Research paper

Comparative thermal analyses of solar milk pasteurizers integrated with solar concentrator and evacuated tube collector

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ABSTRACT

Solar-based milk pasteurization enables decentralized maintenance of milk in remote areas of developing countries like Pakistan. Two innovative and efficient medium temperature range solar techniques; solar concentrator (SC) and evacuated tube collectors (ETC) were employed and compared based on theoretical and experimental analyses for an expedient and effective milk pasteurization. The detailed thermal analyses of both techniques were conducted to investigate the useful energy and losses during pasteurization. The available energy was estimated to be 8.11 and 5.63 kWh at the aperture areas of SC, ETC, respectively. Theoretically, it was also evident that SC, ETC require 4.68 and 4.22 kWh, respectively for a temperature difference of 35–40 °C during pasteurization for the designed milk batch size. However, under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC, ETC was recoded to be 3.56 kWh and 3.91 kWh respectively; this value lies from 3.78–4.32 kWh to pasteurize 100-liters of milk for a temperature difference of 35–40 °C. The predicted value of efficiency for SC, ETC was found to be 57.71 and 74.88% respectively. The efficiency values under field conditions for SC, ETC were found to be 54 and 71.41% respectively. Generally, both systems performed exceptionally however, ETC outperforms SC theoretically and practically attributing to significantly reduced optical and thermal losses. This study concluded that ETC is efficient, simpler in design, stable, compact and cost-effective which provides an excellent opportunity for decentralized milk pasteurization.

1. Introduction

Pasteurization is an energy intensive unit operation. The thermal treatment of raw milk is highly significant to get final product of good quality and in terms of energy demands of dairy production. Pasteurization is a thermal process in which temperatures lower than 100 °C affect the milk and 90%–99% of vegetative forms of microorganisms are eradicated. In developing countries where supply chain has not been developed effectively yet, milk producers have to sell raw milk at low price due to absence of post milking facilities at farm gates. Pakistan stands fourth in the list of milk producing countries in the world after United States of America (USA), China and India (Hussain et al., 2014) however, a significant amount of raw milk is spoiled due to lack of awareness and decentralized energy efficient processing technology in rural areas. Pakistan produces 42 billion liters of milk annually which covers 11% of total Gross Domestic Product (GDP) of the country

(Jassar Farms, 2009) however the quality control measures are still questionable (Ahmad, 2012).

The milk pasteurization is carried out using four ways depending upon the temperature and duration of pasteurization for low-temperature-holding (LTH), high-temperature, short-time (HTST) as well as ultra-heat-treating (UHT) along with batch pasteurization. LTH pasteurization refers to the heating of milk up-to 63 °C for 30 min within an insulated tank where steam enters into the tank from an outer source. Whereas, for high-temperature, short-time (HTST) pasteurization, hot water rises the milk temperature at 72 °C for about 15 s. The milk flows under a defined pressure between metallic plates and between pipelines but heat applied at the outer periphery. In ultra-heat-treating (UHT) pasteurization, the milk heated until 140 °C within 4 s by spraying milk into a chamber containing the high-temp steam under defined pressure. After the heating process, it cooled down suddenly in the vacuum chamber later packed in a pre-sterilized sealed food grade material container. Batch type pasteurization is the common and classic technique for milk pasteurization. For this process, milk is heated until 63 °C (145.4°F) in absence of air and light in a closed container for half an hour at the same temperature. The present study focuses on on-farm milk pasteurization

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Table 1

Comparative review of previous studies regarding solar based milk pasteurization using SC and ETC.

Authors	Heating source	Research development
Wayua et al. (2012)	Solar panels	Design and performance analysis of milk pasteurizer
Nielsen (2002)	Solar panels	Design of solar panels for milk pasteurization
Franco et al. (2008)	SC	Designed an economical tracker-less concentrator
Balghouthi and Qoaider (2017)	SC	Optical, losses: in terms of shadowing and blocking
Tiburcio et al. (2018)	SC	Improved solar pumped laser efficiency
Zhijian et al. (2013), Liu et al. (2017)	ETC	Economic analysis and design using machine learning algorithm
Mishra et al. (2015)	ETC	Thermal modeling of ETC
Daghigh and Shafieian (2016)	ETC	Theoretical and experimental analysis of ETC
Ersöz (2016)	ETC	Energy and exergy analysis of ETC
Khan et al. (2020)	SC	Design and performance analysis of milk chiller
Sur et al. (2020)	SC	Design and development of a solar-based system for milk pasteurization
Mutasher (2021)	SC	Designed parameters of the solar collector and the tilt angle of the collector plate

possibilities using LTH for small-scale farmers and entrepreneurs. The pasteurization using HTST and UHT is discouraged for local unskilled farmers due to complexities in as high-pressure vessels with dedicated mountings and other accessories which are highly expensive. This LTH is equally good and operates under the WHO standers for pasteurization of milk. Additionally, it provides the solution to couple the system with efficient solar thermal technologies (SC, ETC) to make a decentralized low-cost solar dairy farm for value addition and income generation at local-scale farm level in developing countries.

In order to make milk pasteurization an energy efficient process and to provide on-farm pasteurization facility, use of solar energy not only provides an extensive energy resource to address the decentralized and on-farm processing of milk for value addition but also can provide income generation opportunities in rural community of developing nations. Therefore, use of solar energy at milk production sites would be an effective way to maintain the quality of produced milk timely. Hitesh (2017) presented a comparative review of solar based pasteurization. The reported studies were conducted in various regions of the world using different technologies such as solar evacuated tube collector (ETC) and solar flat plat collector milk pasteurization as shown in Table 1.

Use of flat plate collector for pasteurization (Zahira et al., 2009; Atia, 2011; Wayua et al., 2012) discussed remarkable results dealing with small quantity of raw product (milk). In order to get rather a higher temperature, some of them designed a system employing a tank and evacuated tubes for low cost solar operated milk pasteurizer (Doborowsky et al., 2015). Passive solar water heaters are widely used usually for low-medium ranged thermal applications (Hitesh et al., 2018). The single glazed flat plate solar collector and water in glass evacuated tube solar water heater (WGET-SWH) are mostly used. The WGET-SWH is considered as the most prevalent technique to take advantage of solar energy (Zhijian et al., 2013). Being a promising technique, the evacuated tube thermal collector (ETC) is a more recent development compared to the conventional flat plate collector. Its high-performance, reliability and commercial application in cold climate makes it popular as compared to conventional technologies (Liu et al., 2017). In order to process more quantity of milk in reasonable time, limited use of solar concentrators have also been reported. Franco et al. (2008) designed a Fresnel type concentrator based pasteurizing system. The goat milk (10 L) was cooked using steam in an isolated container in about 1 h. Atia (2016) conducted an experimental study to equip a solar concentrator with dual axis sun tracking device for milk pasteurization. The thermal system was comprised a solar parabolic dish, energy conversion sub-system, and heat exchanger. The system was able to pasteurize about 260 ml of milk at 73 °C in average time 110 s. The average hourly productivity of solar pasteurized milk was about 7.5 L.

In order to assess the design and efficiency of a pasteurization process employing solar energy through any of above-mentioned technologies, a detailed thermal analysis is of much importance. Various researcher conducted thermal analyses for dairy processing industry but none of these was about a pasteurization process integrated with both evacuated tube collector and solar concentrator (Scheffler reflector) separately. Singh et al. (2019) performed a thermal analysis of a dairy food processing plant. The overall energy efficiency and efficiency pertaining to executable potential of energy in UHT Milk Processing Unit were reported to be 86.36% and 53.02%. Srinivasan (2018) exhaustively covered the evaporation and drying activities in a milk processing industry and determined that the exergy efficiencies of many thermodynamic units were reported below 20%. Yildirim and Genc (2017) executed a detailed energy and exergy analysis of dairy food powder production system. Moreover, pasteurizers having diverse designs can provide diverse results of thermal analysis using same product. Thus, the key objective of a thermal analysis for an improved or a newly developed process is to find out energy distributions and optimum operating conditions to save energy for effective milk pasteurization. Some studies particularly discussed optical losses in terms of shadowing and blocking of solar radiations (Balghouthi and Qoaider, 2017). Some authors improved thermal efficiency of solar pump while others addressed energy/exergy analyses and thermal modeling of ETC. Similarly, Sur et al. (2020) designed and developed a solar-based system for milk pasteurization due to the gap between milking and storage in remote areas of India. They developed the setup in Pune, Maharashtra state using stainless-steel (SS-304) for storage tank (1.6 × 1.6 × 0.6 mm) having a batch size of relatively higher than the previous pasteurization studies i.e. 150 L. They concluded that the parabolic solar collector (8 m^2) performed efficiently at 1:00 pm attaining a temperature of 75 °C which was maintained for 30 min for 5 L/h mass flow rate. The final storage was carried out between 15–20 °C in a controlled environment.

Mutasher (2021) designed and developed an economically affordable local solar milk pasteurizer in Suhar city at Sultanate of Oman. They mainly focused on designing parameters of the solar collector and the tilt angle of the collector plate. They observed that the solar collector area of 1.5 × 1 m^2 was needed to attain milk temperature between (63–70 °C) within half an hour. They further added that the tilled angle of 27 °C performs much better than 4 °C.

However, all the developed techniques were restricted to pasteurize a small milk batch size of 5 L using 1 m^2 collector area, such techniques could have been used on a small domestic scale. However, for a commercial scale where batch size matters, no viable solution using minimum energy and losses is still available. To achieve a commercial-scale pasteurization (100–200 L) of milk batch, the collector area needs to be increased which not only requires multiple resources (high initial cost, capital) but a precise

engineering design to use maximum available power with least losses at various exposed parts of collectors to sunlight.

Although, significant research work has already been established on the role of both technologies for pasteurization, however, most studies were restricted to local-scale pasteurization using small batch sizes, lacking comparative component-based thermal analyses and unable to address the commercial application to be implemented by the farming community. The small-scale batch sizes do not apply to the local farming communities; therefore, the present study enabled the design of a 200 L batch size using both SC and ETC. The storage of the pasteurized milk was a major problem for the small farmers, this issue was resolved by a previously designed chilling unit (Khan et al., 2020). The quality analysis of pasteurized milk using SC, ETC and payback period for these units has been discussed in (Khan et al., 2022). The development of such units has already addressed the quality and economic analysis in a viable manner for long-term milk storage. However, which of the two methods achieves pasteurization promisingly using optimum energy with minimal losses is still questionable. For the present study, the precise design with commercial-scale pasteurization (200 L) milk batch size was fabricated in terms of a 10 m² collectors' area and 24 tubes of ETC. Such a large area for the collector and a large number of ETC have never been designed so far to achieve efficient pasteurization with minimum losses at all parts. Keeping in view the aforementioned facts, the present study focusses on a widespread comparative thermal analysis of two high-temperature solar applications (SC and ETC) for milk pasteurization. Detailed thermal analyses have been conducted for each combination for comparative assessment of energy distribution and design for the effective use of solar energy in dairy sector. The entire system was divided into segments that were evaluated based on energy flow and results were compared. The study provides a detailed procedure to conduct a comparative thermal analysis of a pasteurization process integrated with two different heating sources.

2. Material and methods

This study aimed at the development and thermal analyses of solar assisted milk pasteurizers coupled with a SC compared with an ETC based system. Both the systems have been developed at Solar Park, University of Agriculture Faisalabad—Pakistan (31.44°N, 73.13°E). Complete methodology adopted for pasteurization and thermal analyses was shown in Fig. 1.

2.1. Solar milk pasteurization using solar concentrator (SC)

Decentralized applications particularly in humid regions enable the milk pasteurization system. The pasteurization process is generally designed conveniently to facilitate various milk batch volume during experimental setup. The process of pasteurization was carried out using Low Temperature Holding (LTH) method. During this process, the milk is placed in a pasteurizer tank and heated by passing steam or hot water in the outer insulated pipes wrapped around the pasteurizer tank. The milk is heated up to a temperature of 63 °C which is maintained essentially at this temperature at least for 30 min duration. The pasteurizer tank is equipped with an agitator for supplying uniform heat to every milk molecule. Finally, the milk temperature is immediately dropped to a temperature not greater than 4 °C for storage purpose. Various kinds of solar concentrators can be used for milk pasteurization but some of versatile paraboloidal solar connectors (e.g., Scheffler fixed focus concentrators) provide fixed focus on the ground surface without mounting the receiver as a part of the solar concentrator; thus, making various food processing applications possible as per approved standards operating procedures.

It also provides very simple and automatic daily and seasonal tracking which automatically reflects the solar radiation at the targeted focus. The solar milk pasteurization system comprises a Scheffler fixed focus concentrator, steam receiver and a milk pasteurizer. The complete solar system was fabricated in the workshop of Energy Systems Engineering, University of Agriculture, Faisalabad. Prior to construction, a jig was fabricated for 10 m² Scheffler reflector for precision and accuracy to make the desired part of solar concentrator. The solar system comprises a 10 m² surface area paraboloidal concentrator which was fixed in standing position facing towards south and its axis of rotation is inclined at an angle of 31.25° (latitude of the site) with the horizontal. The daily tracking system was used to rotate the reflector along the polar axis which triggers according to solar direction.

2.2. Solar milk pasteurization using Evacuated Tube Collector (ETC)

There are different options to couple various types of solar collectors but evacuated tube collector (ETC) was chosen because of its high efficiency, compactness and durability and it does not need any tracking system; ETC with built-in heat pipes were selected to pasteurize the milk. The glass vacuum tubes material was borosilicate glass and structure were concentric dual tube geometer. The outer and inner diameters of tubes were Ø58 mm ± 0.7 mm and Ø47 mm ± 0.7 mm respectively. The glass tube length was 1800 mm ± 5 mm and vacuum was P<5×10⁻³ Pa. The average heat loss coefficient from tubes was 0.8 W/m² °C. For the storage of hot water stainless steel tanks with 200-liter storage capacity were installed. The temperature from ETC can be achieved up to 100+ °C. Fig. 2 shows the schematic layout for the heating of water used for pasteurization using vacuum tube collector.

The ETC area can be calculated using following formula

$$A = \frac{m.C_p.\Delta T}{I_t.\tau.\alpha.t.\eta_{th}} \tag{1}$$

Where, 'A' is the area of receiver tube exposed to radiation (m²); 'm' is the mass of water (kg); 'C_p' is specific heat capacity of milk to be pasteurized (kJ kg⁻¹ K⁻¹); 'ΔT' is the change in temperature of the milk in pasteurizer (K), I_t is the intensity of total solar radiation (W/m⁻²); 'τ' is transmission coefficient of ETC outer glass tubes, 'α' is absorption coefficient of ETC inner absorber tubes and 't' is the time in seconds, 'η_{th}' is the thermal efficiency of the complete solar milk pasteurization system. This includes all the thermal losses from ETC, storage tank, milk pasteurizer and all connected pipe lines from where heat energy is transferred. As this study is focused on the calculation of heat energy required to increase the temperature milk ($m = 100$ kg, Specific heat: 3.89 kJ kg⁻¹ K⁻¹) for a temperature rise of 40 °C in one hour and a half time (t=5400 s) for a tropical region like Faisalabad (N 31° 25' 46.8048", E 73° 4' 14.3112") lying in solar belt having average GHI as 800 kW m⁻² ($I_t = 0.8$ kW m⁻²). Evacuated tube collectors have high values of transmission and absorption coefficient ($\tau = 0.95$; $\alpha = 0.95$). The thermal efficiency was calculated to be 0.85 for the system.

Substituting these values in Eq. (1), the area required is calculated to be 4.695 m² respectively. Aperture area of one tube is calculated by multiplying diameter (0.058 m) of the absorber tube with its length (1.8 m) and calculated to be 0.1044 m² and the number of tubes is calculated by dividing total absorber area by the absorber area of one tube and calculated to be 44.97 and 45 identical tubes were used for the milk pasteurization to process the milk under the aforementioned resources of the system.

Hot water from the storage tank is circuited to the outer side of the pasteurizer with the help of a square pipe in the spiral
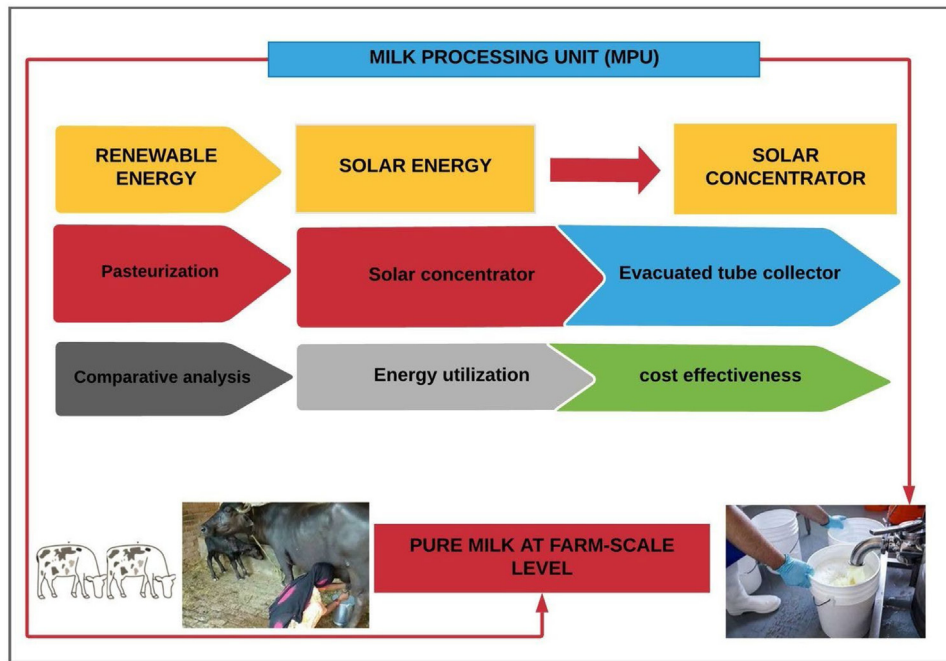
Fig. 1. Methodology flow chart for the comparative analysis of solar concentrator (SC) and evacuated tube collector (ETC).
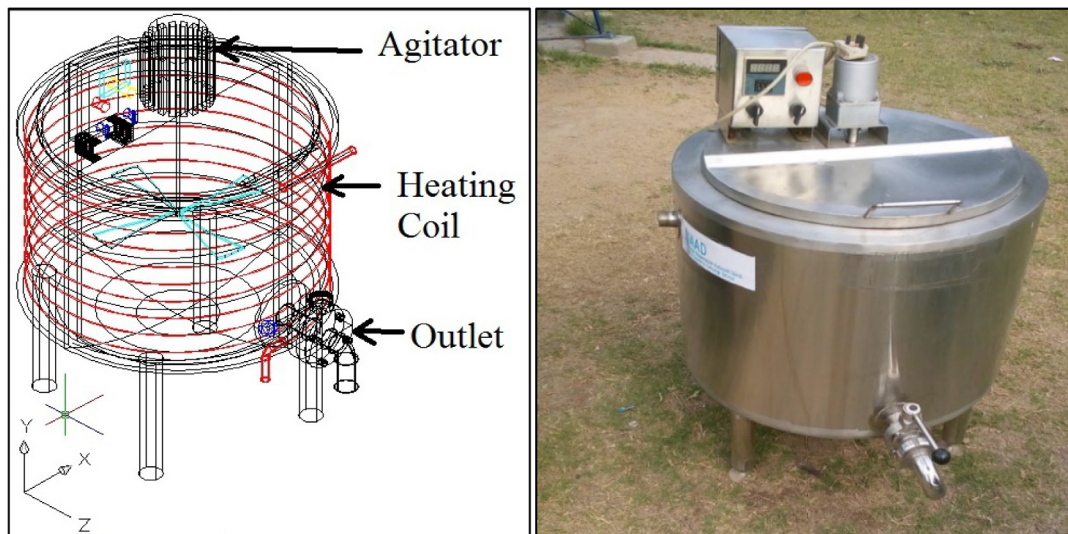

Fig. 2. CAD and developed milk pasteurizer tank.

form for effective heat transfer to the milk filled inside the tank. However, the tank material is of food grade SS-304 as per standards of milk pasteurization. The outer shell of the pasteurizer is insulated with polyurethane. A mechanical stirrer having 60 rpm is installed to distribute heat equally, required for a good pasteurization. It also helps to drop down the milk temperature rapidly to proceed for the chilling process. A temperature above 100 °C can be easily achieved within Global Horizontal Irradiance (GHI) of 600–800 W m^{-2}.

2.3. Combined pasteurizer tanks

A 100-liter combined cylindrical milk pasteurizer tank for both heating sources was fabricated of stainless-steel material (SS 304; Food Grade) having diameter and length as 558.8 mm

and 432 mm, respectively as shown in Fig. 2. An electric motor with stirrer was installed at the top of pasteurizer unit to stirrer milk continuously operated at variable speed. A helix coil made of square pipe (25.4 mm × 25.4 mm) was installed at outside of the inner tank for thermal heat transfer. The hot water which was heated up to 90 to 100 °C through heat source is passed through the helix stainless steel coil to raise the temperature of milk to make it bacteria free during pasteurization process. The hot water was entered inside the helix coil from the top side of inlet pipe and drained from the lower end of the helix pipe for counter current heat transfer application. A centrifugal electric pump was used with three different operating speeds to flow the water inside helix pipe for maintaining optimum milk pasteurization process. Hot water energy was added to the milk to pasteurize it. Second milk pasteurizer tank was also developed having the

Table 2
Metadata for the prototype of solar milk pasteurizer.

| Parameters	Receiver top	Receiver lateral	Receiver bottom	Pasteurizer bottom	Pasteurizer lateral
Vessel section	Top	Lateral	Bottom	Bottom	Lateral
Geometric shape	Circular	Cylindrical	Circular	Circular	Cylindrical
Length (m)	–	0.10	–	–	0.432
Diameter (m)	0.40	0.40	0.40	0.5588	0.5588
Thickness (m)	0.01	0.01	0.01	0.002	0.002
λ-tank (W/m °C)	15	15	15	15	15
Insulation	–	0.10	0.10	0.050	0.050
λ-insl (W/m °C)	–	0.40	0.40	0.40	0.40
λ-gi (W/m °C)	–	0.40	0.40	0.40	0.40
ε-material	0.94	0.25	0.25	0.25	0.25
ε-gi	–	0.35	0.35	0.35	0.35
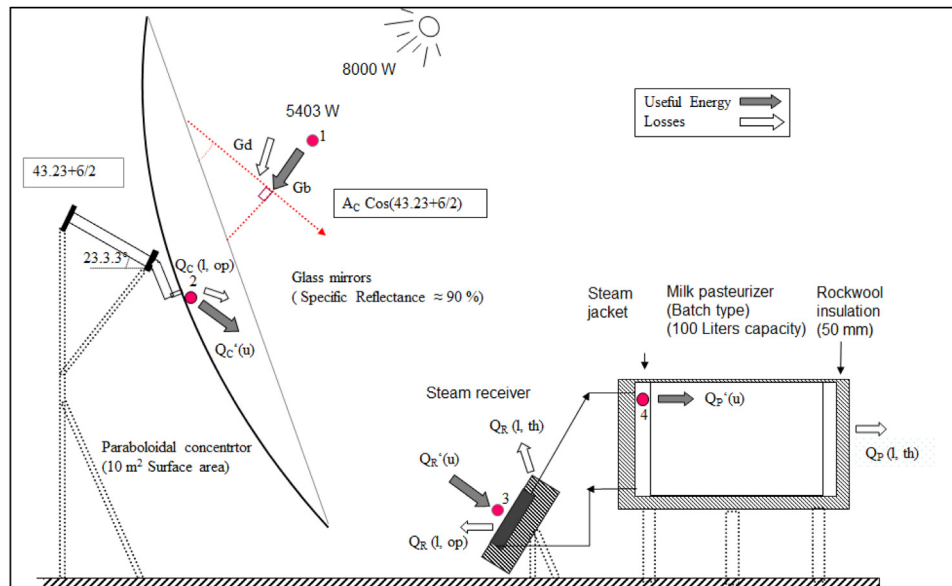
Fig. 3. Explanation of available energy and losses in a solar milk pasteurization coupled with SC.

same dimensions but there is no helix coil but instead only jacket was utilized for steam utilization from steam receiver produced with the help of a SC. Both the pasteurizers are insulated with 50 mm glass wool insulation to minimize thermal losses.

2.3.1. Parameters of the existing prototype of the milk pasteurizer

The milk pasteurizer is composed of four major sections attributed to the geometry as shown in Table 2.

2.4. Available energy and losses in a solar milk pasteurization coupled with SC

Telescopic clamps were used on either ends of the SC (top and bottom) to account for seasonal tracking which is done manually at half the solar declination angle which automatically induces the desired shape required for summer and winter solstice positions. Glass mirrors (specific reflectance > 0.90) were used on the reflector (consisted of a center bar and seven crossbars as well as of aluminum profiles) to form the required lateral part of a paraboloid. The main advantage of Scheffler fixed focus concentrator is that it provides fixed focus near to ground with the changing position of sun with respect to earth throughout the day and hence its utilization from small cooking to industrial configurations is possible; nevertheless, there is great compromise on the reduction of available aperture area to reflect the radiation at targeted focus on fixed place on ground. Solar radiation after reflecting from the SC are absorbed by the aluminum steam receiver. Solar mat was applied on top side of the steam receiver

to behave like a black body to absorb solar radiation reflected from SC. Steam is produced as a result of concentrated radiation at receiver and this steam is used to pasteurize the milk.

With the help of steam jacket surrounded around the milk pasteurizer, the condensate thus produced is again recycled to produce water again thus utilizing the latent heat of vaporization of water for quick rise in temperature of milk. The pasteurization unit is cylindrical in shape (diameter = 0.516 m × 456 m) having total capacity of 100 L. The schematic of solar milk pasteurization using solar concentrator is given in Fig. 3.

After the construction and development process, complete energy balance of the solar milk pasteurization system was carried out by considering the useful energy available and losses at different sections of the system. This study can be used to develop any size of solar milk pasteurization system. The black and white arrows in Fig. 3 represent useful energy available and losses at four main points (1–4) of the system.

2.4.1. Available solar power at paraboloidal concentrator

Though Scheffler concentrators provide fixed focus at ground level, yet there is a big compromise on aperture area as a certain angle has to be maintained in order to reflect the beam radiation at targeted focus. The Scheffler design maintains this angle at $(43.23 \pm \alpha/2)$ with the angle of incident beam radiation and thus aperture area becomes relatively smaller. So, actual input energy is calculated by multiplying this fraction of area with intensity of beam radiation. The pyranometer is mounted on the reflector in the line of beam radiation by mounting a black pipe so that it can
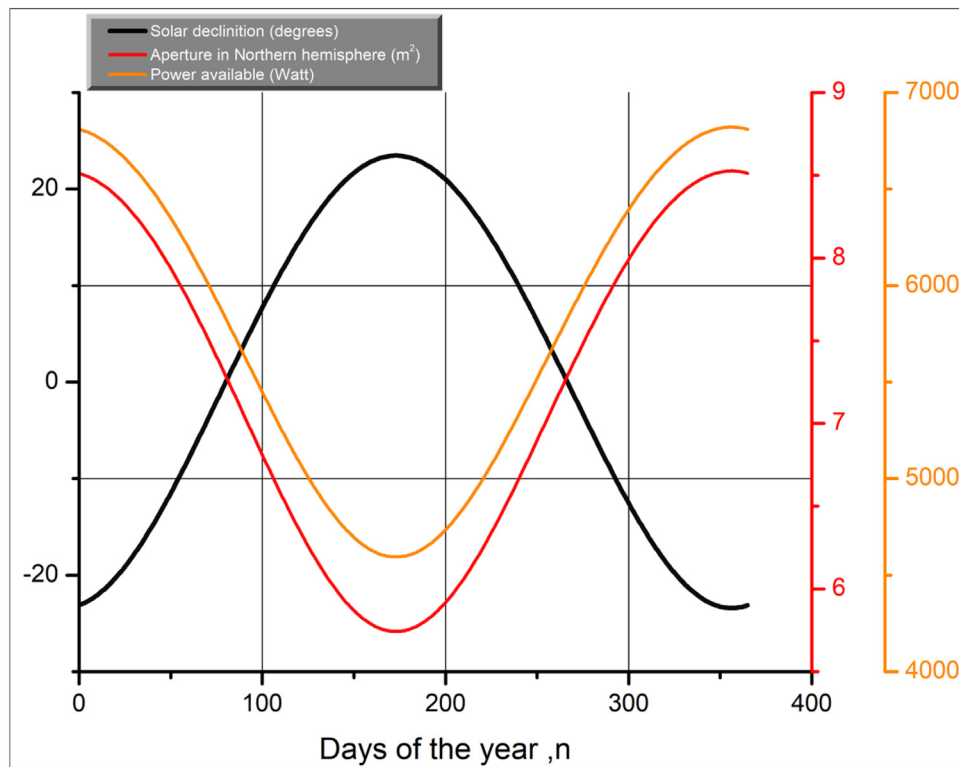
Fig. 4. Solar declination, aperture area (m^2) and solar power (W) available from 10 m^2 fixed focus concentrator at site.

only record beam radiation. All the equations used for the SC and were developed by Munir et al. (2010). Total energy available on SC (Q_p) is given by the following relation

$$Q_c' = G_b A_s \cos\left(43.23 + \frac{\alpha}{2}\right) \quad (2)$$

and

$$A_a = A_s \cos\left(43.23 \pm \frac{\alpha}{2}\right) \quad (3)$$

Whereas, A_s is the total surface area of Scheffler, A_a is the aperture area of paraboloidal concentrator during any day of the year and α is the solar declination;

Solar declination is calculated by using the following equation

$$
\begin{aligned}
\alpha = (180/\pi) & [0.006918 - 0.399912 \cos(n-1)2\pi/365 \\
& + 0.070257 \sin(n-1)] 2\pi/365 \\
& -0.006758 \cos 2(n-1) 2\pi/365 \\
& +0.000907 \sin 2(n-1) 2\pi/365 \\
& -0.002679 \cos 3(n-1) 2\pi/365 \\
& 0.00148 \sin 3(n-1) 2\pi/365
\end{aligned}
\quad (4)
$$

Whereas n is the number of days of the year and solar declination can be find out for any specific day of the whole year. The variation of solar declination, aperture area and power for a 10 m^2 Scheffler concentrator is shown in Fig. 4.

For the standing reflectors, the maximum and minimum aperture area is calculated to be 8.52 and 5.74 m^2 during winter and summer solstice, respectively. However, standing reflectors exhibit similar aperture area (7.27 m^2) at equinox as shown in Fig. 4. The energy absorption of standing Scheffler reflectors for the same intensity of beam radiation is higher in winter as compared to the summer. The provision of fixed focus near the ground level as well as more aperture area in winter as compared to summer for the generation of constant power output throughout the year with proportionally less and more solar

insolation available makes this versatile solar concentrator design even more attractive particularly in tropical regions of the northern hemisphere.

It is also evident from Fig. 3 that 10 m^2 solar concentrator can take 8 kW input power at 800 W m^{-2} beam radiation if all the surface area is fully utilized. The power available on reflector varies from 6819 W in winter solstice to 4593 W in summer solstice while 5794 W at equinox due to change in aperture area as a result of changing solar declination.

2.4.2. Useful energy available at SC

The energy distribution at paraboloidal concentrator is shown on Point No. 2 (Fig. 3). The useful rate of radiant energy available ($Q_{(c,u)}'$) on the face of Scheffler concentrator can be calculated by the following formula.

$$Q_{(c,u)}' = A_a G_b - Q_{c(l,opt)}' \quad (5)$$

Where, $Q_{(c,u)}'$ is the optical losses from SC/reflector. Optical losses from SC include losses due to poor reflectance either due to material or improper surface cleanability, lack of precision of concentrator profiles to approximate the required part of paraboloid as well as inadequacy in daily and seasonal tracking. Glass mirrors with reflectivity greater than 90% were used as reflecting material. Various experiments were conducted to check the accuracy of the reflected radiation on targeted focus and it was invested that 10%–15% radiation are not available on the stationary targeted receive area and this loss is also taken into account as optical loss. It was also investigated that more accurate focus was available at midday as compared to morning or evening time. So, the useful energy component is taken as 85% and showing the fraction of energy available from the reflected radiation from the Scheffler concentrator 11 (Munir et al., 2010). The total useful energy available from the SC is calculated by multiplying specific reflectance with the fraction of solar radiation available on targeted focus and is found to be 0.68.

2.4.3. Useful energy available and losses at steam receiver

Point No. 3 (Fig. 3) indicates the useful energy available at receiver and losses from the receiver. Major losses from the steam receiver include optical and thermal losses as given in Equation.

$$Q'_{r(u)} = Q'_{c(u)} - Q'_{r(l,opt)} - Q'_{r(l,th)} \quad (6)$$

Where $Q'_{r(l,opt)}$ is the optical losses from the receiver and $Q'_{r(l,th)}$ is the thermal losses from the receiver.

In case of receiver, the optical losses are due to lack of absorbance of reflected radiation from the SC on the top side of the receiver. The receiver was painted black with high absorbent solar mat. The thermal losses include losses because of conduction, convection as well as for radiation from the receiver. Whereas the top side of the receiver is exposed to reflected solar radiation from the SC.

2.4.4. Useful energy available and losses at milk pasteurizer

The useful rate of heat energy available at the pasteurizer tank for milk pasteurization is given as:

$$Q'_{p(u)} = Q'_{r(u)} - Q'_{p(l,th)} \quad (7)$$

Where $Q'_{p(l,th)}$ the thermal losses from the receiver and these losses is due to conduction, convection and radiation losses. This area is the cylindrical area of the pasteurizer which is insulated with 50 mm rock wool insulation as shown in Fig. 2.

A complete algorithm was prepared and output of thermal losses is calculated by putting input data (boundary temperature conditions, material characteristics, geometry and characteristics) in the algorithm made for milk pasteurizer. The milk pasteurizer ($\varnothing$ 432 × 559 mm) was insulated from all bottom and lateral sides with 50 mm polyurethane insulation material (thermal conductivity: 0.026 W m^{-1} k^{-1}).

Wet steam from steam receiver was used to quickly pasteurize milk at 65 °C by utilizing the latent heat of vaporization (2257 kJ kg^{-1} K^{-1}) of water.

2.4.5. Thermal losses calculation of the steam receiver and milk pasteurizer

For all kinds of calculations, ambient temperature, space temperature was assumed as 25 and 15 respectively. The steady state heat transfer (φ) between the cylindrical layer which are exposed for convection on either side to fluids are as follows (Cengel, 2006):

$$\varphi = \frac{T_{in} - T_{amb}}{R_{cond} + R_{conv}} \quad (8)$$

Whereas, T_{in} represents the temperature at the inner side of the milk pasteurizer, T_{amb} is the ambient temperature, R_{cond} represents the conduction resistance, R_{conv} denotes convection resistance

Whereas the Thermal conduction resistance from the cylindrical part of pasteurizer can be calculated from following relation (Cengel, 2006):

$$R_{cond} = \frac{1}{2\pi \lambda L} \ln \left(\frac{r_{ext}}{r_{int}} \right) \quad (9)$$

whereas λ shows the thermal conductivity of the material used, L stands for its lateral length of the cylindrical pasteurizer/receiver, r_{ext} is external radius of cylindrical pasteurizer, r_{int} represents internal radius of the cylindrical pasteurizer or receiver.

The conduction resistance of the circular part of pasteurizer or receiver can be calculated from following relation (Cengel, 2006):

$$R_{cond} = \frac{t}{\lambda A} \quad (10)$$

whereas 't 'is the thickness of wall of circular section of pasteurizer or receiver, A represents cross-sectional area of the circular section of pasteurizer or steam receiver bottom

With this insulation, the resistance conductive for more layers and plane wall along with cylindrical segments can be calculated by adding the conductive resistance of all layers and generalized as follows:

$$R_{cond} = \sum R^i_{cond} \quad (11)$$

whereas "i" shows the layer of stainless steel, insulation material also cover plate with different thermal conductivities as well as thicknesses.

Convection resistance can be calculated from this relation.

$$R_{conv} = \frac{1}{hS} \quad (12)$$

Heat losses from radiation can be calculated from following relation.

$$Radiation\ losses = \varepsilon\ \delta\ S\ \left(T_{ext}^4 - T_{space}^4 \right) \quad (13)$$

Whereas ε is the emissivity, δ shows Stephen Boltzmann constant, T_{space} denotes space temperature (K), T_{ext} represents external area temperature (K) and can be calculated from the this formula.

$$T_{ext} = T_{amb} + \varphi\ R_{conv} \quad (14)$$

By substituting the value of T_{ext} in Eq. (13), the total heat losses by radiations are calculated. By adding all the losses, the total losses of the system can be calculated

2.5. Available energy and losses using ETC

The input energy for evacuated tube collector is given by the following Equation

$$G = \frac{I_t A_c}{1000} \quad (15)$$

Where G is the rate of incident solar energy at collector (kW), I_t represents total solar irradiance (W/m^2), A_c represents the surface area of evacuated tube collector (m^2) and is calculated by multiplying effective tube length (exposed to solar radiation) by its diameter (aperture) and number of tubes.

The thermal efficiency of solar evacuated tube collector depends on solar input energy, losses and heat transferred to the working fluid and it can be taken in the rage of 70%–80%. Main objective of the study is the thermal analysis of solar milk pasteurization and heat is transferred to glycol and water solution from ETC header and then this hot water is used to heat the outer shell of the cylindrical pasteurizer from the hot water storage tank as shown in Fig. 5. So, the amount of heat energy (Q'_F) transferred to working fluid (water + glycol solution) and then to milk can be estimated by multiplying the mass flow rate with the specific heat of the fluid and change in temperature. The additional benefit of this system is the heat energy storage in hot water tank which can be used for effective milk pasteurization even during low solar radiations hours. The complete schematic of milk pasteurization working on ETC is presented in Fig. 5.

The amount of energy required to raise the temperature of 150-liter water in the storage tank from ambient temperature (25 °C) to almost 90 °C can be calculated using the following equation

$$Q'_W{}^{'} = mC_p\ (\Delta T) \quad (16)$$

Where Q' is the rate of heat energy need to be transferred to water, m is mass of water (kg or L), C_p is specific heat capacity of water (kJ/kg. C)
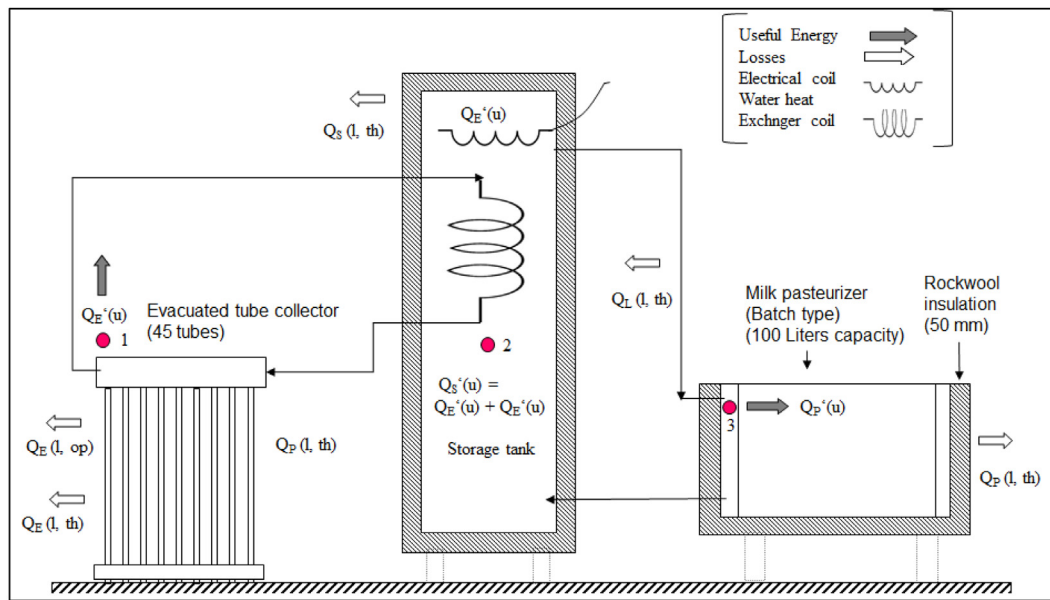
Fig. 5. Schematic layout of milk pasteurization working on ETC and thermal storage.

Similarly, the amount of energy required to raise the temperature of 100-liter milk (Q'_M) up to temperature difference of 40 °C can be estimated in similar fashion.

The total useful power received from ETC '$Q_{E'(u)}$' and useful power available for milk pasteurization tank '$Q_{P'(u)}$' are calculated to be 5460 W and 4070 W respectively. Total thermal losses '$Q_{L(l,th)}$' from 18.8 m length piping (∅25.4 mm) and fittings connecting all these three components (pasteurizer, hot water tank and ETC) is estimated to be 638 W.

Thermal losses from hot water tank '$Q_{S(l,th)}$' and the pasteurizer '$Q_{P(l,th)}$' were calculated to be 116 and 90 W respectively.

3. Results and discussion

3.1. Field experiments of milk pasteurization using SC

Many experiments were conducted for milk pasteurization using SC and process curve of one of the experiments is presented in Fig. 6. It is evident that under the constant range of beam radiation, pasteurization process is quite smooth with gradual increase in temperature and the process completed in 80 min to reach a temperature of 63 °C. The average value of beam radiation was recorded to be 734 W m^{-2} during pasteurization process.

The temperature was maintained for a period of 30 min more to meet WHO standards and steam flow rate was maintained accordingly. The average power consumed was recorded to be 2.67 kW to reach this pasteurization temperature of 63 °C and experiment was started from 30 °C as shown in Fig. 6. The total energy required for the pasteurization of 100-liter batch of milk was calculated to be 3.566 kWh. The average input solar power and total solar energy available on 6.75 m^2 aperture area (for the month of August) of SC was recorded to be 4.95 kW and 6.60 kWh respectively during 80 min of pasteurization time with 54% efficiency. The results show that solar milk pasteurization can be successfully done using SC.

3.2. Field experiments of milk pasteurization using ETC

Fig. 7 shows the solar irradiance, temperature of glycol–water mixture, water temperature and temperature of milk. It is evident from the Figure that under the constant range of solar radiation,

the glycol solution temperature increased rapidly and reaches its maximum value of 100 °C and maintains almost at this temperature throughout the experiment. It is also evident from Fig. 7 that hot water temperature in the storage tank increases slowly and reaches up to 80 °C. The average GHI during pasteurization process was recorded to be 780 W m^{-2} and the average input power on aperture area (4.695 m^2) of ETC was recorded to be 3.66 kW and total input energy was found to be 5.49 kWh to reach the pasteurization temperature in 90 min. Power utilized during this test was calculated to be 2.615 kW with total used energy of 3.91 kWh in 1.5 h. The efficiency of the complete system was found to be 71.41% under the existing set up of the milk pasteurization system working on ETC. Similar results were obtained from other experiments.

3.3. Power distribution in milk pasteurization using SC

Energy balance of the milk pasteurizer using available parameters and specification of the milk pasteurizer different losses were calculated as shown in Fig. 8. In order to perform a detail thermal analysis, the entire system has been divided into different segments (solar concentrator, receiver, piping and fitting and the pasteurizer) to describe the power losses occurred in working fluid during pasteurization process.

The rate of useful thermal energy available and losses from the current solar milk pasteurization prototype using SC have already been indicated by black and white arrows in Fig. 3. Due to changing aperture area of the Scheffler reflector, input data set was taken for August 31 (one sample day of August for comparison when most field experiments were conducted) with average beam radiation 800 W m^{-2} under similar conditions in order to evaluate and compare two solar based milk pasteurization systems under identical premergers. Total power available using full surface area (8 m^2) of SC is 8000 W while available power (G_b) is equal to the product of average beam radiation (800 W m^{-2}) and aperture area (6.75 m^2) available under prevailing condition to have a fixed focus on ground level and this value is found to be 5403 W. Out of this available power, the optical losses ($Q'_{c(l,opt)}$) are found to be 1081 W (20%) and available power ($Q'_{c(U)}$) in the radiation after reflecting from SC is calculated to be 4322 W and this power is available at steam receiver. The optical losses from steam receiver (($Q'_{R(l,opt)}$) are found to be 432 W and thermal
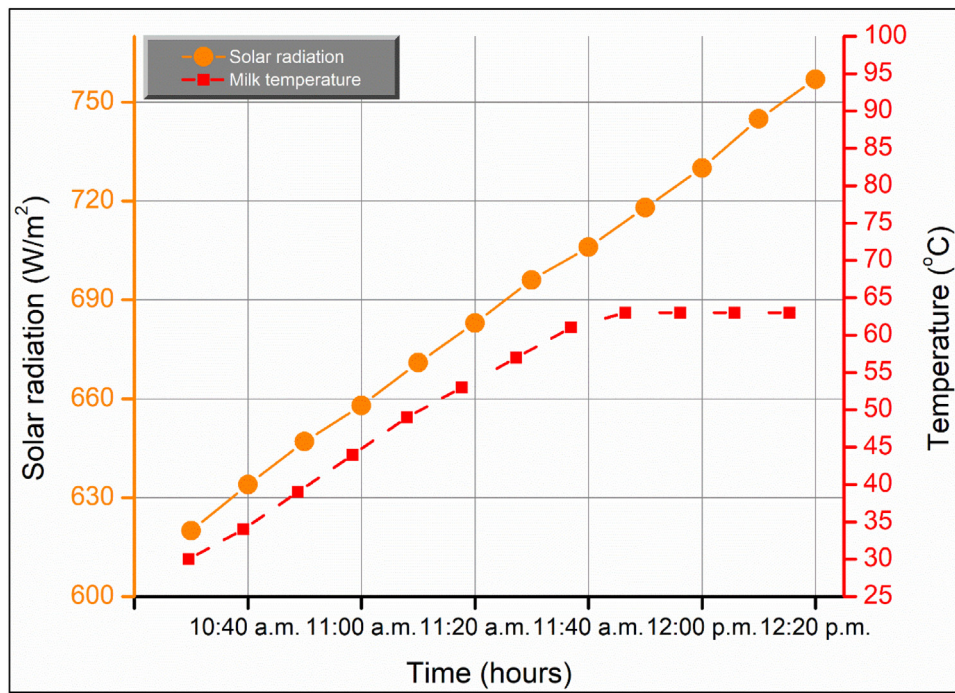
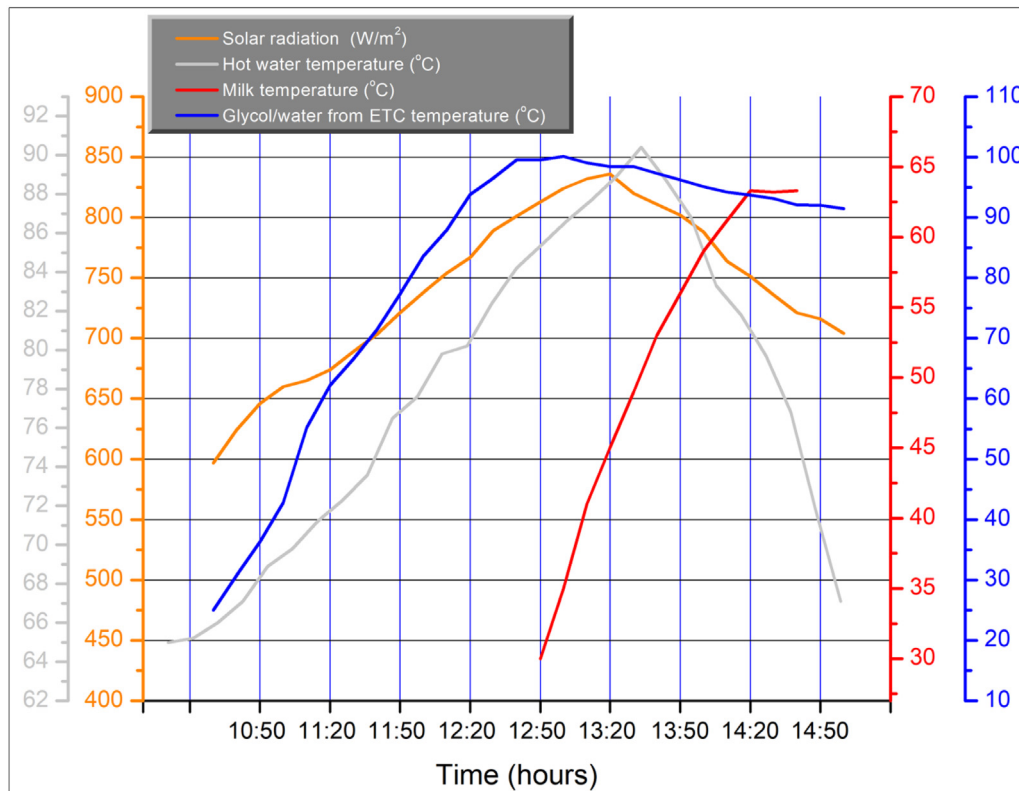**Fig. 6.** Temperature variation during milk pasteurization under varying solar irradiance using SC.

Fig. 7. Change in hot water, glycol solution and milk temperature and solar irradiance during milk pasteurization using ETC.

losses $(Q'_{c(l,th)})$ are 521 W. The useful power from receiver was calculated to be 3369 W by using Eq. (6). The line losses from piping and fittings are found to be 303 W and available energy to pasteurizer was found to be 3066 W. The thermal losses at pasteurizer section $(Q'_{P(l,th)})$ are found to be 90 W and useful power $(Q'_{c(U)})$ available to milk is calculate to be 2976 W. The

theoretical efficiency was calculated as 55% with the existing system installed for milk pasteurization.

3.4. Power distribution for milk pasteurization using ETC

Complete power balance of the milk pasteurizer using ETC has been presented Fig. 5. The average solar radiant power received
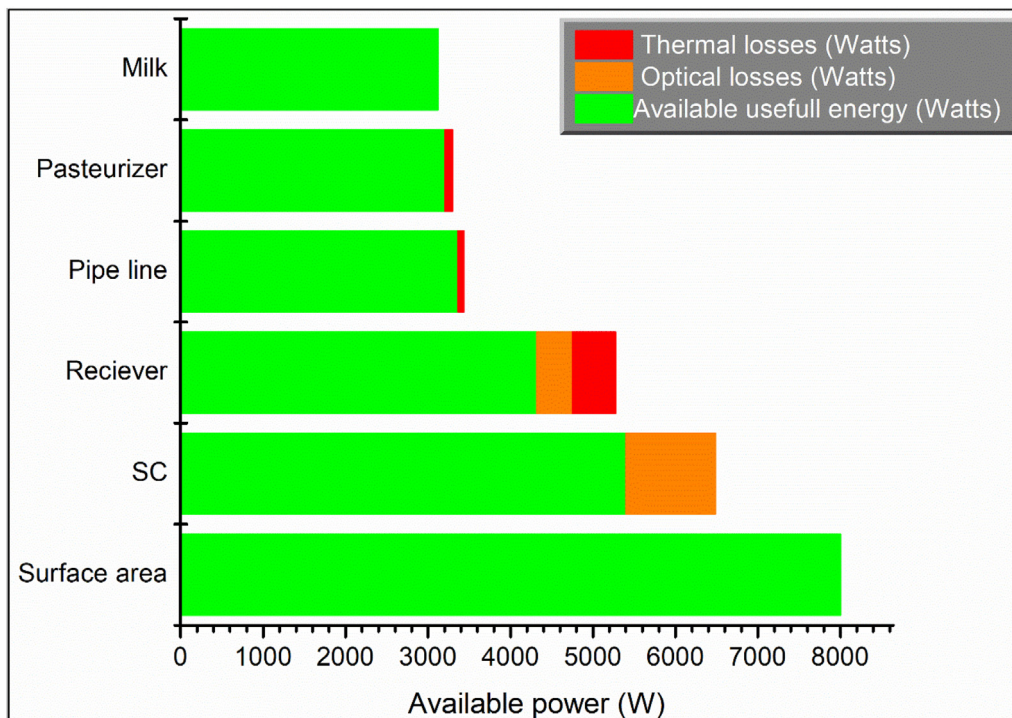
Fig. 8. Expected energy distribution per unit time from solar milk pasteurizer (for the standing reflectors in the northern hemisphere on Aug, 31 for 800 W m^{-2}).

at ETC ($Q_{E'(u)}$) was found to be 3.756 kW and useful energy available for milk pasteurization tank 'QP'(u)' are calculated to be 5.63 kWh. Optical losses from ETC ($Q'_{E(l,opt)}$) were found to be 376 W and these were in the form of transmittance and absorbance losses. Thermal losses from hot water tank $Q'_{T(l,th)}$, pipe line ($Q'_{L(l,th)}$) and pasteurizers ($Q'_{c(l,th)}$) were found to be 115, 359 and 90 respectively and showing that about 15% losses are being taking place as thermal losses. The theoretical efficiency of the system was found to be about 75%.

3.5. Comparative analysis of SC and ETC

This research is focused on thermal analysis and comparison of heating sources used for effective milk pasteurization. Fig. 9 shows energy distribution of solar pasteurization system couples with SC and ETC both with respect to their gross and aperture areas.

It is evident from Fig. 9 that the input energy available on gross areas of SC and ETC were calculated to be 12 kWh and 7.02 kWh respectively while energy values available on aperture area for SC and ETC were calculated to be 8.12 and 5.63 kWh respectively during the pasteurization process. Energy required to pasteurize 100 kg of milk were calculated to be 4.68 and 4.22 kWh respectively for a temperature difference of 35–40 °C. Under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC and ETC was recoded to be 3.56 kWh and 3.91 kWh respectively; this value lies from 3.78–4.32 kWh to pasteurize 100 kg of milk for a temperature difference of 35–40 °C. It is also worth mentioning here that the total energy available (7.02 kWh) from 7.75 m^2 aperture area of SC for a sunny day of August 31 having average bean radiation as 800 W m^{-2}. However, this energy value goes on changing in case of SC as the aperture area ranges from 6.819 m^2 (Winter solstice) to 4.593 m^2 (summer solstice). There is a big comprise on reduction of aperture area due to seasonal variation of sun position (solar declination) in summer that resulted in reduction in power in spite of larger surface area of the SC. On the other

hand, aperture area remains the same to ensure uniform power through the year under the same range of GHI. Moreover, more power can be harvested using ETC with comparatively less area loss and space required to pasteurize milk with solar energy. For the milk pasteurization, ETC also provided excellent opportunity to process the milk even during slight fluctuation in sunny conditions and the system utilizes the stored energy which always remains available in the storage tank for the consistency of the process. Moreover, ETC can perform efficiently without using any tracking system, complex design consideration and more area needed as required in case of SC. ETC provides more flexibility for increasing or decreasing heat sources by simply addition or removal glass tubes according to quantity of milk to be processed.

The complete breakup of optical and thermal losses for SC and ETC are given in Figs. 10 and 11. The rate of heat energy losses at pasteurizer, receiver, pipes and optical losses are shown for both technologies. The results have shown that optical losses of the reflector and receiver for SC were found to be 1083 W and 953 W respectively with total losses of 2033 W. This huge difference in optical losses in SC is due to lack of specific reflectance and absorbance of SC and receiver as well as in inadequacy of precision of manufacturing and tracking inefficiency. On the other hand, optical losses of ETC were found to be 376 W only and this minor loss is due to the transmittance of the cover glass and absorbance of the absorber tube.

In case of thermal losses, both the system exhibited the same losses of 90 W from pasteurizer contributing only 2% of the total and this is actually due to good insulation of the milk pasteurizers from bottom as well as from the lateral side. The thermal losses from hot water storage tank is calculated to be 116 W. However, pipe line losses were calculated to be 161 W (3%) and 359 W (10%) for SC and ETC respectively. The available rate of useful energy figures was found to be 3118 and 2816 W, respectively. Fig. 12 illustrates the efficiency comparison of predicted and actual values of both the heating sources (SC and ETC).

One to one efficiency comparison is presented in Fig. 12. The predicted value of efficiency for SC and ETC were found to be
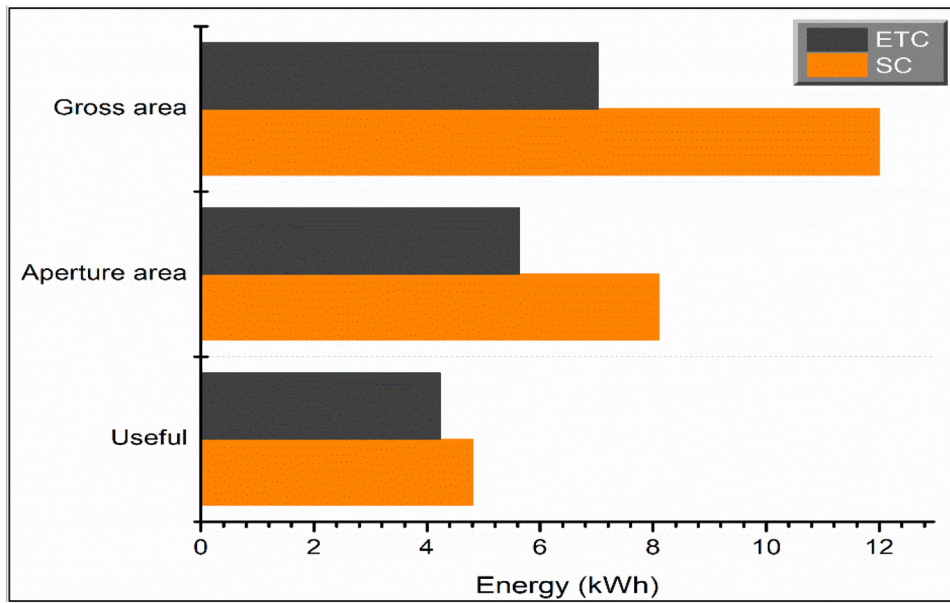
Fig. 9. Input energy available on gross area of SC and ETC during pasteurization.
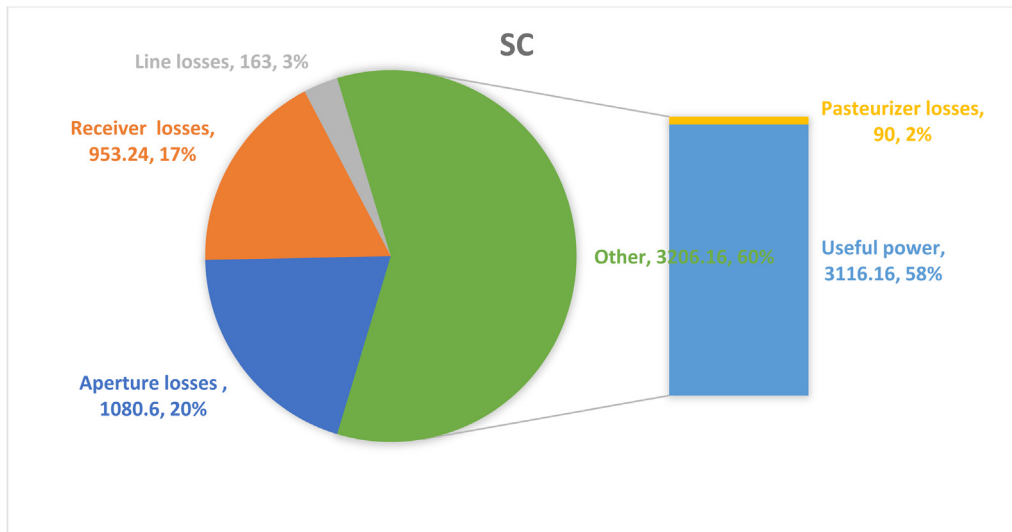

Fig. 10. Power losses during pasteurization for SC.

57.71 and 74.88% respectively. The efficiency values under field conditions for SC and ETC were found to be 54 and 71.41% respectively. In both cases (Theoretical and practical), efficiency of ETC is significantly higher than that of SC. This is due to the fact that the optical losses and thermal losses in ETC are very less as compare to that of SC. This is main limitation of using a SC due to complicated and inclined design as well as lack of accuracy while focusing the reflected rays on receiver during tracking under practical condition. It is also evident from Fig. 11 that the practical values for both the cases are almost same but a slight on lower side as compared to theoretical ones. This is due to the reason that some unaccountable losses (due to change in wind velocity, ambient conditions, and the values of physical and thermal parameters used in calculation do not match the actual conditions.

Solar based milk pasteurizer enables decentralized preservation of milk quality at zero or minimum operating cost, particularly in remote areas of Pakistan. With the introduction of innovative and efficient medium temperature solar technologies,

two approaches can be conveniently used to accomplish pasteurization i.e., SC and ETC. The present study focused on a widespread comparative thermal analysis of above-mentioned techniques for a solar-driven milk pasteurization unit. The detailed thermal analyses of both the solar based systems were conducted to investigate the useful energy and losses during the process of milk pasteurization. The available energy values were found to be 8.11 and 5.63 kWh at the aperture areas of SC and ETC, respectively. Energy required to pasteurize 100 L of milk were calculated to be 4.68 and 4.22 kWh respectively for a temperature difference of 35–40 °C. Some of the recent studies regarding ETC, Shafieian (2019) proposed that the temperature of the solar working fluid increased as the number of glass tubes increased, however, the temperature increase rate decreased and became comparatively insignificant for the number of tubes greater than 25 to 30. They attributed this reduced or even stable temperature increase to increased surface area and consequently increasing absorption capacity of ETC. Our findings are completely inconsistent with the above-mentioned findings
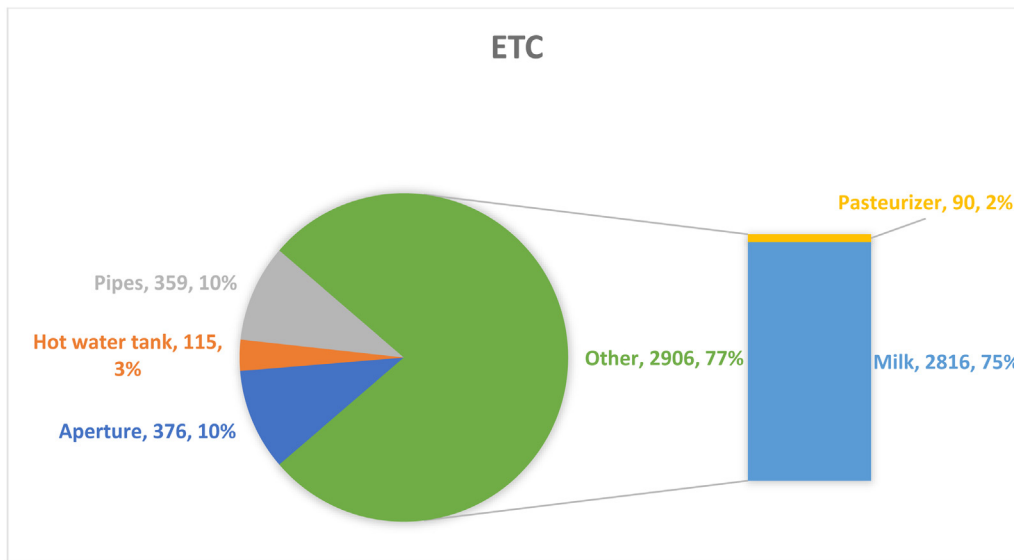
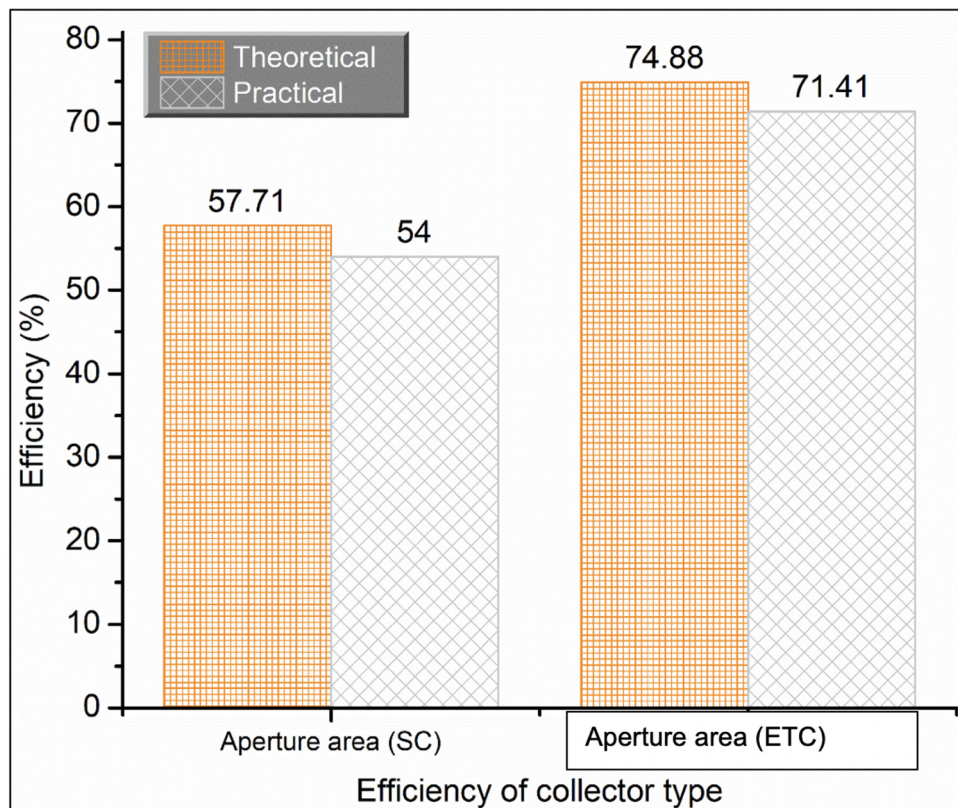**Fig. 11.** Power losses during pasteurization for ETC.

Fig. 12. Efficiency comparison of milk pasteurization systems working on SC and ETC (Theoretical and practical).

as we observed that the temperature of working fluid (water in our case) increases with increase in number of tubes. The temperature was restricted to 40 °C in case of 15 tubes, however, a significant rise was noted as the number of tubes increased to 45. For Faisalabad region during bright sunny summer days, the above-mentioned fact is true which slightly fluctuates in case of a cloudy/dense day. We also noted that for this region, rate of increasing temperature stabilizes at 45 tubes as opposed to the Perth (Australia) where Shafieian (2019) made the experimental

setup with 25 tubes. In our case we have employed a storage tank (fully insulated with PU) and extra energy is stored in the storage tank which can be used for next batches.

Another important factor involves the regional wind velocity of the study area. The average wind velocity for the Faisalabad region is 2 m/s. We observed a negligible effect on temperature variation in ETC. Similarly, Du et al. (2013) prepared a platform for studying the performance of a HPSC in a solar water heating

system. The obtained results including collector outlet temperature, instantaneous efficiency, and pressure drop were presented in detail. The maximum achieved efficiency of the collector was 60% which occurred at the solar radiation of 860 W/m^2. Whereas, in our research the efficiencies for SC and ETC were recorded to be 58% and 74% respectively under the average solar radiation of 750 W/m^2. These figures conclude that the efficiency of improved milk pasteurization employing ETC, and Sc are greater than the research conducted by Du et al. (2013).

Rassamakin et al. (2013) proposed the application of specially extruded aluminum heat pipes in the HPSC of a solar water heating system to reduce the contact thermal resistance. Under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC and ETC was recorded to be 3.56 kWh and 3.91 kWh respectively; this value lies from 3.78–4.32 kWh to pasteurize 100 L of milk for a temperature difference of 35–40 °C. The predicted value of efficiency for SC and ETC were found to be 57.71 and 74.88% respectively. The efficiency values under field conditions for SC and ETC were found to be 54 and 71.41% respectively. In both cases (theoretical and practical), efficiency of ETC is significantly higher than that of SC. Since the optical losses and thermal losses in ETC are very less as compared to that of SC. The heat energy losses per unit time (W) were also calculated in terms of optical losses study concluded that both the systems can be effectively utilized for the milk pasteurization; however, ETC based solar milk pasteurization system proved to be more efficient, simpler in design, cheaper, stable, compact, portable, and cost effective and provides excellent opportunity for decentralized milk processing.

4. Conclusion

Milk processing in rural areas needs efficient decentralized renewable energy solutions not only for handling the fresh milk at the farm level but also providing a cheaper sustainable solution to the small entrepreneur. The present study enables an in-depth thermal analysis of milk pasteurization and comparison of Scheffler fixed focus concentrator and ETC to investigate the useful energy and losses during pasteurization. It would help designers to make the right decision for fabricating solar energy applications in the dairy sector. The available energy was estimated to be 8.10 and 5.63 kWh at the aperture areas of SC and ETC, respectively. Under the constant range of solar radiations (GHI), the pasteurization process is quite smooth with the gradual increase in temperature and process completed in 80–90 min to reach a temperature of 63 °C from the ambient temperature. The total power consumed was recorded to be 2.67 kW to reach this pasteurization temperature. The total energy required for the pasteurization of 100-liter batch of milk is 3.57 kWh. Though results showed that solar milk pasteurization can be successfully done using SC yet under the average beam radiation range of 686 Wm-2, the overall efficiency of the system was found to be 58%. On the other side, in case of ETC, the overall efficiency of the system was found to be 74%. These results are in accordance with results obtained from predicted values (54% for SC and 71% for ETC) showing the reliability of the developed algorithm. The research concluded that both systems can be effectively used for the milk pasteurization system, however, the system coupled with ETC is more efficient, simple in design and provides thermal storage to continue the process under varying weather conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2022.06.001.

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