Utilization of Solar Heated Water in Shell and Tube Heat Exchanger for Pasteurization of Milk

(Milk Pasteurization by using Solar Energy)

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***Abstract*- The present investigation is aimed to evaluate the performance of solar water heated shell and tube heat exchanger, to develop milk pasteurization system using solar heated water and to assess the chemical and microbial qualities of pasteurized milk prepared using solar heated water. The shell and tube heat exchanger performance was evaluated considering solar water flow rates of 3, 5, and 7 l/min at 85ºC and cold water flow rates at 0.5, 1.0 1.5 l/min at 35ºC. The parameters like effectiveness of heat exchanger (ε), tube side (h_i) and shell side (h_o) convective heat transfer coefficient and tube wall temperature (T_w) were calculated. The highest values for ε and T_w were observed to be 0.79 and 75.46^{0}C at flow rate of hot water at 7 l/min and flow rate of cold water at 0.5 l/min. Therefore this combination of flow rates of hot water and milk was subsequently utilized for pasteurization. The pasteurized milk was evaluated for its chemical and microbial qualities and was compared with raw milk. The pasteurized milk had 0.15% acidity, 3.49% fat, 8.44% solid not fat and 11.93% total solids. In this way pasteurized milk was found more or less similar with raw milk. In microbiological quality evaluation, methylene blue reduction time was found 1.4 h for raw milk and 5.4 h for pasteurized milk. The total bacterial count were found 4.27 log 10 cfu/ml and coliform was found to be absent in 0.01 dilution for pasteurized milk. All the microbiological test findings found within the BIS standards specified for pasteurized milk. The cost of processing in conventional and solar water heated pasteurization was estimated to be Rs. 2.75 and Rs. 1.90 respectively. The finding of this investigation have shown that solar water heating system assisted shell and tube heat exchanger system can be used to produce pasteurized milk with acceptable quality.**

Key words: Solar water heater, solar energy, 1-2 heat exchanger, non-renewable energy

I. INTRODUCTION

Solar thermal system can greatly contribute to energy saving during the production process in the dairy sector, which demand water temperature of <80^{0}C. The hot water produced by solar collectors can also be used for pre-hating the water entering the steam boiler. In this case, the energy contribution of the solar system is relatively small both in comparison with the total energy demand. The Indian dairy sector has acquired substantial growth momentum from the 9th plan onwards. As a result of this India is first amongst the world milk producing nations achieving an annual output of about 140 million tonnes during 2013-14 [1].

In dairy processing plant milk and milk products are subjected to various unit operations like filtration, clarification, homogenization, pasteurization, sterilization (UHT treatment), cooling, packaging, refrigeration etc. Among various heat treatments the main operation is pasteurization in which steam required is 0.3kg/l of milk. Traditionally, fossil fuels (coal, gas, diesel etc.) are utilized to generate heat to produce steam/hot water and are subsequently used as a heating medium in PHE. Burning of these fossil fuels contribute to pollution as well as to green house gases (GHGs) resulting into global warming. Further, these energy sources are conventional. If solar heated water is used for fully or partially, it would reduce the cost of fuel charges (Katre and Prasad, 1989). Several renewable energy sources like wind, geothermal, solar etc are available. Among various types of renewable energy sources, solar energy (from sun) is the most readily available and important source of energy because it is non-polluting, renewable, clean and inexhaustible. Solar energy also helps in reducing pollution and maintenance of eco balance [2].

Tubular heat exchangers are so important and so widely used in the process industry that their design has been highly developed. When the required heat transfer surface is large, the recommended type of exchanger is the shell–and-tube [3]. In the present investigation, 1-2 shell and tube heat exchanger is used for pasteurization of milk. Shell and Tube heat exchangers are applied where high temperature and pressure demands are significant and can be employed for a process requiring large quantities of fluid to be heated or cooled. Due to their design, these exchangers offer a large heat transfer area and provide high heat transfer efficiency in comparison with others.The 1-2 exchanger is normally arranged so that the cold fluid and the hot fluid enter at the same end of the exchanger, giving parallel flow in the first tube pass and counter flow in the second. This permits a close temperature approach, at least at the exit end of the exchanger. With a view to overcome various disadvantages of using conventional fuels, the investigation was carried out to evaluate the performance of solar water heating system assisted shell and tube heat exchanger for milk pasteurization.

II. MATERIALS AND METHODS

Solar water heating system works on the principle of thermosyphon. Thermosyphon systems are similar in configuration to active systems; with the exception that circulation through the collector loop is achieved through the fluid buoyancy forces, resulting from temperature gradients in the storage tank and collector. This buoyant force is utilized by placing the collector outlet at a lower level than the tank outlet that supplies fluid to the collector, producing a difference in fluid density that drives the circulation.

A. Design and length of holding tube (Holder)

The holder ensures the product is held for a specified time, not less than 15 s, when heated to 72^{0}C or more. The time of 15 s must be elapsed by most rapidly moving particle passing through the holding tube. For a particular holder, timing is based on the milk pump flow rate. The milk temperature is determined at the discharge of the holder.

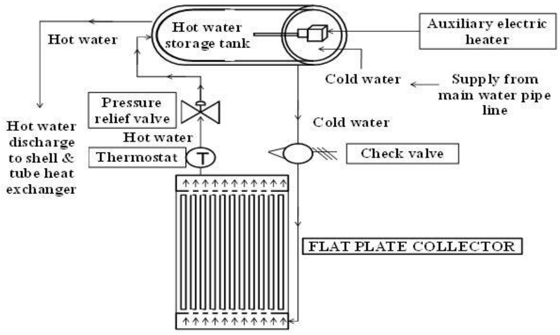


Fig. 1: Schematic diagram of solar water heating system

$$Residence\ time\ (t) = \frac{volume\ of\ the\ tube}{volumetric\ flow\ rate} \quad (1)$$

Milk flow rate is 0.5 l/min, than

$$Residence\ time\ (t) = \frac{\pi r^2 L}{0.5\ l/m} \quad (2)$$

$$Residence\ time\ (t) = \frac{\pi r^2 L}{0.0083\ l/s} \quad (3)$$

$$Residence\ time\ (t) = \frac{\pi r^2 L}{0.0000083\ m^3/s} \quad (4)$$

In present case, a stainless steel pipe of length 0.064 m having inner radius r_i is 0.025 m and outer radius r_o is 0.026 was taken for holder. In eqn. (2) by putting the value L=0.064 m, r_i = 0.025 m, the required residence time of 15 s is achieved.

Fig. 2: Holding tube attached at hot milk outlet of shell and tube heat exchanger

B. Experimental Set up

Experiments were conducted on a 1-2 Shell and tube heat exchanger. The Fig. 3 shows the schematic diagram of the heat exchanger. The Fig. 1 shows the schematic diagram and of solar water heating system. The solar water heating system was connected to S&THE using an insulated pipe. The hot water was circulated in the shell and flow through it, while the medium to be heated was allowed to flow through the tubes.

C. Experimental observations

Preliminary trials were carried out between water to water for performance evaluation. The performance evaluation of solar water heating system assisted shell and tube heat exchanger was done with two parameters viz. flow rate of hot water at 3, 5 and 7 l/min and flow rate of cold water at 0.5, 1.0 and 1.5 l/min. The following heat transfer parameters were considered for evaluating the solar water heating system assisted S&THE.

D. Heat exchanger Effectiveness (ε)

Heat capacity rate ratio, C* is the ratio of the smaller to the larger heat capacity rate to hot and cold fluids.

$$m_c c_{pc} = C_c \ \&\ m_h c_{ph} = C_h \quad (5)$$

$$\text{Then, } \varepsilon = \frac{T_{cb} - T_{ca}}{T_{ha} - T_{ca}} \quad \text{When } C_c < C_h \quad (6)$$

$$\varepsilon = \frac{T_{ha} - T_{hb}}{T_{ha} - T_{ca}} \quad \text{When } C_c > C_h \quad (7)$$

Where,

ε = Heat exchanger effectiveness

C_c = Heat capacity rate ratio of lower temperature stream (dimensionless)

C_h = Heat capacity rate ratio of higher temperature stream (dimensionless)

E. Convective heat transfer coefficient (h)

1. Tube side coefficient (h_i)

$$h_i = \frac{N_{Nu} k}{d} \quad (8)$$

$$N_{Nu} = 0.023 N_{Re}^{0.8} N_{Pr}^{0.3} \quad (9)$$

$$N_{Re} = \frac{\rho v d}{\mu} \quad (10)$$

$$N_{Pr} = \frac{\mu C_{pc}}{k} \quad (11)$$

Where,

N_{Nu} = Nusselt number (Dimensionless)
N_{Re} = Reynolds number (Dimensionless)
N_{Pr} = Prandtl number (Dimensionless)
d = Inner diameter of tube (m)
k = Thermal conductivity of cold water (W/m^{0}C)
ρ = Density of cold water (kg/m^3)
v = Velocity of cold water (m/s)
μ = Viscosity of cold water (N m/s)
C_{pc} = Specific heat of cold water (kJ/kg^{0}C)

2. Shell side coefficient (h_0)
By Donohue equation [4]

$$h_o = 0.2\ k/D_o \left(\frac{D_o G_e}{\mu}\right)^{0.6} \left(\frac{C_{ph}\mu}{k}\right)^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (12)$$

Where,

μ = Viscosity of the shell fluid (hot water) (N.s/m^2)
μ_w = Viscosity of the shell fluid at tube wall temperature (N.s/m^2)
D_o = Outside diameter of tube (m)

here,

$$G_e = \sqrt{G_b G_c} \quad (13)$$

$$G_b = \frac{m}{S_b} \quad \text{and} \quad G_c = \frac{m}{S_c} \quad (14)$$

Where,

m = Mass flow rate (kg/s)
G_e = Average mass velocity of the fluid flowing parallel and across the tube (kg/m^{2}s)
G_b = Mass velocity of fluid flowing parallel with the tube (kg/m^{2}s)
G_c = Mass velocity of fluid flowing across the tube (kg/m^{2}s)
S_b = Area for flow in baffle window (m^2)
S_c = Area for transverse flow between the tube (m^2)

Here,

$$S_b = f_b \frac{\pi D_s^2}{4} - N_b \frac{\pi D_o^2}{4} \quad (15)$$

Where,

f_b = Fraction of cross sectional area of shell occupied by baffle window (0.1955), [5]
D_s = Inside diameter of shell (m)
N_b = Number of tube in baffle window

N_b = f_bx total no. of tubes
N_b = 0.1955 x 32
N_b = 6.25 (say, 6)

and

$$S_c = P\ D_s \left(1 - \frac{D_o}{p}\right) \quad (16)$$

Where,

p = Center to centre distance between tubes (m)
P = Baffle pitch (m)

F. Tube wall temperature (T_w)

For heating

$$T_w = T + \Delta T_i \quad (17)$$

For cooling

$$T_w = T - \Delta T_i \quad (18)$$

Here,

$$\Delta T_i = \frac{\frac{1}{h_i}}{\frac{1}{h_i}+\frac{D_i}{D_o h_o}} \Delta T \quad (19)$$

Where,

T = Average fluid temperature (^{0}C)

ΔT = Overall temperature drop (^{0}C)

ΔT_i = Temperature drop through inside tube (^{0}C)

G. Pasteurization of milk

The pasteurized milk was prepared using time temperature combination (71.5^{0}C for 15 s) [6]. Samples were analyzed for their chemical [7], microbial [8] qualities. The pasteurized milk was also checked for alkaline phosphatase activity [9]. Statistical analysis of chemical parameters was carried out using t-test.

III. RESULTS AND DISCUSSION

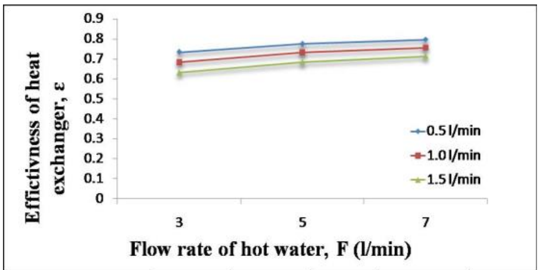
A. Performance evaluation of solar water heating system assisted S&THE

The results on performance evaluation of solar water heating system assisted shell and tube heat exchanger for various heat transfer parameters is presented in Table 1.

TABLE I AVERAGE HEAT TRANSFER PARAMETERS

F_h	F_c	ε	h_i	h_o	T_w
l/min	l/min	-	kW/m^2°C	kW/m^2°C	°C
3	0.5	0.73	0.38	0.58	71.93
	1.0	0.68	0.67	0.57	67.40
	1.5	0.63	0.91	0.56	64.20
5	0.5	0.77	0.39	0.76	74.00
	1.0	0.73	0.68	0.75	69.30
	1.5	0.68	0.95	0.74	66.37
7	0.5	0.79	0.40	0.95	75.46
	1.0	0.75	0.70	0.94	71.32
	1.5	0.71	0.97	0.93	69.16

B. Effect of flow rates of hot and cold water on effectiveness of heat exchanger

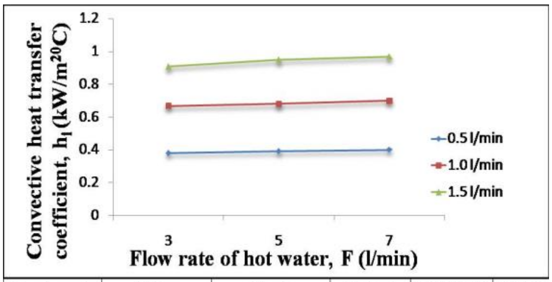


Treatments	S Em	F cal	F- Test	CD (5%)	CV%
F_h	0.001	198.86	S*	0.01	1.25
F_c	0.001	309.52	S*	0.01	
F_h x F_c	0.001	1.26	NS	-	

Figure. 3: Effect of flow rates of hot and cold water on effectiveness of heat exchanger (ε)

From Fig.3, the values of effectiveness of heat exchanger ranged from 0.63 at 3 l/min to 0.71 at 7 l/min. The ANOVA had shown that both flow rate of hot and cold water had significant ($p \leq 0.05$).

C. Effect of flow rates of hot and cold water on tube side convective heat transfer coefficient (h_i)



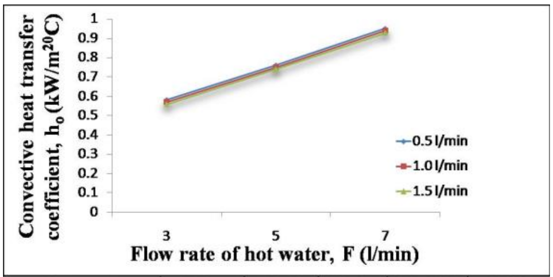
Treatments	S Em	F cal	F- Test	CD (5%)	CV%
F_h	0.001	45.50	S*	0.1	1.40
F_c	0.001	10346.96	S*	0.1	
F_h x F_c	0.001	5.75	S*	0.1	

Figure. 4: Effect of flow rates of hot and cold water on tube side convective heat transfer coefficient (h_i)

The average values of tube side convective heat transfer coefficient ranged from 0.65 kW/m^2°C at 3 l/min to 0.69 kW/m^2°C at 7 l/min. The highest h_i value found was 0.69 kW/m^2°C at 7 l/min and the lowest value of 0.65 kW/m^2°C at 3 l/min and these values are statistically significant ($p \leq 0.05$) at each flow rate of hot water.

D. Effect of flow rates of hot and cold water on shell side convective heat transfer coefficient (h_o)

The average values of shell side convective heat transfer coefficient ranged from 0.57 kW/m^2°C at 3 l/min to 0.94 kW/m^2°C at 7 l/min. The highest h_o was found 0.94 kW/m^2°C at 7 l/min and the lowest 0.57 kW/m^2°C at 3 l/min and they are statistically significant ($p \leq 0.05$) at each flow rate of hot water.

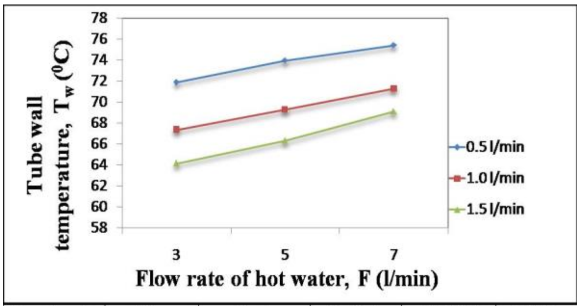


Treatments	S Em	F cal	F- Test	CD (5%)	CV%
F_h	0.001	7922.58	S*	0.01	0.96
F_c	0.001	23.14	S*	0.01	
F_h x F_c	0.001	0.00	NS	0.01	

Figure. 5: Effect of flow rates of hot and cold water on shell side convective heat transfer coefficient

E. Effect of flow rates of hot and cold water on tube wall temperature (T_w)

The average values of tube wall temperature increased from 67.84°C at 3 l/min to 71.98°C at 7 l/min. The highest value of tube wall temperature found was 71.98°C at 7 l/min and lowest 67.84°C at 3 l/min and each flow rate had shown significant ($p \leq 0.05$) effect on tube wall temperature.



Treatments	SEm	F cal	F-Test	CD(5%)	CV%
F_h	0.03	6520.20	S*	0.07	0.13
F_c	0.03	20225.80	S*	0.07	
F_h x F_c	0.04	85.56	S*	0.13	

Figure. 6: Effect of flow rates of hot and cold water on tube wall temperature (T_w)

Similarly, while considering flow rate of cold water, tube wall temperature values ranged from 66.57°C at 1.5 l/min to 73.79°C at 0.5 l/min had also shown significant ($p \leq 0.05$) at each flow rate of cold water. The highest tube wall temperature found was 73.79°C at 0.5 l/min and lowest was recorded as 66.57°C at 1.5 l/min.

All heat transfer parameters show increase in their values with increase in flow rates. The values of heat exchanger effectiveness ε (0.79) and tube wall temperature T_w (75.46°C) were found to be maximum in combination of flow rate of hot water at 7 l/min and flow rate of cold water at 0.5 l/min.

Therefore, combination of flow rate of solar heated water (85°C) at 7 l/min and flow rate of cold water at 0.5 l/min was adopted for pasteurization. For pasteurization, cow milk was fed at 35°C for heating and it attained maximum temperature of 73°C in a tube side (stainless tubes) in the heat exchanger, while the heating medium i.e. solar heated water was admitted at 85°C in the shell side and its was allowed to discharge from the outlet side where its temperature was recorded to be 69°C. The pasteurized milk was analyzed for its chemical and microbial quality and compared with raw milk samples.

F. *Chemical quality of raw and pasteurized milk*

The samples of raw and pasteurized milk were analyzed for chemical parameters like acidity, fat, solid not fat and total solids and the data are presented in the Table 2

TABLE II EFFECT OF HEATING ON CHEMICAL PARAMETERS OF MILK

Parameters	**Raw milk (Mean± SD)**	**Pasteurized Milk (Mean± SD)**	**t-stat**	**t-test**
Acidity	(0.150±0.0085)	(0.151±0.0093)	-1.483	NS
Fat	(3.491±0.066)	(3.466±0.065)	1.914	NS
Solid not fat	(8.446±0.032)	(8.438±0.053)	0.560	NS
Total solids	(11.938±0.079)	(11.905±0.085)	1.483	NS

Pasteurized milk had 0.151% acidity, 3.46% fat, 8.43% SNF and 11.905 total solids and there were no significant changes between chemical parameters of raw and pasteurized milk. The pasteurization process does not change the level of fat, SNF and solid not fat of milk. The data obtained in this study is in accordance with value reported by [10].

G. *Alkaline phosphates test of pasteurized milk*

It is observed that in all the replications the alkaline phosphatase test had shown negative result. It indicates that efficacy of pasteurization was good and acceptable as per the requirement for pasteurization.

H. *Microbial quality of pasteurized milk*

The methylene blue reduction time was recorded to be 1.4 h for raw milk and after heating to pasteurization temperature it was found 5.40 h [11]. The average standard plate count of raw milk was 3.7 x 10^5cfu/ml and after pasteurization it was reduced to 1.9 x 10^4cfu/ml [11]. The coliform was found absent in 0.01 dilution in prepared pasteurized milk [11].

IV. CONCLUSION

It can be concluded that, the values of heat exchanger effectiveness, number of transfer units, and tube wall temperature were found to be maximum in combination of flow rate of hot water at 7 l/min and flow rate of cold water at 0.5 l/min. Solar water heating assisted shell and tube heat exchanger system could be used to produce properly pasteurized milk with acceptable quality without using conventional energy source for heating.

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