i)}$$

Where, Q_1 is the heat to be removed from the milk, m= mass of milk (kg), Cp= specific heat (j/kgºC), and Δ is milk temperature difference of initial temperature of milk and the final temperature of the milk, at which it is to be cooled.

2.2 The Coolness Energy Storage Requirement for 24 Hours

The second motto of this paper is to maintain the cooled milk temperature for almost 24 hours, since the temperature at which the milk should be kept ranges from 5-10˚C and this temperature will be maintain for almost 24 hours, this will continuous his heat be losing to the environment so, the storage system also needs an added capacity of storage material to meet the cooling.
The coolness storage to be designed to maintained the milk temperature up to 10°C upto 24 hours, with the possibility that the milk could not be transported to the desired plant.

Following Assumptions are made:-

(a) Temperature of the room where system is installed is 35°C
(b) Temperature of milk after 24 hours is 10°C
(c) PUF insulation thickness of the whole system is 0.075m and thermal conductivity is 0.021 W/m°C.

Therefore, the total heat loss can be calculated as

$$Q_2 = U_oA_o\,(-T_{milk} + T_{room}) \times \text{Time(sec)} \qquad \text{(ii)}$$

Where, U_o is Overall heat transfer coefficient to surrounding environment, A_o is the outer surface area, T_{milk} is the temperature of cold milk, and T_{room} is the temperature of the room, where the machine is kept. To calculate the Q_2, following data has been used:-

Table 1: Various parameters to estimate the heat loss to surroundings by milk cooler

Parameters	A(m^2)	U($W/m^{2\circ}C$)	T_{milk}(ºC)	T_{room}(ºC)	Time(seconds)
Value	5.1	0.5	10	35	3600×24

2.3 Calculation for the PCM Quality for the Cooler

To cool the raw milk up to 5°C and to maintain its temperature up to 10°C for 24 hours, the quality of PCM to be calculated as:-

$$M_{PCM} \times L_{PCM} = Q_1 + Q_2 \qquad \text{(iii)}$$

Where, M_{PCM} is the mass of PCM in kg, L_{PCM} is the latent heat of the selected PCM, Q_1 and Q_2 are obtained from equations (i) and (ii).

2.4 Selection of PCM

The major desirable properties of a PCM to be selected for an application are (i) should be able to meet the desired temperature, (ii) should have high latent heat of fusion, (iii) should have congruent melting/freezing behavior, (iv) should be abundantly available easily and (iv) should have at-least 5 years life. Therefore, a water based PCM has been identified and the thermo-physical properties are given in table 2.

Table 2: Thermo-physical properties of the used PCM

Melting/Freezing Temperature	Latent Heat	Specific Heat
-3 °C	271 kJ/kg	4 kJ/kg °C

Using equation (i) to (iii) and PCM & milk properties for 100 kg milk, the quantity of PCM required will be 96 kg at 70 % effectiveness. The PCM was encapsulated in cylindrical plastic bottles with a capacity of 500 ml each.

2.5 Heat Transfer Area Calculation

Since the milk is being cooled by the PCM material, The heat balancing equation at equilibrium will be shown as-

Heat rejection by milk= heat gain by brine solution = heat gain by PCM material.

The total heat rejected from the milk will be transferred to the PCM by conduction and convection method through the material made for fabricating the storage unit.

The heat gain by brine will be transferred from the milk through the surface of the material used for the fabrication of the brine tank.

$$\therefore \text{Heat gain by brine} = \mathbf{U A \Delta T} = \text{heat rejected by the milk} \qquad \text{(iv)}$$

Where, U= overall heat transfer co-efficient from milk to brine.

A= Total heat transfer area required.

ΔT= Average temperature difference between brine and milk.

Using equation (4) and other design parameters, the total heat transfer area between milk and brine cum PCM side comes to 3.75 m^2. The design value of U was considered 50 W/M^2 °C. The effective surface area available from the brine cum PCM tank surfaces is 1.5 m^2. To meet the heat transfer surface area, it was decided to add fins.

2.5 Design of the fins

To meet the requirement of additional heat transfer surface area between milk and brine cum PCM tanks 132 fins have been used i.e. 33 numbers of fins were attached to the each side of the inner tank. The gap between the two fins was 2 cm. The fins were installed at the outer side of the inner tank. Details of fins are given in table 3 and a photo of the fins is shown in figure 1.

Table 3: Fin specifications

Length	0.40 m
Thickness	0.5 mm
Width	0.025 m
Number of Fins	132
Fins surface Area	2.6 m^2

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Figure 1: A photo of the Fins attached to Brine cum PCM Tank

2.7 Calculation of the required size of the refrigerating machine

The refrigerating machine needs to charge PCM which cool the 100 kg milk from 37 °C to 5 °C and to maintain the temperature of the milk up-to 10°C for 24 hours i.e. it to be met by the PCM stored coolness. Total heat to be removed is comes out 7.2 kWh which is equivalent to 2.06 TRH. If the PCM is to be charged in 3 hours with brine then the required size of refrigerating machine is 0.7 TR. Based on it, a refrigeration of 2 TR (at 7.2 °C evaporating temperature and 54.4 °C condensing temperature) was procured, at -10 °C, it can deliver 0.9 TR, assuming that lowering down 1°C temperature of evaporator will de-rate 3% cooling capacity of the refrigerating machine.

2.8 Size design of the system:

The system requires two tanks i.e. one for PCM and brine and second for milk & its storage. Therefore, two tank system needs to be designed. The refrigerating system has been selected on the basis of heat load and operating temperature. It was decided that PCM and brine tank would be inner tank and surrounded by the outer tank to be used for milk cooling and storage. Design dimension calculations of the outer and inner tank, which is basically a two concentric cuboidal tank for the storage milk and PCM storage is as given in table 4 and a photo is shown in figure 2.

Table 4: The Design dimensions of 100 kg Milk Storage Tank and PCM Storage Tank

Dimension	Inner Tank for PCM, brine solution and evaporator tubes (meter)	Outer Tank for Milk Storage Tank (meter)	Outermost dimensions after insulation also housed compressor and condenser (meter)
Length	0.35	0.51	0.92
Breadth	0.35	0.51	0.66
Height	1.14	1.27	1.42

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Figure 2: Photo of the Milk chilling system with cold thermal storage

III. RESULTS AND DISCUSSION:

To evaluate the performance (i) during storing the coolness i.e. charging of PCM and (ii) cooling the milk i.e. discharging of PCM, experiments were conducted in the laboratory. K type thermocouples have been used to measure the temperature of the brine solution and representative PCM container. The reading interval of this experiment was 15 minutes.

3.1 Charging of PCM

To study the charging performance, the liquid PCM at -1.3 ºC was charged to store the coolness using chiller machine during 13:30 hrs. to 18:30 hrs., the temperature of brine and PCM were recorded at an interval of 15 minutes. During this period there was no heat load of the milk i.e. the outer milk tank was empty. At 18:30 hrs., the physical status of the PCM was observed and was found fully in solid phase and the data is tabulated in table 5 and plotted in figure 3.

Table 5: Temperature of brine and temperature of PCM during the charging of PCM

Time (Hrs.)	Brine Temperature (ºC)	PCM Temperature (ºC)
13:30	3.4	-1.3
13:45	-3.2	-1.2
14:00	-4.6	-1.3
14:15	-4.7	-1.4
14:30	-4.8	-1.6
14:45	-4.9	-1.9
15:00	-5.3	-2.2
15:15	-5.4	-2.4
15:30	-5.5	-2.9
15:45	-5.6	-2.9
16:00	-5.6	-3.2
16:15	-5.8	-3.2
16:30	-6.1	-3.4
16:45	-6.4	-3.9
17:00	-6.8	-4.0

17:15	-6.6	-4.2
17:30	-6.7	-4.3
17:45	-6.7	-4.3
18:00	-6.8	-4.8
18:15	-6.9	-4.8
18:30	-7	-4.7

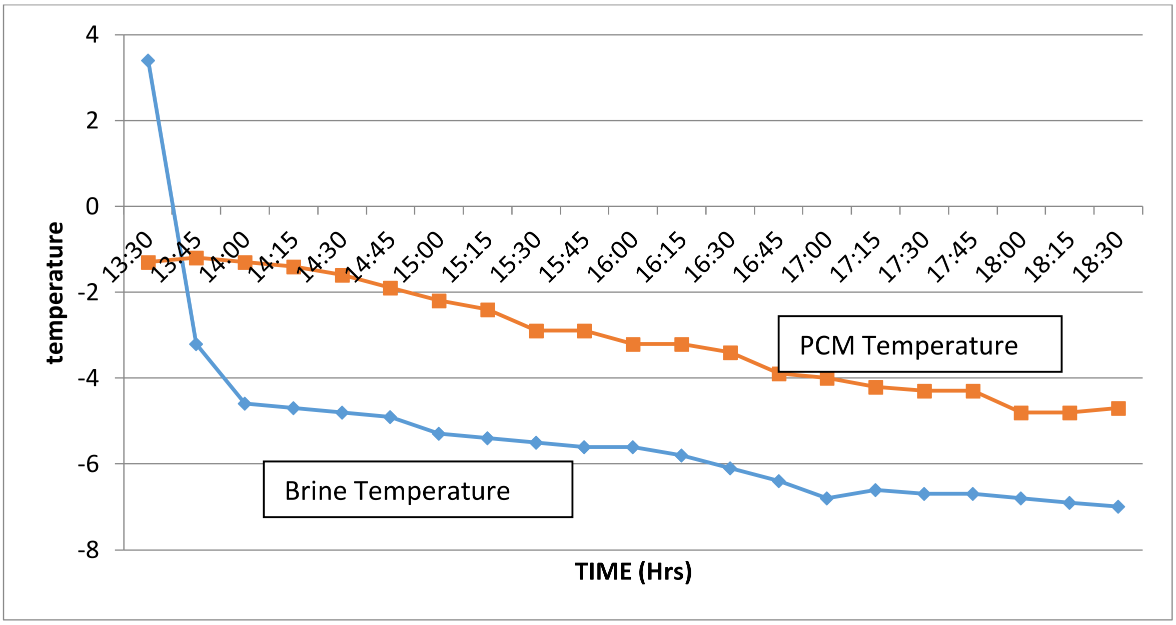

Figure 3: Temperature variation of brine and PCM during the period of charging of PCM

3.2 Discharging of PCM and Cooling of Milk

To study the coolness back up, 100 kg water at 25 °C was filled in the outer tank. It is assumed that the thermo-physical properties of the milk and water are nearly same. The chilling machine was kept off. The water gets started cooling effect from PCM. During the process, the PCM discharges the coolness and the water receives the cold to get chilled. The temperature of water and PCM were recorded at an interval of 15 minutes till the temperature of outer tank water drops from 25°C to 8°C. The recorded data is tabulated in the table 6 and plotted in figure 4.

Table 6: Temperature of water during cooling period

Time (Hrs.)	Water Temperature (ºC)
12:15	24.3
12:30	17.3
12:45	13.8
13:00	11.0
13:15	10.4
13:30	9.5
13:45	9.3
14:00	9.2
14:15	8.9
14:30	8.5
14:45	8.1
15:00	8.1

15:15	8.1
15:30	8.0
15:45	8.0
16:00	7.9

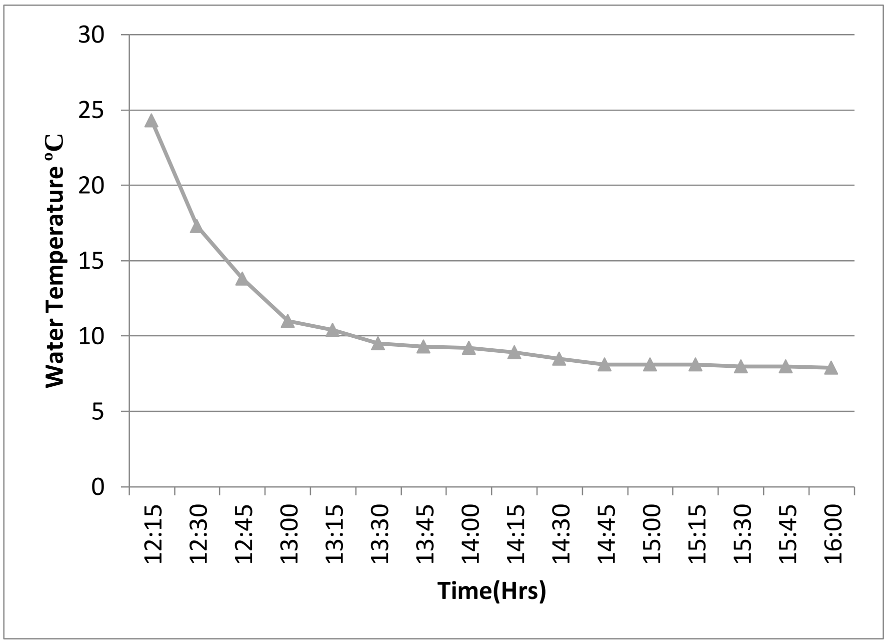

Figure 4: Temperature profile of water being cooled by PCM

From figure 3, it can be seen that during trial run the PCM was fully charged in 5 hours, which was also verified physically. It has been noticed from the table 5 and figure 3 that there are few variations in terms of up and down of values of temperature; it may be possible due to the disturbance during measurement of temperature. Similarly, from the figure 4, it can be observed that the water was cooled to 8 ˚C in 3 hours. However, no variations in terms of up and down of values of temperature have been noticed during the cooling of water which is representing the milk.

IV. CONCLUSIONS

In this paper the designed and fabricated bulk milk cooler with cold thermal was tested for its thermal performance for storing the coolness and cooling the milk up-to 8 ˚C successfully. The experimental performance showed that installations of such systems in the field can improve the quality of milk hence, the livelihood of villagers. If these systems are connected with solar power or utilization of off-peak power then it can be very advantageous and attractive for the villagers and electric companies.

V. ACKNOWLEDGEMENT: The help of Mr. Govind Satirth and Mr. Sachin Joshi are thankfully acknowledged during the experiments.

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