Sādhanā (2020)45:110
https://doi.org/10.1007/s12046-020-01334-0

A standalone PV operated DC milk chiller for Indian climate zones

SHAJI SIDNEY, JOSE THOMAS and MOHAN LAL DHASAN*

Refrigeration and Air Conditioning Division, Department of Mechanical Engineering, Anna University, College of Engineering Campus, Chennai 600 025, India
e-mail: shajisidney@gmail.com; josemanjananickal@gmail.com; dr.mohanlal29@gmail.com

MS received 20 May 2019; revised 31 January 2020; accepted 3 February 2020

Abstract. This work illustrates the design of a standalone solar power system used to power a milk chiller with 200 W DC compressors using the PVsyst software for different climatic zones in India. The design includes determination of minimum number of PV panels and batteries and also the means of obtaining annual solar fraction values for five different climatic zones of India using the software. Simulations were performed considering two different operational modalities. The first modality considered a milk chiller with an inbuilt ice bank tank for cool thermal energy storage. The ice formed during sunshine hours take care of the cooling of the milk throughout. The second modality considered a milk chiller coupled with a battery backup to get charged during sunshine hours and to run the compressor throughout. The first modality was found to be advantageous in terms of PV panel requirement, battery backup as well as better solar fraction. Hence the same was experimentally studied for Chennai's climate condition to confirm the maintenance of milk temperature. The power supply from the PV panel was simulated using a regulated power supply. While doing so, considering the maximum power point, the power supply was varied every hour as predicted by the PVsyst software. From the experiment, it was found that the required number of PV panels got reduced from 4 to 2 panels when considering the maximum power point for a typical summer day. The custom built milk chiller was able to chill down the milk from 37°C to 4°C within 2 hours on all days using cold energy from the ice bank tank.

Keywords. Maximum Power Point; DC compressor; milk chiller; solar fraction; ice bank tank.

1. Introduction

India is one of the largest milk producing nations in the world. Unfortunately, a large quantity of milk is wasted and the quality of the milk degenerates owing to the absence of proper preservation facilities. Globally milk chilling is the most widely chosen method of milk preservation. Chilling of milk to 4°C within two hours inhibits the growth of bacteria that spoils the milk. In countries like India, where many rural areas are either gridless or have irregular power supply, there is a need to augment solar based refrigeration systems. The standalone photo-voltaic (PV) systems also known as off grid systems are designed to provide electricity to devices without taking any additional power from the utility grid [1, 2].

As per the Bureau of Indian Standards (BIS), India has the following climatic regions namely hot and dry, hot and humid, moderate and cold zones [3]. A region is classified as one of the four climatic regions only when the defined conditions prevail there for more than six months. Otherwise, it is classified as the fifth zone namely composite climatic zone [4]. Based on the five major climatic zones, five major cities were chosen to represent each zone namely Jodhpur (hot and dry zone), Chennai (hot and humid zone), Bangalore (moderate zone), New Delhi (composite zone) and Shillong (cold zone).

Limited works have been reported on solar based milk chilling applications with direct current (DC) compressor. De-Blast *et al* [5] experimentally studied a standalone solar powered refrigeration facility with two HFC-134a compressors for chilling 150 liters of milk using ice as a thermal storage. Torres-Toledo *et al* [6] used two units of a DC refrigerator, one at −10°C for producing 3 kg ice to increase the rate of cooling of milk from 30°C to 10°C and the other at 4°C for preserving 17 liters of milk in a conventional 20 liters milk can. A variable voltage power unit set to 12 V was used for the testing. Axaopoulos and Theodoridis [7] converted a domestic refrigerator to be solar PV powered using a 440 W_p solar panel and a BD35F DC compressor. It was found that the coefficient of performance (COP) of the compressor was better at low speeds. Zhang *et al* [8] studied the performance of a refrigerator with DC compressor at Shanghai area and concluded that the performance of the DC refrigerator was reliable and suitable for storage of perishable foods, vaccines, and drugs.

*For correspondence

Published online: 08 May 2020

Suresh and Thomas [9] performed simulation analysis of a standalone PV system under non-uniform operating conditions using the PVsyst software. The steps followed while designing a standalone PV system include determination of load, determination of solar radiation for the site location, sizing of battery and PV array sizing. Palmero-Marrero *et al* [10] compared the simulation results of the PVsyst software with that of the TRNSYS software with the same meteorological data for a PV plant and observed that the results of both softwares were nearly the same with a difference within 2%. Yilmaz *et al* [11] performed numerical analysis with PVsyst software and compared it with experimental results with indicated agreement with the results. Dube *et al* [12] used the PVsyst software to analyse the economic efficiency of solar PV systems in India and accepted it as a suitable software to study the realistic losses encountered while using PV panels.

Modi *et al* [13] redesigned a conventional refrigerator to be PV powered by adding an inverter, a charge controller and a battery bank. The COP was observed to decline with time with maximum COP in the morning, this was due to the low ambient temperature in the morning than in the afternoon. The exergy analysis in the PV powered refrigerators reported that maximum exergy loss was observed in the PV panel [14–17]. Thus there is a need of the maximum power point tracking (MPPT) technique to improve the performance of the PV panels. The maximum power point (MPP) fluctuates with variation in solar irradiation and cell temperature. Thus to maximize power output, the PV panel must be operated at a voltage corresponding to the MPP (V_m) and MPPTs are used to achieve this [18, 19]. MPPT is an ideology used to continuously deliver the highest possible power from the PV array to the load when variations in the insolation and temperature occur [20]. With the variation in atmospheric conditions, the internal resistance of the PV panel varies, but load resistance remains the same. DC-DC converters with MPPT algorithm are used to achieve load matching and to extract the maximum power from the PV panel [18, 20–22].

Thus, PVsyst software is a vital tool used in the design of the solar PV system. To further promote the use of solar energy in refrigeration applications, DC compressors have been used. There has been no work done to analyse the minimum number of panels and batteries for different Indian climate zones with DC compressors used in milk chillers. The novelty of this work is to predict the minimum number of PV panels and batteries required for the five major climatic zones of India using the PVsyst software. Two different modalities are considered while using the PVsyst software. The first modality is a milk chiller with ice bank tank (IBT) for cold thermal energy storage and the second modality is a milk chiller with battery backup to store electrical energy that will be used to power the DC compressors of the milk chiller for non-sunshine hours. Further an experimental study was done considering Chennai's climatic conditions to test the operational feasibility of the milk chiller operating as per the first modality (with IBT).

2. Simulation and design of IBT

2.1 *Simulation using PVsyst software*

The design of the standalone system was done using the PVsyst software to perform the sizing in the number of panels and batteries required to operate a 200 W milk chiller with DC compressor. PVsyst which was developed by André Mermoud, University of Geneva, is a photovoltaic simulation tool (PC software package) used as an educative tool as well as a design tool for commercial applications. The PVsyst software has options for testing grid connected systems, standalone systems, pumping systems and DC grid systems. The software has a graphical user interface through which the required inputs can be fed into the system. In the present study, the standalone option was used for the simulation study. The input parameters fed into the PVsyst software were the National Renewable Energy Laboratory (NREL) meteorological data [23] for the five cities, selection of location under study and the users' need, (load with hours of operation) followed by the PV panel and battery specifications. Though the software had inbuilt meteorological data, the addition of NREL data enabled the attainment of better updated and realistic reports. The outputs obtained were the tilt angle, solar fraction and a report of oversized or under sized data. The outline of the simulation process is shown in figure 1. The software also has provisions to generate I-V curves based on the solar insolation and ambient temperature from which the operating current and voltage can be obtained.

In this study, two modalities were considered and compared using the stand alone option in the software:

- Modality 1 (M_1): Ice was formed and stored on the first day in the IBT as cold thermal energy during the sunshine hours (approximately 8 hours). From the second day onwards, 10 liters of milk were added in two phases (morning and evening). This was cooled and maintained solely by the cold thermal energy stored in the IBT and during the sunshine hours, the compressors were operated using the stored cold thermal energy in the IBT. The same process was repeated every day.
- Modality 2 (M_2): During the sunshine hours (approximately 8 hours), the batteries were charged and the DC compressors were operated throughout using the battery backup. Milk was added, similar to that in the first modality.

Simulations were performed with reference to major cities in India i.e. Chennai, Bangalore, New Delhi, Shillong and Jodhpur representing the different climate zones and considering the above modalities. In the first modality, the

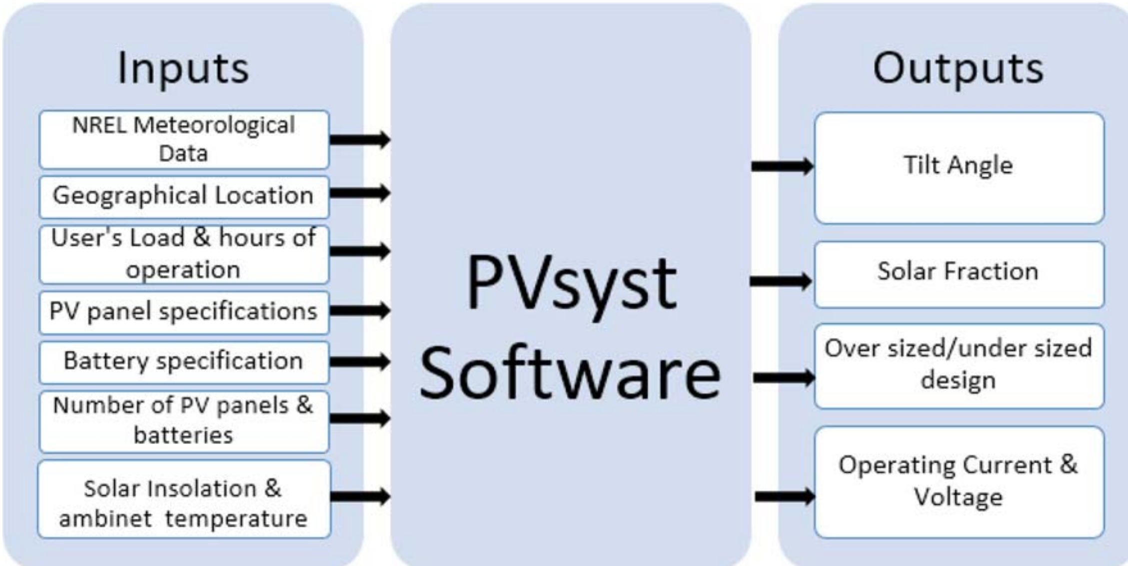

Figure 1. Outline of the simulation process using the PVsyst software.

hours of operation of the compressor was 8 hours whereas, in the second modality, the hours of compressor operation was 24 hours. The output generated were the solar fraction for all the twelve months, report of the minimum number of PV panels and batteries required to effectively operate the milk chiller and the I-V characteristics of the panel.

2.2 *Design of the IBT and compressor capacity*

In dairy farms, milking is done in two phases i.e., morning and evening. In most of the remote villages in India where dairy farming is extensively done, there is poor road connectivity and transportation facilities to transport milk to the milk processing plants. The milk got during the morning hours is transported to the milk processing plants while the milk got in the evening is kept till the next morning to be transported to the milk processing plants or part of the milk is sold locally. In some situations, milk transportation to the milk processing plants happens during both the milking sessions and this is often not economical to the farmers. To overcome such difficulties and loses, milk got during the morning/evening is chilled and stored in refrigerators along with the upcoming milk and milk from both milking sessions are transported to the milk processing plants. Considering the scenario of a small milk farm in which 10 liters of milk is produced in the morning and 10 liters of milk is produced in the evening, a milk chiller of 20 liters capacity is built and operated using DC compressors utilizing solar energy in lieu of conventional energy and IBT in the place of batteries.

The energy required to chill the milk from 37°C to 4°C for both the morning and evening sessions was determined using Eq. (1) and the heat infiltration into the milk chiller with PUF insulation was determined using Eqs. (2) and (3). Since the cooling is to be provided by the IBT, the IBT was designed based on the heat loads. The compressor capacity was subsequently determined based on the IBT load.

The step by step procedure in calculation is explained. The dimensions of the milk chiller tank was based on the holding capacity and the surface area required for winding the cooling coils.

$$Q_{milk}\,(kJ) = mass\ of\ milk \times C_p\ of\ milk \times \Delta T \qquad (1)$$

where,

$$C_p\ \text{of milk} = 3.93\,\text{kJ kg}^{-1}\,\text{K}^{-1}$$

ΔT = Temperature difference between the initial and final Temperatures of milk

The heat infiltration into the milk chiller was obtained using Eq. (2)

$$Q_{infiltration} = \frac{\Delta Ti}{R} \times time \qquad (2)$$

Where,

ΔTi = Temperature difference between inner and outer walls of insulation (32°C)

R = Thermal resistance offered by the insulation.

$$= \frac{1}{2\pi kl} ln\left(\frac{r_2}{r_1}\right) \qquad (3)$$

Where,

$r_{1:}$ Inner radius of insulation
r_2: Outer radius of insulation
k: Thermal conductivity of insulation material (PUF = 0.041 W m^{-1} K^{-1})
l: Height of the milk chiller = 880 mm

$$Q_{total} = Q_{milk\,20l} + Q_{infiltration\,for\,24\,hours} \quad (4)$$

The total heat load for 24 hours was obtained from Eq. (4) and the quantity of ice required is determined using Eq. (5).

$$m_{ice} = \frac{Q_{total}}{L} \quad (5)$$

Thus for one full day, a minimum of 11.85 kg of ice was required and to be on the safer side, the IBT of the milk chiller wais considered to be of 14 liters capacity. The refrigeration load was decided based on the cooling needed to freeze 14 kg of water from 20°C to ice at 0°C and to offset the heat infiltrated in 24 hours.

$$Q_{ref} = (m \times c_p \text{ of water} \times \Delta T) + (m \times \text{latent heat of fusion of water}) \quad (6)$$

Where,

m = 14 kg
C_p of water = 4.18 kJ kg^{-1} K^{-1}
Latent heat of fusion of water (L) = 335 kg^{-1} K^{-1}
Initial temperature of water = 20°C
ΔT = 20°C

The minimum refrigeration capacity required was 5860.4 kJ. As the milk chiller was designed to operate with solar energy, the operation hours were considered to be 8 hours (i.e. 09:00 hrs to 17:00 hrs).

$$\text{Compressor Capacity} = \frac{Q_{ref}}{OperatingTime}. \quad (7)$$

Thus a compressor of 200 W cooling capacity was required to operate the milk chiller. From the Danfoss compressor manufacturer's catalogue, a DC compressor of 100 W capacity was available and thus, two DC compressors were selected. The use of two individual compressors was advantageous as it enabled the operation of atleast one compressor during periods of low solar insolation.

3. Experimentation

3.1 *Solar milk chilling test facility*

A milk chiller of 20 liters capacity was built to chill milk from 37°C to 4°C. The custom built solar milk chiller consisted of an IBT of 14 liters capacity which surrounded the milk tank. In the IBT, cold thermal energy was stored in the form of ice for non-sunshine hours [24]. The schematic layout and the photographic view of the custom built milk chillers are shown in figures 2 and 3, respectively.

Two hermetically sealed variable speed DC compressors BD35K (10-45 V DC) and BD35F (12-24 V DC) operating with HC-600a and HFC-134a refrigerants with a total capacity of 200 W were used. These compressors had inbuilt electronic control units that aided to regulate the power supplied to the compressor and to regulate the speed of the compressors [25]. The cooling capacity and power consumption of the BD35F compressor was higher than that of the BD35K compressor. The use of the BD35K compressor aided the operation of the unit under low solar insolation conditions.

Each compressor was connected to separate evaporator coils helically wound [26] inside the IBT along with individual condensers and expansion devices as shown in figure 2. The evaporator coils were made of copper tubes with a diameter 9.525 mm and length 14 m for each circuit individually. The milk tank was made up of food grade stainless steel (SS 316), cylindrical in shape having a diameter of 200 mm and a height 700 mm. The value of height to diameter ratio increased the heat transfer rate from the IBT to the milk tank, without using a stirrer in the milk tank. The milk tank was encapsulated inside the IBT of diameter 260 mm with a height of 730 mm insulated with polyurethane foam of thickness 75 mm. The IBT tank had an overflow tube at the top through which water overflew when ice formation commenced in the IBT. The milk and IBT temperatures were measured at three different heights of 200 mm, 400 mm and 700 mm from the top of the tanks respectively.

The use of the DC compressors helped to eliminate the use of inverters. Furthermore, the use of the ice bank tank helped to minimize or even eliminate the use of batteries. The IBT could store the cold used as ice thermal storage system, and this could be utilized when the PV output was not sufficient to run the compressors as well as during cloudy periods. The weight of ice formed was determined based on the quantity of overflow water that was collected via the over flow tube. Using the volume of the overflow water, the weight of ice was determined using the method followed by Xu *et al* [27] and Han *et al* [28].

3.2 *Experimental procedure*

An experimental study was performed only for the first modality for Chennai's (hot and humid zone) climatic conditions using the designed solar milk chiller with IBT. The solar milk chiller was tested in a psychrometric facility maintained at 32°C as per the BIS norms [29]. With an intention to perform the testing at the MPP as predicted by the PVsyst software with weather independency and repeatability, an RPS was used to simulate the output of the PV panel that supplies power to the DC compressor directly [16]. The RPS could regulate the voltage and current based

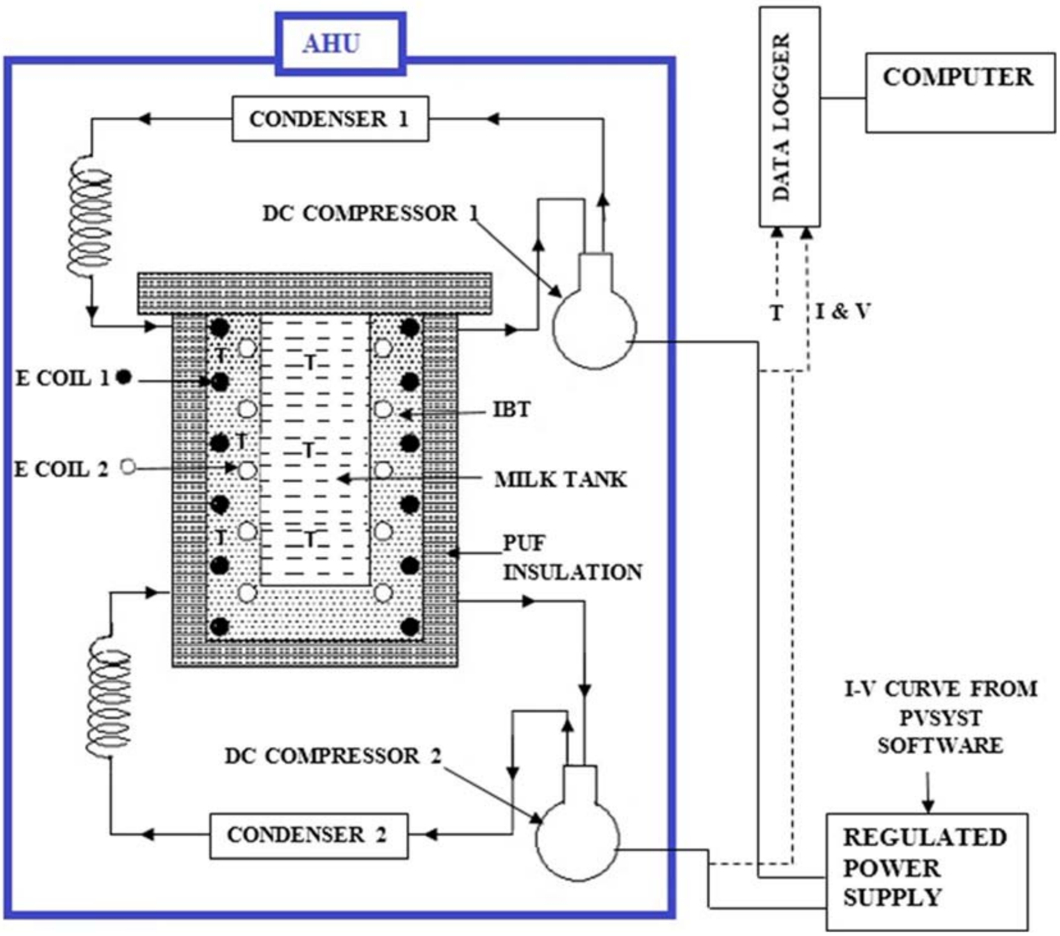

Figure 2. Schematic layout of the milk chiller and test facility.

on the requirement. The output of the RPS was manually set every hour based on the output of the PVsyst software.

The PV panel specifications as per the manufacturer's catalogue shown in table 1 were the inputs to the PVsyst software. The hourly solar insolation and ambient temperature obtained from the weather-station were also the inputs to the PVsyst software.

The outputs obtained were in the form of I-V curves of the specified PV panel corresponding to hourly solar insolation and ambient temperature fed into the software as shown in figure 4. Hourly I-V curves were generated, V_{oc}, I_{sc}, I_m and V_m were obtained and the I_m and V_m values subsequently corresponded to the MPP. The I_m and V_m values were used as the operating current and voltage. The operating current and voltage were varied in the RPS every hour with respect to the hourly solar insolation and ambient temperature starting from 09:00 to 17:00 hours.

The milk chiller was designed to avoid the use of batteries but to make use of the cold thermal energy stored in the IBT. The milk chiller was operated one day in advance without milk to enable ice formation (11.03 kg) in the IBT. On the next day at 06:00 hours, 10 liters of milk were added at 37°C. Water heated to 37°C was used in the place of milk for the experimentation [6]. The milk was chilled down solely with the cold thermal energy from the IBT. From 09:00 to 17:00 hours, the compressor was operated with hourly variation of current and voltage during which the molten ice in the IBT was frozen again and the cold thermal energy was stored in the IBT. At 18:00 hours, 10 liters of milk was further added at 37°C (evening milk) along with the morning milk. The milk was discharged on the next day morning at 06:45 hours. As the milk could be transported at a temperature below 4°C, the quality of milk was be affected and the transportation expenses were reduced for the farmer. Then the fresh milk obtained on the third day

Figure 3. Photographic representation of the vertical milk chiller.

Table 1. Electric performance of the solar panel (WS-125).

Property	Value
Isc:	8.061 A
Voc:	21.250 V
Pm:	127.653 W
Im:	7.627 A
Vm:	16.737 V
FF:	74.42%
EFF:	12.69%
Rs:	0.32 Ohm
Rsh:	76.91 Ohm
Cell Efficiency:	16.20%
Current temp coeff.:	1.600
Voltage temp coeff.:	−180.00 mV/centigrade
Cell Area:	0.024336 m^2
Cells in Parallel:	1
Cells in Series:	36

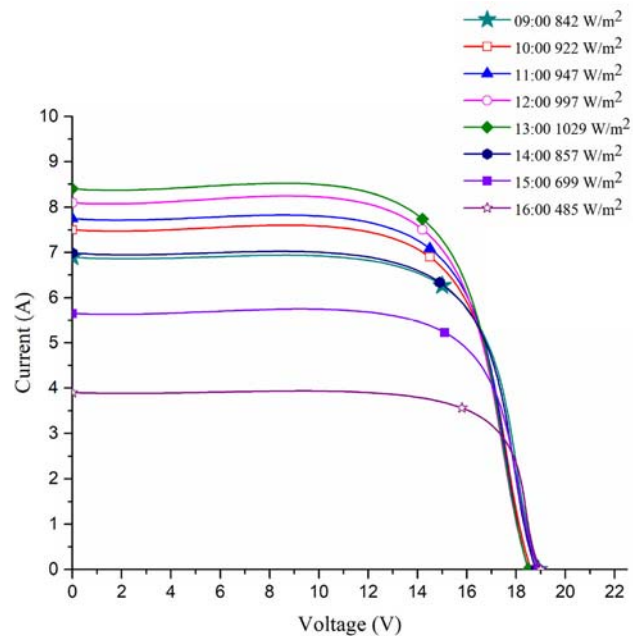

Figure 4. Hourly I-V curves for different solar irradiation generated from PVsyst software.

was similarly cooled and the process was repeated. The temperatures across all the major components in the milk chiller along with the IBT and milk temperatures were logged using an Agilent data logger (Model No: 34970A). Similarly the power consumed by each compressor along with the suction and discharge pressures were measured and logged in the data logger.

3.3 *Uncertainty analysis*

The experimental study mainly concentrated on the pull down characteristics. The measured parameters were the temperatures of the milk and the IBT, which was done with PT-100 type of temperature sensors (Range: −50°C to 200°C, Uncertainty: ±0.15°C). The temperature was measured with a time interval of 60 seconds. The uncertainty calculation procedure followed was based on the uncertainty analysis reported by Moffat [30]. The uncertainty was observed to be 0.1% for the pulldown study.

$$\frac{\Delta t_{pull\,down}}{t_{pull\,down}} = \left[\left(\frac{\Delta T_{IBT}}{T_{IBT}}\right)^2 + \left(\frac{\Delta T_{milk}}{T_{milk}}\right)^2 + \left(\frac{\Delta t_{data\,logger}}{t_{data\,logger}}\right)^2\right]^{0.5} \tag{8}$$

4. Results and discussion

4.1 Simulation results

Using the PVsyst software the optimum tilt angle was determined using the latitude of the location as the reference. The optimum tilt angle of the PV panels were fixed based on the maximum solar insolation (kWh m^{-2}) that could be captured on the PV panel using yearly solar insolation data of the location. The optimum tilt angles for all the locations under test are shown in table 2.

Simulations were performed for the five cities, for the two modalities to determine the minimum number of PV panels, batteries and solar fraction for all the climatic zones. For each city, the simulation was performed by varying the number of PV panels, the panel configuration (i.e., parallel and series connections) and the minimum number of batteries for the milk chiller. The performance of the solar powered system was estimated by considering the obtained monthly solar fraction shown in table 3. Solar fraction is the ratio of energy supplied to the user to the energy need of the user. The highest and the lowest average solar fraction was obtained for Jodhpur (hot and dry zone) and Shillong (cold zone) respectively.

The PVsyst simulation results for the 5 major Indian zones elucidated that for the first modality (M_1) for Jodhpur (hot and dry zone), Chennai (hot and humid zone), Bangalore (moderate zone), New Delhi (composite zone) and Shillong (cold zone), the annual average solar fractions were 0.994, 0.963, 0.929, 0.961 and 0.927 respectively. In general, for the first modality, the solar fractions were observed to lie between 1 and 0.805 as shown in table 3. The minimum number of PV panels required was four in series (each 125 W_p) with one battery (12 V, 100 Ah) to operate the 200 W solar milk chiller for Jodhpur (hot and dry zone), Chennai (hot and humid zone), Bangalore (moderate zone) and New Delhi (composite zone). A minimum of five PV panels in series with one battery were needed for Shillong due to the low solar insolation in the cold zone areas.

While for the second modality (M_2), the annual average solar fractions for Jodhpur (hot and dry zone), Chennai (hot

Table 2. Optimum tilt angle of the PV panels.

Location/Climate Zone	Tilt Angle
Chennai (hot and humid zone)	13°
Bangalore (moderate zone)	17°
Jodhpur (hot and dry zone)	31°
New Delhi (composite zone)	31°
Shillong (cold zone)	31°

Table 3. Monthly solar fraction for all climatic zones in India for both modalities.

	JODHPUR		CHENNAI		BANGALORE		NEW DELHI		SHILLONG	
Month	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2
JAN	1	1	1	1	1	1	0.964	0.940	1	1
FEB	1	1	1	1	1	1	1	1	0.981	1
MARCH	1	1	1	1	1	1	1	1	0.992	1
APRIL	1	1	1	1	0.998	1	1	1	0.988	0.901
MAY	1	1	1	1	0.988	1	1	1	0.912	0.776
JUNE	1	1	0.967	0.981	0.819	0.769	0.955	0.811	0.805	0.680
JULY	0.977	0.934	0.956	0.902	0.810	0.684	0.838	0.769	0.796	0.679
AUG	0.958	0.929	0.945	1	0.806	0.756	0.884	0.805	0.863	0.737
SEPT	0.997	1	0.965	0.927	0.828	0.796	0.954	0.918	0.885	0.780
OCT	1	1	0.929	0.805	0.916	0.894	1	1	0.963	0.896
NOV	1	1	0.878	0.852	0.985	1	0.986	1	0.969	1
DEC	1	1	0.923	0.923	1	1	0.962	1	0.971	0.920
Average	0.994	0.988	0.963	0.949	0.929	0.908	0.961	0.940	0.927	0.863

Table 4. Comparison of Chennai's location with and without MPPT.

	With MPPT	Without MPPT
Modality 1 (Milk chiller with IBT)	No. of Panels: 2 No. of Batteries: 0	No. of Panels: 4 No. of Batteries: 1

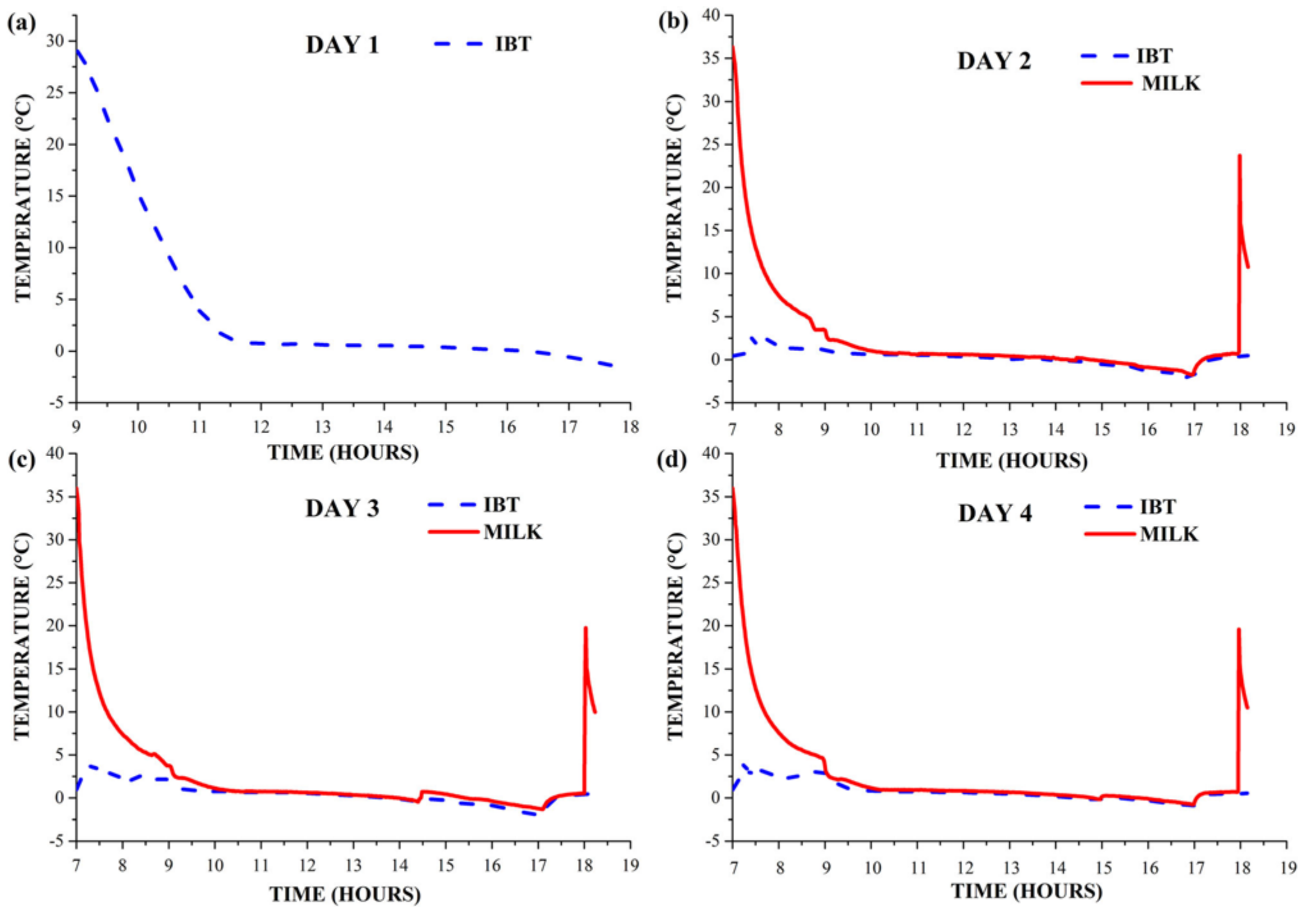

Figure 5. Pull down characteristics of the milk chiller day 1 to 4.

and humid zone), Bangalore (moderate zone), New Delhi (composite zone) and Shillong (cold zone) were 0.988, 0.949, 0.908, 0.940 and 0.863 respectively.

In the second modality (M_2), the number of PV panels required were 10 (each 125 W_p) i.e. five modules in series and two such PV module strings in parallel connection with 10 batteries (12 V, 100 Ah) for all the climatic zones. The solar fractions were observed to lie between 1 and 0.679.

It is observed that for all the climatic zones, the first modality reduces the number of panels and batteries thus reducing the costs, maintenance and space requirement related problems and disposal related issues of old batteries. It is also evident that the average solar fraction is better for all the zones when it is used with IBT.

4.2 *Experimental performance of the milk chiller*

The first modality was found to be superior to the second modality. An experimental work was carried out with the custom built milk chiller in accordance with Chennai's conditions. In order to conduct the study at the MPP as predicted by the PVsyst with repeatability, an RPS was used. Initially, as per the software simulation, 4 panel outputs were kept as the operating power in the RPS. As this was done with an aim of reducing cost, the trial test was conducted with the RPS output corresponding to the minimum number of panels. It was observed that a minimum of 2 PV panels (2 × 125 W_p) were sufficient enough to run the 200 W milk chiller when the panels were operated at MPP. A comparison for Chennai's climatic condition with and without MPPT is shown in table 4. The power output from the RPS was varied hourly to match with the MPP corresponding to the respective hourly data predicted by the PVsyst. This substantiates the need for the use of MPPT as a vital part to be incorporated in the system.

In the experimental study conducted in the milk chiller, the compressor was run for 8 hours (sunshine hours 09:00 hours to 17:00 hours) to produce ice and store latent energy in the IBT with hourly variation of the current and voltage of RPS output. The first day of operation was designed to produce ice only by freezing 14 liters of water without any milk load in the system as in figure 5a. At the end of the first day, the system was capable to produce 11.03 kg of ice after 8 hours of operation (09:00 to 17:00 hours). The average IBT temperature was observed to be −1.76°C. On

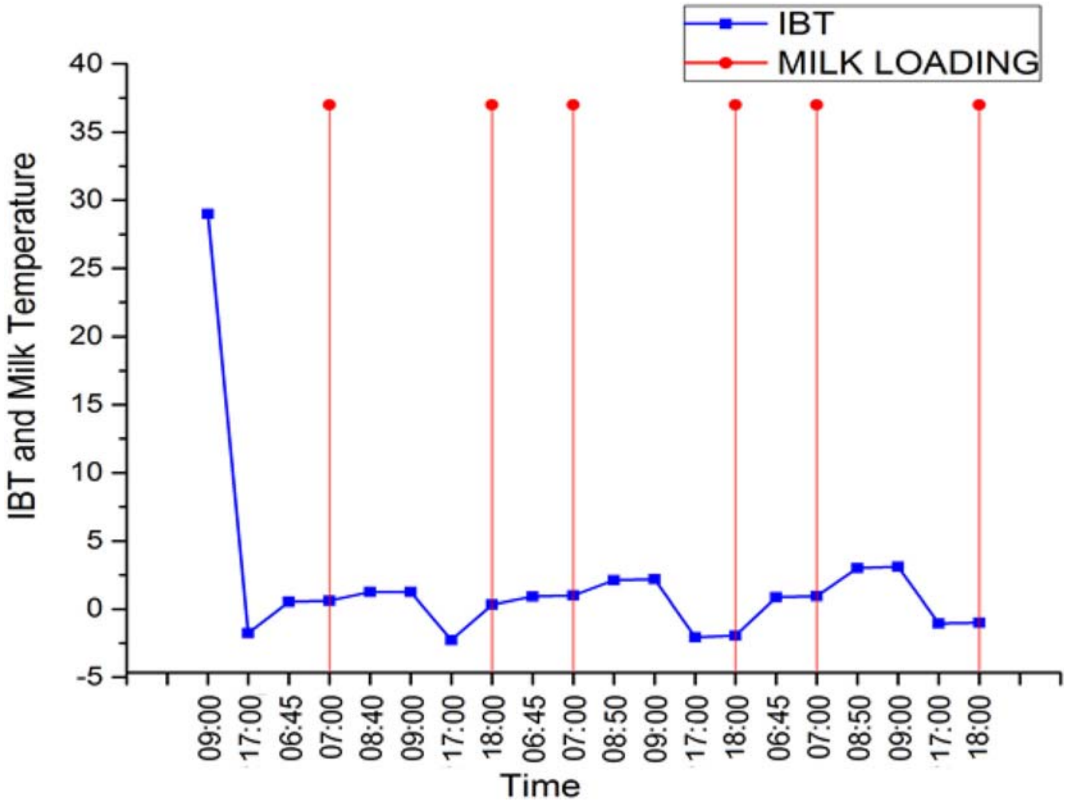

Figure 6. Temperature of the IBT from day 1 to day 4.

the subsequent day, at 06:45 hours, the average IBT temperature was 0.54°C. The overflow water obtained on the previous day was added back into the IBT till overflow condition in the IBT. The difference between the volume of overflow water obtained from the previous day and the remaining water after refilling the IBT was used to determine the weight of ice remaining in the IBT.

Due to infiltration of heat, the total quantity of ice present in the ice bank tank got reduced to 7.73 kg (2590 kJ). At 07:00 hours, 10 liters of milk at 37°C were added, thus adding 1297 kJ of heat load, and this milk was cooled solely with the latent energy stored in the milk chiller. It was observed that in 1 hour 40 minutes, the milk was chilled to 4°C, which is the storage temperature of milk. By 09:00 hours, only 3.2 kg of ice was present, as nearly 4.4 kg of ice was used for cooling and was lost due to heat infiltration from the surrounding. At 09:00 hours, the DC milk chiller was supplied with 33.2 V by the RPS simulating the solar PV output as predicted by the PVsyst software. The average IBT and milk were at 1.3°C and 3.4°C respectively. As seen in figure 5 the IBT and milk temperatures were maintained throughout the day. In the evening at 17:00 hours, the average IBT and milk temperatures were observed to be −2.27°C and −1.7°C, respectively with a total of 11.45 kg of ice. At 18:00 hours, the average IBT and milk temperatures were 0.340°C and 0.687°C respectively. At 18:00 hours 10 liters of milk (evening milk) were added at 37°C. This resulted in a thermal spike in the milk but was controlled immediately by the IBT.

On the third day at 06:45 hours, the average temperatures in the IBT and that of milk were observed to be as 0.91°C and 0.94°C, respectively. This milk was then discharged at that temperature itself. The same study was carried out for the third and fourth day. The milk was chilled within 1 hour 50 minutes as seen in figures 5c and d, respectively and preserved for further processing. The total quantities of ice formed at the end of the third and fourth day were 12.27 kg and 13.08 kg. Thus the milk obtained in two milking phases were preserved and transported in a single trip to the processing centers on the next day. The temperature of the IBT was maintained below 1°C for all the 4 days as shown in figure 6. In case of absence of sunlight in any of the days, the IBT will be able to autonomously maintain the milk temperature below 4°C.

5. Conclusion

In this work, a simulation study for a solar DC milk chiller of 20 liters capacity was carried out for all the five different climatic zones in India using the PVsyst software considering two modalities. The first modality was with an ice bank tank (IBT) and the second modality was with a battery backup.

The PVsyst simulation results for the 5 major Indian zones elucidated that for the first modality, the solar fraction was between 1 and 0.805, while for the second modality the solar fraction was between 1 and 0.679. The minimum number of PV panels required for the first modality was four PV panels (each 125W_p) with one battery (12 V, 100 Ah) to operate the solar milk chiller for all the climate zones except for the cold zone (Shillong). For the second modality, the number of PV panels required were 10 (each 125 W_p) with 10 batteries (12 V, 100 Ah) for all the climatic zones. The first modality with cold thermal energy storage was better owing to better solar fraction with minimum number of PV panels and batteries.

An experimental study was conducted with a custom built milk chiller with the IBT as the cold thermal energy storage for Chennai's conditions (first modality). The experimentations were carried out considering the operation of the system using an MPPT. This brought down the number of PV panels required to two (2 × 125 W_p). Considering the power from the two PV panels with MPPT, the experimental studies validated that with the IBT cold thermal energy, the milk could be chilled from 37°C to 4°C within 2 hours.

Acknowledgements

The authors would like to acknowledge the following: UGC-MANF (F1-17.1/2016-17/MANF-2015-17-TAM-51497) India for the financial support. DST-SERB (EMR/2016/00159) for the financial support in developing the experimental setup. DST-FIST for the financial support in developing the psychrometric facility.

Nomenclature

Ah	Ampere hour
BD35F	Battery Driven DC compressor (HFC-134a)
BD35K	Battery Driven DC compressor (HC-600a)
BIS	Bureau of Indian Standards
COP	Coefficient of Performance
C_p	Specific Heat (kJ kg^{-1} K^{-1})
DC	Direct Current
E Coil 1	Evaporator coil 1
E Coil 2	Evaporator coil 2
EFF	Efficiency (%)
FF	Fill Factor
HC	Hydrocarbon
HFC	Hydrofluorocarbon
h_{fg}	Enthalpy (kJ kg^{-1})
IBT	Ice Bank Tank
Im	Mean current (A)
Isc	Short circuit current (A)
I-V	Current-Voltage
M_1	Modality 1
M_2	Modality 2
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
PUF	Polyurethane Foam
PV	Photo-Voltaic
Q_{day1}	Refrigeration Capacity end of first day (kW)
$Q_{infiltration\ loses}$	Heat Infiltration Loses (kW)
$Q_{refrigeration\ 8hrs}$	Refrigeration Capacity after 8 hours of sunshine (kW)
RPS	Regulated Power Supply
Rs	Resistance Series
Rsh	Resistance Shunt
SS	Stainless Steel
V	Voltage
Vm	Mean voltage (V)
Voc	Open circuit voltage (V)
W	Watt
W_p	Watt Peak

References

[1] Askari I B and Ameri M 2009 Optimal sizing of photovoltaic—battery power systems in a remote region in Kerman, Iran. *Proc. IMechE., Part A: J. Power and Energy* 223(5): 563–570

[2] Odeh I, Yohanis Y G and Norton B 2010 Simulation procedure for the co-optimization of photovoltaic water pumping systems. *Proc. IMechE., Part A: J. Power and Energy* 224: 629–640

[3] National Building Code of India 2005. Bureau of Indian Standards, New Delhi

[4] Bansal N K and Minke G 1988 *Climatic zones and rural housing in India*. Kernforschungsanlage, Juelich, Germany

[5] De Blas M, Appelbaum J, Torres J L, García A, Prieto E and Illanes R 2003 A refrigeration facility for milk cooling powered by photovoltaic solar energy. *Prog. Photovoltaics Res.* 11(7): 467–479

[6] Torres-Toledo V, Meissner K, Coronas A and Müller J 2015 Performance characterisation of a small milk cooling system with ice storage for PV applications. *Int. J. Refrig.* 60: 81–91

[7] Axaopoulos P J and Theodoridis M P 2009 Design and experimental performance of a PV ice-maker without battery. *Sol. Energy* 83(8): 1360–1369

[8] Zhang P, Liu Q S and Wang R Z 2010 Performance and applicability of a dc refrigerator powered by the photovoltaics *J. Renewable and Sustainable Energy* 2: 013101

[9] Suresh P and Thomas J 2014 Performance analysis of standalone PV systems under non-uniform operating conditions using PVsyst. *Advanced Research in Electrical and Electronic Engineering* 1(4): 19–25

[10] Palmero-Marrero A, Matos J C and Oliveira A C 2015 Comparison of software prediction and measured performance of a grid-connected photovoltaic power plant. *J. Renewable and Sustainable Energy* 7: 063102
[11] Yilmaz S, Ozcalik H R and Dincer F 2015 Assessment and analysis on numerical and experimental performance of the photovoltaic systems for Germany and Turkey. *J. Renewable and Sustainable Energy* 7: 053114
[12] Dube A, Rizwan M and Jamil M 2018 New approach for maximizing generation and optimal utilization of available space for solar PV system. *J. Renewable and Sustainable Energy* 10: 063703
[13] Modi A, Chaudhuri A, Vijay B and Mathur J 2009 Performance analysis of a solar photovoltaic operated domestic refrigerator. *App. Energy* 86(12): 2583–2591
[14] Ekren O, Yilanci A, Cetin E and Ozturk H K 2011 Experimental performance evaluation of a PV-powered refrigeration system. *Elektron ir Elektrotechnika* 8(8): 7–10
[15] Deshmukh S D and Kalbande S R 2015 Performance evaluation of photovoltaic system designed for DC refrigerator. *Int. J. Sci. Res*. 4(2): 18–22
[16] Sidney S and Mohan Lal D 2016 Exergy analysis of a solar PV driven DC refrigerator for different ambient conditions In: *International Conference on Energy Efficient Technologies for Sustainability (ICEETS,) IEEE Xplore*. pp. 280–284
[17] Riza M, Minwon P, Mohammed D, Matsuura K, Akira T and Masakazu M 2003 A maximum power point tracking for photovoltai-SPE system using a maximum current controller. *Sol. Energy Mater. Sol. Cells* 75: 697–706
[18] Salas V, Olías E, Lázaro A and Barrado A 2005 Evaluation of a new maximum power point tracker (MPPT) applied to the photovoltaic standalone systems. *Sol. Energy Mater. Sol. Cells* 87: 807–815
[19] Rajani S V and Pandya V J 2015 Simulation and comparison of perturb and observe and incremental conductance MPPT algorithms for solar energy system connected to grid. *Sadhana* 40: 139–153
[20] Matsukawa H, Koshiishi K, Koizumi H, Kurokawa K, Hamada M and Bo L 2003 Dynamic evaluation of maximum power point tracking operation with PV array simulator. *Sol. Energy Mater. Sol. Cells* 75: 537–546
[21] Dixit T V, Yadav A and Gupta S 2015 Optimization of PV array inclination in India using ANN estimator: Method comparison study. *Sadhana* 40: 1457–1472
[22] Barnam J S and Kamala K S 2016 Simulated Study on Non isolated DC-DC Converters for MPP Tracking for Photovoltaic Power Systems. *J. Energy Eng*. 142(1): 04015001
[23] National Renewable Energy Laboratory website (2011) http://rredc.nrel.gov/solar/newdata/India/nearestcell.cgi (Accessed August 2015)
[24] Zhao H, Zhang H, Sharpe P, Hamanaka B, Yan W and Jeong W S 2013 Ice thermal storage systems for nuclear power plant supplemental cooling and peak power shifting. *J. Energy Eng.* 139(1): 41-47
[25] Danfoss 2007 DC Compressor (http://www.danfoss.com/)
[26] Elsayed A, Al-Dadah R K, Mahmoud S and Rezk A 2012 Experimental and theoretical investigation of small-scale cooling system equipped with helically coiled evaporator and condenser. *Proc. IMechE. Part C: J. Mechanical Engineering Science* 226(3): 724–737
[27] Xu Y, Ma X, Hassanien R H E, Luo X, Li G and Li M 2017 Performance analysis of static ice refrigeration air conditioning system driven by household distributed photovoltaic energy system. *Sol Energy* 158: 147–160
[28] Han Y, Li M, Wang Y, Li G, Ma X, Wang R and Wang L 2019 Impedance matching control strategy for a solar cooling system directly driven by distributed photovoltaics. *Energy* 168: 953–965
[29] Bureau of Indian Standards (BIS) BIS 1476-1 2000 Performance of Household Refrigerating Appliance, Refrigerators with or without Low Temperature Compartment, Part 1: *Energy Consumption and Performance*
[30] Moffat R J 1998 Describing the uncertainties in experimental results. *Experimental Thermal and Fluid Science* 1: 3–17