International Journal of Engineering Applied Sciences and Technology, 2022
Vol. 7, Issue 6, ISSN No. 2455-2143, Pages 149-156
Published Online October 2022 in IJEAST (http://www.ijeast.com)

DESIGN AND NUMERICAL SIMULATION OF A SOLAR ENERGY DRIVEN SMALL-SCALE MILK PASTEURIZATION SYSTEM

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Abstract— **The conventional sources of heat generation are widely prevalent in the food industry like the electricity and usage of fossil fuels. However, they have some associated drawbacks with them like rising fuel prices, associated pollution level etc. These clearly mandate the use of renewable sources of energy like wind, hydrothermal or solar energy. Solar energy is the one of the major sources of energy, which is renewable, inexhaustible, and clean. It can significantly contribute the world energy requirement with available conversion technology. The present study is about to designing and numerical modeling a solar energy driven small-scale milk pasteurization system. The design and operating parameters were evaluated first and then computer-aided-designing (CAD) software was used to create a 3-D diagram of the system. Then a prototype has been developed and its performance evaluation was carried out. Collector of focal length 12 cm, aperture width 31.5 cm, rim angle 131.5 ° was fabricated with a 3 m long absorber tube. The milk was passed through absorber tube at flow rate 30 L/h giving an outlet temperature of 72 °C. Computation fluid dynamics (CFD) analysis of the data showed good correlation between experimental data and simulation.**

Keywords— **Solar energy, pasteurization, renewable energy**

I. INTRODUCTION

Milk is a very important commodity in human nutrition and serves an important role in the diet throughout life. It is perishable as it is an excellent medium supporting the growth of spoilage microorganisms (lactic acid bacteria, psychrotrophs, thermoduric bacteria) and pathogens (Mycobacterium tuberculosis, Escerichia coli, Coxiella Burnetti, Staphylococcus aureus etc.). Raw milk spoils rapidly at room temperature and needs processing [1]. Heat treatment and chilling of milk ensures market milk remains safe up to the point of consumption by humans. These methods aim to prolong shelf life of milk. For heat treatment, thermal energy is needed for processing of milk, even at a very modest scale of operations. Energy from conventional sources (fossil fuels) is becoming increasingly expensive [2] and are scarce.

Capturing solar energy may be a logical and cheaper solution to solve the energy problem caused by scarce fuels. It is renewable and environment-friendly. India receives abundant solar energy. The daily average solar energy incidence varies from 4-7 kWh/m^2 [3, 4], and for 250 to 300 days per year in most parts of the country.

Solar energy heating systems have been used for heating of water as well as milk. Several research have been carried out for developing milk pasteurization systems using solar energy. The systems essentially comprise of solar concentrator systems which include a reflecting element that reflects sun's energy and focusses it on absorbing element. Several designs have emerged and have been studied. The main designing element is the reflector that has been designed in various configurations such as a parabolic bowl type, parabolic trough type, or Fresnel lens type. Some of the previous research [2,5-13] in this direction reveals that there exists a great scope for the development of solar energy powered milk pasteurization system. They are ideally suited for processing milk at small-scale dairy plants and milk collection systems.

Therefore, this research aims to design a milk pasteurization system which operates by applying solar energy for pasteurizing the milk that could be useful at remote areas and in village cooperative societies, where the small quantities of milk are delivered by individual producers. While earlier designs have been used for milk pasteurization, this research was to introduce CFD simulation to visualize flow and temperature profiles in the tube.

THEORY ON DESIGN ASPECTS

A. Design of parabolic trough collector

The system includes a concentrating type solar collector in which pumping milk from the feed tank through the absorber pipe placed at the focal axis of the parabolic trough collector, on which solar radiation falls after reflecting from the parabolic collector (Fig. 1 and 2). The design parameters of the parabolic trough were calculated according to the following relations as obtained from Kalogirou [14].

- Focal length, f

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- Half-sun acceptance angle, Θ_s

(It is the angle subtended by conical sun rays at a point on earth. Value of Θ_s was taken as 0.27^o from literature)

- Aperture width, W_a

(It is the edge to edge distance of the trough)

$$W_a = 2r_R \sin\varphi_R = 4f \tan(\tfrac{\varphi_R}{2}) \qquad (1)$$

- Rim angle , ϕ_R

(Angle made by vertical axis of the trough and the line joining focal point and edge of the trough)

$$\phi_R = \tan^{-1} \frac{4f\, W_a/2}{4f^2 - (W_a/2)^2} \qquad (2)$$

- Rim radius, r_R

(It is the distance of line joining focal point and edge of the trough)

$$r_R = \frac{2f}{1+\cos\phi_R} \qquad (3)$$

- Curved length of parabolic reflector, S

$$S = \frac{4f}{2}\left[\sec(\tfrac{\phi_R}{2})\tan(\tfrac{\phi_R}{2}) + \ln\left\{\sec(\tfrac{\phi_R}{2}) + \tan(\tfrac{\phi_R}{2})\right\}\right]$$
(4)

- Collector area, A_c
- Length of absorber tube, L

$$L = \frac{A_c}{S} \qquad (5)$$

- Outer diameter of absorber tube, D_o

$$D_o = 2r_R \sin\theta_s \qquad (6)$$

A schematic diagram and front, side and top views of the parabolic trough is given in Fig. 1 and 2, respectively.

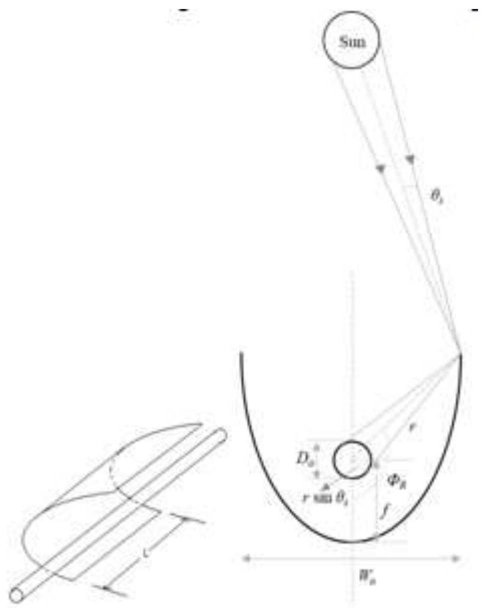


Fig. 1. Schematic of the parabolic collector

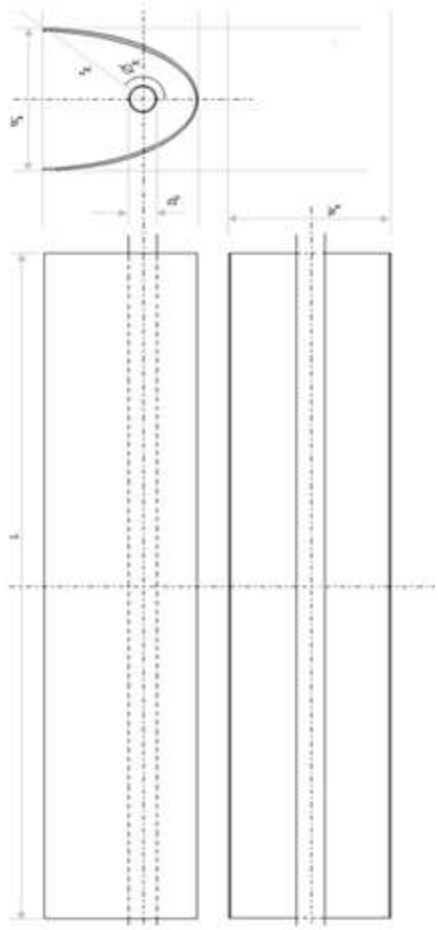


Fig. 2. Front, side and top views of the parabolic collector

B. **Thermal analyses**

Average daylight hours throughout the year are about 10 hours. The concentrator comprises of a parabolic trough collector and an absorber tube at the focal axis of the reflector. The milk is passed through the absorber tube to heat it up to the pasteurization temperature. Radiation from sun to collector and then to absorber is given by Eqn. 7 and 8, respectively.

$$Q_{Sun\rightarrow coll} = A_c E_d \cos\varphi_i \qquad (7)$$

$$Q_{coll\rightarrow abs} = A_c E_d \cos\varphi_i \varepsilon\alpha \qquad (8)$$

Where, ε = Emissivity of surface of collector; α = Absorptivity of absorber tube.

- Energy required for pasteurization of milk

The energy absorbed by the absorber tube was utilized in heating of the milk to the pasteurization temperature.

$$Q_{abs\rightarrow milk} = mc_{pm}(T_o - T_i) = A_c E_d \cos\varphi_i \varepsilon\alpha$$
(9)

Where, m = mass flow rate of milk, kg/s.

- Heat available to the milk from absorber

$$Q_{abs\rightarrow milk} = A_c E_d \cos\varphi_i \varepsilon\alpha = U_o A_r (T_o - T_i)$$

(10)
Where, U_o = Overall heat transfer coefficient, W/m^2K; A_r = Absorber tube area, m^2.
U_o was calculated considering the heat losses from the absorber tube surface, conductive heat transfer from the tube material and heat transfer to milk inside the tube. Heat losses from absorber were total conductive (h_c), convective (h_w) and radiation (h_r) losses. Heat losses from absorber were quantified as heat loss coefficient (U_L) as given in Eqn. 11.

$$U_L = h_c + h_w + h_r \quad (11)$$

1) Conductive losses, h_c: depending on the structure and frame of the system
2) Convective losses, h_w: wind loss, depends on wind velocity
Nusselt number (Nu) correlations were used to obtain the h_w by using Eqn. 12 and 13.
For (0.1<Re<1000),

$$Nu = 0.4 + 0.54(\mathrm{Re})^{0.52} \quad (12)$$

For (1000<Re<50000),

$$\mathrm{Nu} = 0.3(\mathrm{Re})^{0.6} \quad (13)$$

Where, Re = Reynolds number for wind flow, given by Eqn. 14.

$$\mathrm{Re} = \frac{\rho_{air} L v_{air}}{\mu_{air}} \quad (14)$$

Where, ρ_{air} = air density at ambient temperature, kg/m3; v_{air} = air velocity, m/s; μ_{air} = viscosity of air at ambient temperature, Pa-s; L = characteristic length; for air flow (perpendicular) past a cylindrical tube having diameter/length <<1. So, L assumes value of diameter of tube, D_o.
After determining Nu value, the value of heat loss coefficient was obtained from the following equation Eqn. 15. k_{air} = Thermal conductivity of air, W/mK

$$Nu = \frac{h_w L}{k_{air}} \quad (15)$$

3) Radiation heat loss, h_r

$$h_r = 4\sigma\varepsilon_{abs} T_{abs}^4 / T_{abs}^4 \quad (16)$$

Where, σ = Stephan-Boltzmann constant = 5.678 x 10^{-8} W/m^2K^4; ε_{abs} = Absorber emissivity; T_{abs} = Absorber surface temperature, K.

- Heat transfer within milk

Heat from the absorber tube material is transferred to the milk flowing inside the tube. The milk side heat transfer coefficient, h_{fi} (W/m^2K) was calculated from Nusselt number (Nu) value as given by Eqn. 17 and 18.
For (Re>4000)

$$Nu = 0.023(\mathrm{Re})^{0.8}(\mathrm{Pr})^n \quad (17)$$

For (Re<2100)

$$\mathrm{Nu} = 1.86(\mathrm{Re}\,\mathrm{Pr}\,\frac{D_i}{L})^{0.33}(\frac{\mu_{bm}}{\mu_{wm}}) \quad (18)$$

Where, n = 0.3 for milk being cooled and 0.4 for milk being heated (n is taken as 0.4); μ_{bm} = viscosity of milk at bulk mean temperature, Pa-s; μ_{wm} = viscosity of milk at tube temperature, Pa-s; Pr = Prandtl number given by Eqn. 19 and 20, respectively.

$$\mathrm{Re} = \frac{\rho_m D_i v_m}{\mu_m} \quad (19)$$

Where, v_m = milk velocity, m/s; D_i = inner tube diameter, m;

$$\mathrm{Pr} = \frac{c_{pm}\mu_m}{k_m} \quad (20)$$

Where, k_m = thermal conductivity of milk, W/mK.

- Overall heat transfer coefficient

Overall heat transfer coefficient was given by Eqn. 21.

$$\frac{1}{U_o} = \frac{1}{U_L} + \frac{D_o \ln(D_o/D_i)}{2k_{tube}} + \frac{D_o}{D_i h_{fi}} \quad (21)$$

Where, k_{tube} = thermal conductivity of tube, W/mK (for stainless steel k_{tube} = 15 W/m-K)
Where, L = absorber tube length, m

- Concentration ratio

$$C = \frac{A_c}{A_r} \quad (22)$$

$$A_r = \pi D_o L \quad (23)$$

- Holding tube design

After the heating of milk to the pasteurization temperature (72 °C), it has to be passed through the holding tube for a minimum residence time of 15 s. Length of holding tube, L_h, is to be fitted at the end of absorber tube. Based on the milk flow velocity, v_m, to ensure holding time of minimum 15s, the length of holding tube was given by Eqn. 24.

$$L_h = v_m \times 15 \quad (24)$$

II. MATERIALS AND METHODS

The research work is undertaken to design and develop a small-scale solar energy driven system for milk pasteurization at Agricultural and Food Engineering Department, IIT Kharagpur. The necessary equipment for basic operation of pasteurization system is feed tank for constant supply of liquid, pumps, parabolic trough collector (made of aluminium), absorber tube, holding coil, thermocouples, and cooling medium (cold water). The setup is drawn with the help of Autodesk Inc. AutoCAD 2016 Software (Fig. 3)

Table -1 Parameters of the product for designing

Product	**Milk**
Initial temperature of milk, T_i	60 °C (after pre-heating)
Pasteurizing temperature of milk, T_o	72^0C (Heating upto 75 °C)

Specific heat of milk, c_{pm}	0.93 kcal/kg °C (3.89 kJ/kg °C)
Density of milk, ρ_m	1030 kg/m^3 (at bulk mean temperature about 67 °C)
Viscosity of milk, μ_m	0.00164 Pa-s (at bulk mean temperature about 67 °C)
Thermal conductivity of milk, k_m	0.59 W/mK (at 50^{0}C and 15 % Total solid)
Ambient temperature, T_a	40 °C
Emissivity of collector (Black painted aluminium), Ɛ	0.95
Absorptivity of absorber (Black painted Stainless Steel AISI 316), α	0.97
Intercept angle, φ_i	0° (summer)
Intercept factor, $k(\varphi_i)$	1

A. Study area

The study area was Kharagpur, West Bengal, India, (22.346° N –latitude, 87.232° E – longitude) The average annual solar insolation at Kharagpur ranges from 4-5 kWh/m^2-day [15]. The solar declination angle δ (Eqn. 25) defined as the angle between sun ray and its projection on a horizontal plane. Solar declination depends on the number of day of the year.

$$\delta = 23.45 \sin[284 + n] \quad (25)$$

where, n = number of day of the year.

Number of daylight hours, N is given by the Eqn. 26:

$$N = \frac{2}{15}\cos^{-1}[-\tan(Latitude)\tan(\delta)] \quad (26)$$

Considering a summer day (21st May), the values of δ and N are 22.04° and 13.24 hours respectively; and similarly, 22.107° and 10.72 hours respectively obtained for a winter day (21st December).

Intercept angle (φ_i) and intercept factor ($k(\varphi_i)$) are calculated by equation given in Kalogirou [14]. The values of φ_i and $k(\varphi_i)$ during summers at Kharagpur are 0° and 1, respectively.

The values of solar insolation or Direct Normal Irradiance (DNI), denoted by E_d (W/m^2), was measured hourly using a solarimeter during 4 different days in different weather conditions days, viz., spring (21st March), summer (21st May), monsoon (21st July) and winter (21st December).

B. Fabrication

The fabrication of the equipment was done with the help of local technicians at Agricultural and Food Engineering Department, IIT Kharagpur. Following parameters of the parabolic collector were calculated for the fabrication as given in the Table 2.

Table-2 Parameters calculated for parabolic collector

Parameters	**Values**
Focal Length of parabolic collector	0.12 m
Aperture width	0.315 m
Curved length	0.6 m
Height of the collector	0.24 m
Outer diameter of absorber tube	0.0254 m
Inner diameter of absorber tube	0.022 m
Length of absorber tube	3 m
Concentration ratio	7.53
Rim angle	131.5

The frame of the collector was fabricated using a 4 mm thick and 20 mm wide mild steel strips. The frame was made as a parabolic trough like structure for supporting of the collector with a provision for holding the absorber tube using clamps. An aluminium sheet of average thickness 0.42 mm was used as a collector which was fixed and riveted on the frame (Fig. 3a). The absorber tube of stainless steel AISI 316 was clamped with the frame in such a way that the focal axis of the collector passes through it. The absorber tube was welded with thermocouple sensors at inlet and outlet. A flow regulating ball valve was fixed at the inlet side of the tube. An extension of the absorber tube was used as holding tube for ensuring minimum residence time of the milk. Whole setup was painted in black.

(a)

(b)

Fig. 3 (a) Aluminium sheet used for fabrication (b) fabricated solar pasteurization equipment

C. Testing of equipment

The equipment was tested on a plain surface with proper connections of piping water and milk. The collector surface was oriented along the north-south line. Study was done from 12- 2 pm for trapping the maximum amount of solar energy. Tests were carried out using water and milk. Both water and milk were preheated to ~60 °C using an electrical heater and the flow rate was manipulated using the ball valve to get the desired temperature rise up to 75 °C. The flow rate was measured as the amount of liquid collected in a 1000 mL graduated measuring cylinder for a period of 1 minute measured using a stopwatch as shown in Fig. 3.12. The flow rates were varied as 28 L/h, 30 L/ h, 32 L/h, 35 L/h, 37 L/h and 40 L/h. Corresponding temperatures at inlet and outlet were measured with sensors connected to digital thermocouple (K-type, Model: Lutron TM-903 A). Flow rate giving the desired temperature rise (sufficient to pasteurize the milk) was chosen for experiment and calculated length of holding tube according to flow rate was fitted. The minimum holding time of 15 s was ensured by passing milk through the holding tube.

D. Numerical simulation

Numerical simulation of the solar pasteurization equipment was carried out using computational fluid dynamics (CFD) analysis. The CFD analysis was carried out to study the fluid flow and temperature rise of milk and water when passed through the absorber tube. All the analyses were carried out using Ansys FLUENT (ver. 2020). Firstly, the system was drawn into a 3D geometry using Ansys DesignModeler comprising the parabolic trough and absorber tube based on the specifications mentioned in the Table . The drawn 3D model was meshed smaller elements. The parabolic reflector material was set as aluminium, while absorber tube was set as stainless steel AISI 316. The fluid inside the tube was set as either water or milk. The thermal conductivity, specific heat and density of aluminium were set as 202.4 W/mK, 871 J/kg-K, and 2719 kg/m^3, respectively. Corresponding values for stainless steel were 15 W/mK, 768 J/kg-K, and 7600 kg/m^3. For water, values were 0.598 W/mK, 4187 J/kg-K and 998 kg/m^3. For milk, the values were 0.559 W/mK, 3931 J/kg-K and 1032 kg/m^3. The viscosity values for water and milk were set as 0.001 and 0.00213 Pa-s, respectively. For solving, viscous flow under realizable κ-ε model was chosen and energy was set as ON. For radiation model, solar tracing calculator was selected and parameters like time zone, longitude, and latitude as well as solar irradiation values and mesh orientation directions were appropriately set. Energy transfer mode (mixed mode) was set such that the solar radiation falling on the reflector would be used for heating the fluid flowing through the absorber tube.

For initial and boundary conditions, the initial temperature of water/milk was set as 60 ^{o}C, Initial velocity was calculated based on the flow rates (28-40 L/h) used for pumping. The outlet conditions were set as pressure outlet. The CFD code was solved for the different conditions using coupled method with convergence criterion set at residuals, 10^{-6}. The code solves the energy equation (radiation, conduction, convection heat transfer) and Navier-stokes equations (Eqn. 27 and 28) [16].

$$\partial\rho/\partial t + \nabla\rho v_{avg} = 0 \qquad (27)$$

$$\rho(\partial v_{avg}/\partial t) + \rho(v_{avg}.\nabla)v_{avg} = -\nabla\rho + \rho g + \mu\nabla^2 v_{avg} \quad (28)$$

The solutions were visualized as contour plots of flow velocity and fluid temperatures.

III. RESULS AND DISCUSSIONS

A. Computer-Aided-Designing of the setup

The preliminary design of the whole setup was drawn using CAD Software. Autodesk Inc. AutoCAD 2016 software. Fig. 4 give the isometric view and side view of the setup respectively.

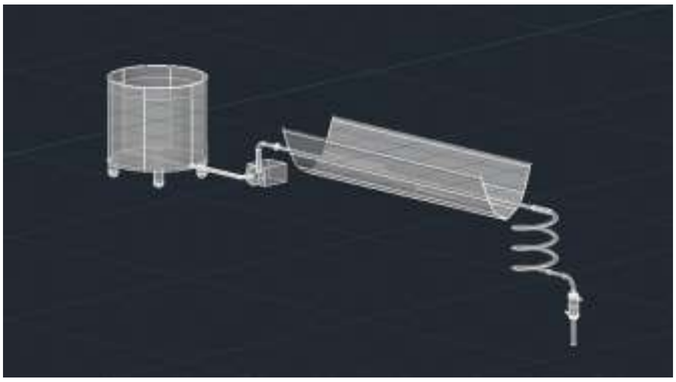


Fig. 4. AutoCAD drawing of the solar pasteurization unit

B. Solar insolation data

The hourly solar insolation or DNI values were measured during four different days of the years as given in Fig. 5. Peak value of insolation were significantly varying for the different days as DNI as high as 986 W/m^2 was obtained for a summer day whereas peak value during a winter day of 507 W/m^2. It was evident that solar insolation is very high during summer time which is significant enough for reaching pasteurization temperature.

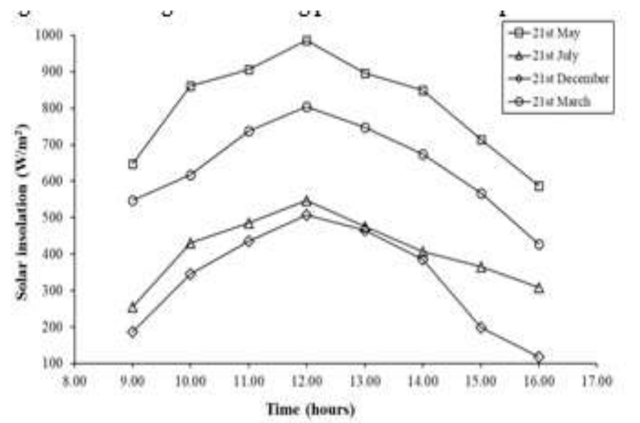


Fig. 5. Hourly solar insolation data for different days of year

C. Effect of flow rate on temperature rise

The initial temperatures of watre and milk were 60.53 ± 0.19 and 60.53 ± 0.24 °C, respectively. The liquid flow rate affetcts the temperature gain by water/milk and thus their outlet temperature during the process. Too low flow rate will lead to much rise in temperature (above pasteurization temperature) because of longer residence time inside the absorber tube. Too high flow rate thus lead to lower temperature rise.

Water showed much temperature rise for the same flow rate as milk. A flow rate of 28 L/h of milk gave an outlet temperature of 75.2 °C from inlet temperature of 60.53 °C. At the same flow rate water gave considerably higher outlet temperature of 80.8 °C. Flow rate of 32 L/h of water was good enough to reach a temperature of 74.8 °C from inlet temperature of 60.53 °C. It was due to higher specific heat capacity of water than milk. The inlet and outlet temperatures of water and milk at varying flow rates are given in Fig. 6.

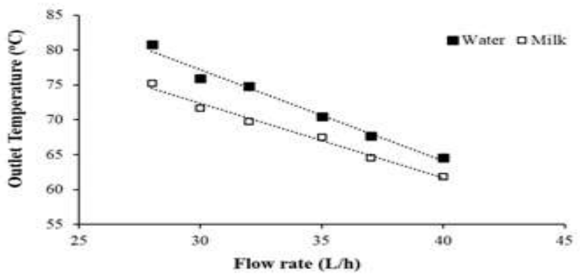


Fig. 6. Outlet temperatures of water and milk at varying flow rates

The calculated heat transfer parameters are given in Table 3.

Table-3. Heat transfer parameters for solar pasteurizer

Flow rate (L/h)	Velocity (m/s)	Reynolds number (Re)		Fluid heat transfer coefficient, h_{fl} (W/m^2K)		Overall Heat transfer coefficient, U_o (W/m^2K)	
		Water	Milk	Water	Milk	Water	Milk
28	0.0051	112.37	70.713	0.758	0.842	0.629	0.695
30	0.0055	120.39	75.763	0.776	0.861	0.643	0.711
32	0.0058	128.42	80.814	0.792	0.880	0.656	0.725
35	0.0064	140.46	88.391	0.816	0.906	0.675	0.746
37	0.0068	148.48	93.442	0.831	0.923	0.687	0.759
40	0.0073	160.52	101.02	0.853	0.947	0.704	0.778

D. Numerical simulation studies

The result for the numercial simulations in terms of the flow velocity and temperature contours is given in Fig. 6 and 7, respectively. The velocity profile obatined using CFD revealed that the flow was parabolic inside the pipe indicating laminar conditons.

The temperatuire profiles inside the absorber tube show that preheated milk at 60 °C enters at the inlet and gets heated at the outlet section of the tube. As seen in the Fig. 7, higher outlet temperature was reached in the case of water as compared to milk. Also, lower flow rates (28 L/h) (Fig. 7) lead to highest outlet temperature in each case. The results of the CFD are in agreement with the experimental observations.

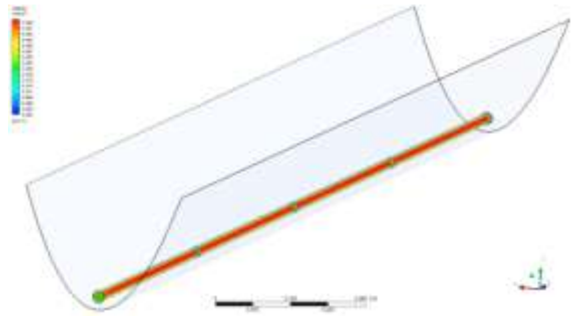
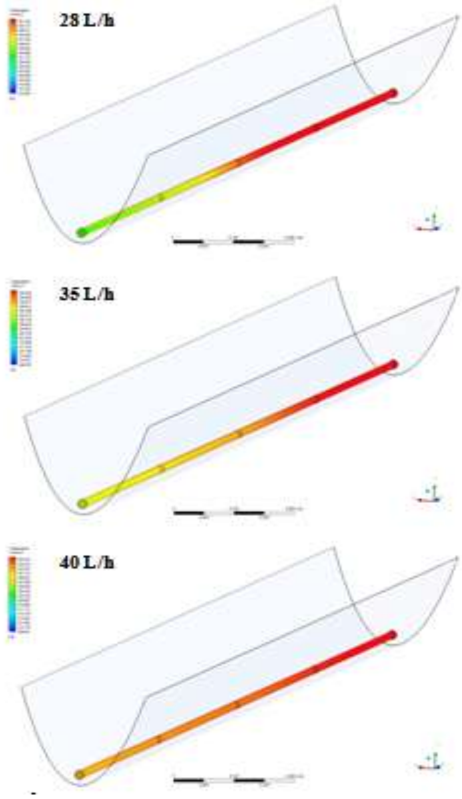
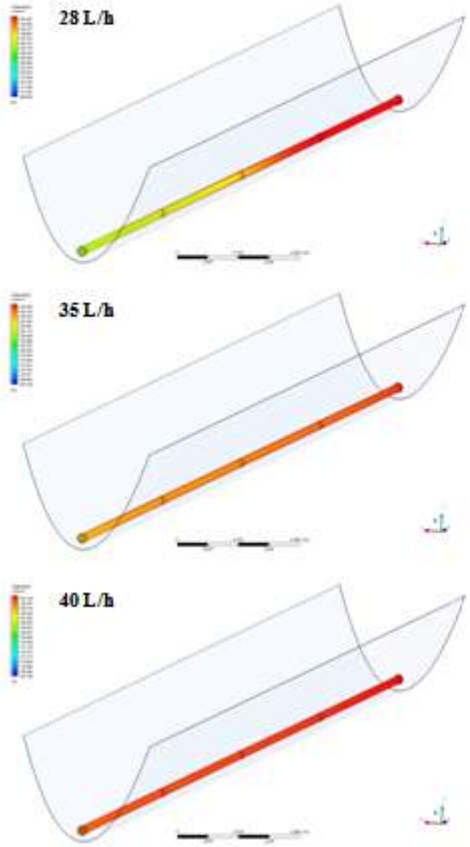


Fig. 6. Velocity profile of fluid within the absorber tube at 30 L/h flow rate



(a)



(b)

Fig. 7. Temperature contours within the absorber tube for (a) water and (b) milk

IV. CONCLUSION

The conventional sources of thermal energy have been used since time immemorial for the processing of food products. Associated pollution with conventional energy sources as well as rising fuel prices have made humans look into the renewable resources of energy for applications in daily operations. Some of the renewable sources of energy include solar, wind, geo-thermal, hydro-electrical energy etc.

Solar energy is a renewable clean and environmentally friendly source of energy. India has a vast amount of landmass which receives large amount of sunlight. About 250-300 clear sunny days are obtained on an average annually in India. The DNI value ranges from 4-7 kWh/m^2-day. Use of solar energy could replace the conventional thermal power generation sources used in the food processing industry.

The present study utilized of solar energy for development of a small-scale milk pasteurization system. A concentrating type of system was studied for its applicability to pasteurize milk. The concentrator consisted of a parabolic trough collector with an absorber tube at the focal axis of the parabolic trough. Design and operating parameters were evaluated for the system. Milk (initially preheated to 60 °C) was passed through absorber tube at flow rate 28 L/h. Final temperature up to 75.2 °C was obtained.

There is considerable scope of further research and development for utilizing solar energy for milk pasteurization. In view of the present study, the capacity of the system can be increased by using a longer absorber tube. Similar system with polished aluminium surface can be studied. The system can be mounted on a manually driven pulley for movement of the solar collector along with the sun movement for maximum intercepting of sunlight. A solar tracking mechanism can be developed for automatic movement of the collector towards the direction of sun.

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