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Integration and Simulation of Solar Thermal Energy to Diary Processes

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Abstract. The application of the Solar Thermal Energy (STEn) systems to the dairy processes have shown a great potential for reducing fossil fuels use and greenhouse gas (GHG) emissions. There are thirty- three STEn systems currently operating in the dairy industries worldwide providing temperatures from 140 ºC to 200 ºC that are mainly used for the heating purposes in the processes like pasteurization, preheating, and cleaning. The challenges of those systems include various operational issues such as shad and unoptimized equipment that affect the performance of the collector, tracking and control systems and other apparatus that could be overcome by a preliminary analysis of the dairy plant's thermal load and use of integrated STEn systems. This study relates to a case study of the dairy industry, analyses the current thermal and cooling demands for production of skimmed milk, yogurt and cream, recommends two new scenarios for the integration and simulation of the STEn systems and evaluates the potential the process optimization. The Specific Energy Consumption (SEC) for each product and operational capacity requirement for the current and simulated processes are calculated and the most technically efficient solution considered.

INTRODUCTION

The application of Solar Thermal Energy (STEn) to the diary processes has received considerable attention in the recent years due to its great potential to reduce the use of the fossil fuels and greenhouse gas emissions. There are thirty-three STEn systems currently applied to the dairy industry worldwide. They mainly use solar collectors like flat plate, parabolic trough and Fresnel reflectors to supply heat for the temperature range from 140 ºC to 200 ºC and pressure from 4 to 12 bar for pasteurization, preheating, and cleaning. Those systems reported various issues that affect their operation, including: (i) shade effect on the collector's efficiency and tracking systems; (ii) variable temperature of the returning heat transfer fluid which affects the control system and (iii) use of several components (heat exchangers, pipes, etc) by two heat sources (solar and gas boiler) of different tmperature of operation and mass flow rate which affects the efficiency of the systems (1,2). They can mostly be avoided by preliminary analying of the industrial processes and integrated STEn system (3).

The studies dealing with the environmental impact of the solar thermal systems, applied to the dairy industry, showed that the GHG emissions could be reduced by 32-144 thousand tonnes CO_2 annually when collector area from 1.54 to 1.83 million m^2 and solar fraction from 0.18 to 0.3 are used to generate 6.4 PJ energy (4). The solar thermal and storage systems are apparent in the remote areas where electricity is not consistently available (5). Different collectors like a parabolic trough for milk pasteurisation at 75 ºC and flat plate for absorption chiller at 15-20 ºC have been used to supply 150 litres of hot water per hour at 90 ºC or run the solar water heaters at the temperatures from 63 to72 ºC (6). A number of characteristics such as temperature, type and area of the solar collectors, solar radiation and climatic conditions are crucial for the performances of the solar heating systems in the dairy processes (7). Those

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systems could achieve temperature of maximum 184 °C and pressure of 10.55 bar with the use of the parabolic dish and parabolic trough collectors (7).

Several studies have already used simulation to the dairy processes to improve a liquid-liquid extraction for removing milk fat from the milk (8) or milk drying systems for production of milk powder (9,10) but there is no study that considers the integration of the STEn systems to improve efficiency and sustainability of the processes.

This study involves a case study of the dairy industry, analyses the current thermal, heating and cooling systems for production of skimmed milk, yogurt and cream, develops two different scenarios for STEn system integration and recommends the most technically efficient solution to enhance processes efficiency and increase solar contribution.

METHODOLOGY

The main processes for production of skimmed milk, yogurt and cream include pasteurization, separation, homogenization, mixing and fermentation (Figure 1). The plant requires around 1,600 MWh of electricity and 119,000 m^3 of Liquified Petroleum Gas (LPG) annually to produce around 4.5 million kg of milk, yogurt and cream. Table 1 presents the nominal capacity of the components involved in the production process. The majority of them like pumps, ice bank, chiller use electricity between 3.8 kW and 206 kW while the two boilers use Natural Gas (NG) to generate energy of 600 kW and 300 kW.

TABLE 1. The nominal capacity (NC) of the components used in the dairy processes

Component	Source	NC[kW]
Boiler 1	NG	600
Boiler 2	NG	300
Boiler 1 pump	Electric	10.0
Boiler 2 pump	Electric	5.0
Chiller	Electric	206.2
Cooling pump 1	Electric	5.5
Cooling pump 2	Electric	3.8
Milk pump	Electric	11.0
Centrifugal separater	Electric	15.0
Cream Pump	Electric	5.5
Homogeniser	Electric	37.0
Mixer	Electric	18.5
Fermantetion tank	Electric	6.0
Ice Banks	Electric	19.5
CIP	Electric	6.0

The data were used to design and simulate the existing dairy processes at the steady state operation for STEn system integration using ASPEN Plus software (Aspen Technology Inc, USA). In order to ensure maximum contribution of the STE, two different scenarios were developed to provide heat to the pasteurizer and fermenter in: (i) parallel and (ii) series. In both scenarios the STEn system was simulated as a heater and integrated directly to the hot and cold tanks to operate at the required temperatures with a capacity of 32% of the nominal consumption. Solar contribution and energy savings are calculated to evaluate the most energy efficient scenario. The energy consumption of the apparatus presented in Table 1 and the amount of milk, yogurt and cream produced are simulated and used to calculate the specific energy consumption (SEC) of each product.

RESULTS AND DISCUSSION

Figure 1 presents the schematic the existing dairy plant (Scenario A). The production line marked in green represents the processes involved for production of the skimmed milk, yogurt and cream that include pasteurization, separation, homogenization, mixing and fermentation. The heating line marked in red represents two boilers that provide steam to a header, which splits between five lines in parallel as follows: 45% for pasteurization, 16%

fermentation, 10% preheat, 25% losses and 4% cleaning in place (CIP). The steam returns from the five lines as a condensate to the hot tank. The cooling line marked in blue represents a chiller that cools a cold tank, which provides coolant to two lines in parallel: (i) pasteurization process and raw milk tanks, and (ii) pasteurized milk tank.

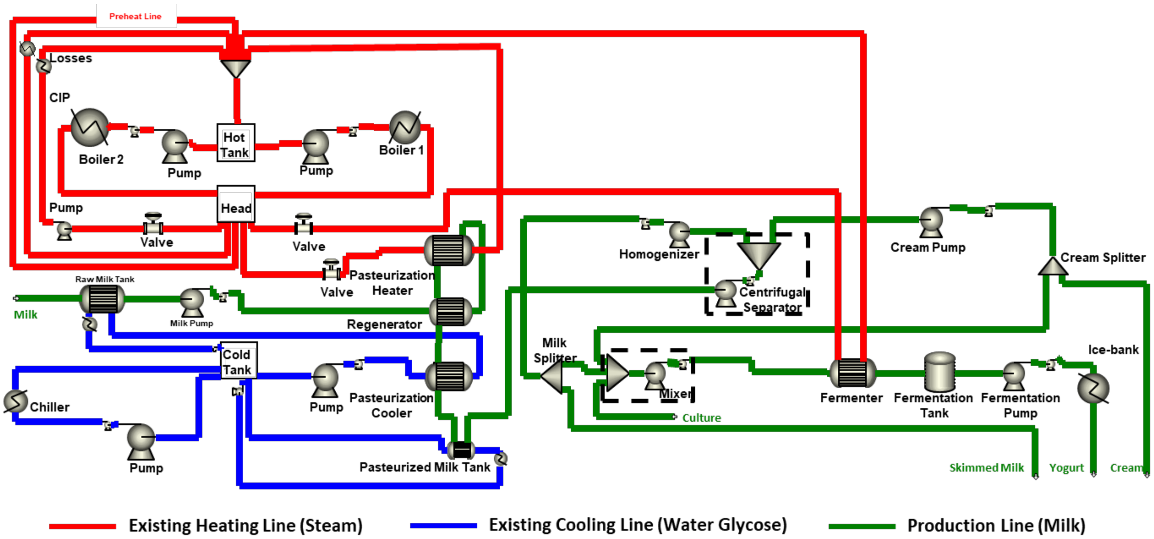

FIGURE 1. Schematic of Simulated Scenario A - the Dairy Plant.

Figure 2 presents the schematic of the simulated Scenario B for the STE integration to the processes. The STE system supports: (i) the cooling line as a cooling component connected to the cold tank in parallel to the existing chiller and (ii) the heating line as a heating component connected between the hot tank and the header in parallel to the existing boilers. In this scenario, the pasteurizer and fermenter are kept connected in parallel as same as Scenario A. Due to the steam returning with the high temperature from the pasteurizer, the Scenario C was considered to utilize the energy more efficiently (Figure 3).

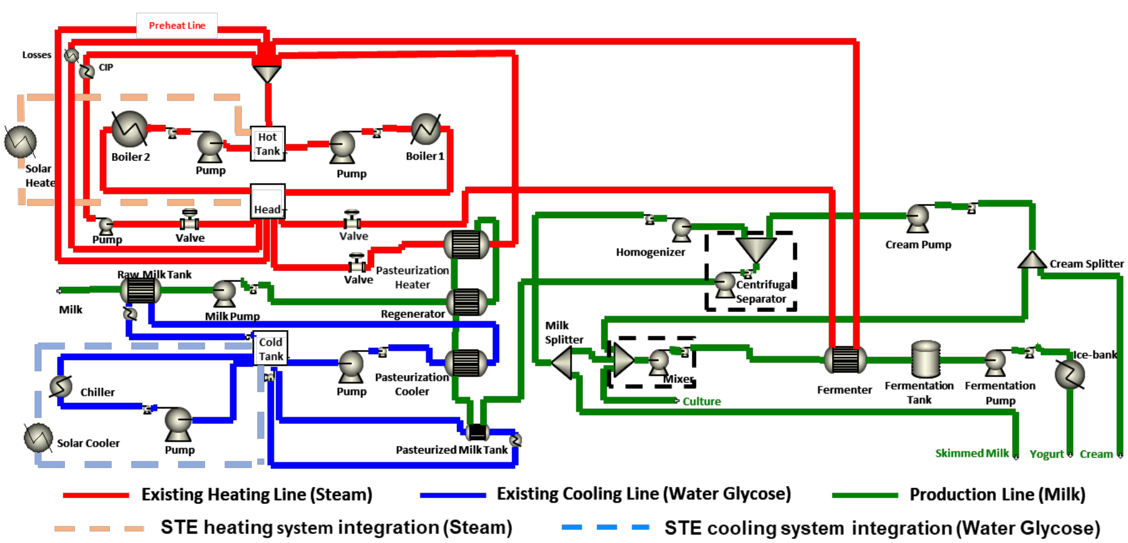

FIGURE 2. Schematic of integration Scenario B which provides steam to pasteurizer and fermenter in parallel.

It can be seen that the STEn heater and cooler connections were kept the same, however, the steam was provided from the header to pasteurization and fermentation processes on a single line in series. It is expected that the integration of the STEn system as an indirect heating/cooling system to the hot/cold tank will provide the higher solar contribution. On the other hand, the rearrangement of the pasteurizer and fermenter on a single line will utilize the excess heat in the system and reduce its required heating load.

The recovery of excess heat in dairy plants has been considered in few studies that used evaporators to pre-heat fluids in the boiler or inlet air in the spray driers to produce milk powder (11,12). It reduced the heat loads of the processes, final energy cost and GHG emissions by 20.8%, 33.8% and 45.7 %, respectively. The utilization of the excess heat from the pasteurizer to the fermenter in Scenario C demonstrated additional economic and technical benefits. Although it may involve an additional cost to the current process due to the connection of the pasteurizer to the fermenter, the total heat capacity of the company is reduced by around 200 kW and capacity of the integrated STE system by 91 kW as compared to Scenario B. This approach requires a lower number of STEn collectors leading to a more cost and space efficient solution. It can be concluded that the recovery of the excess heat can reduce the required heating load and enhance the overall efficiency of the processes.

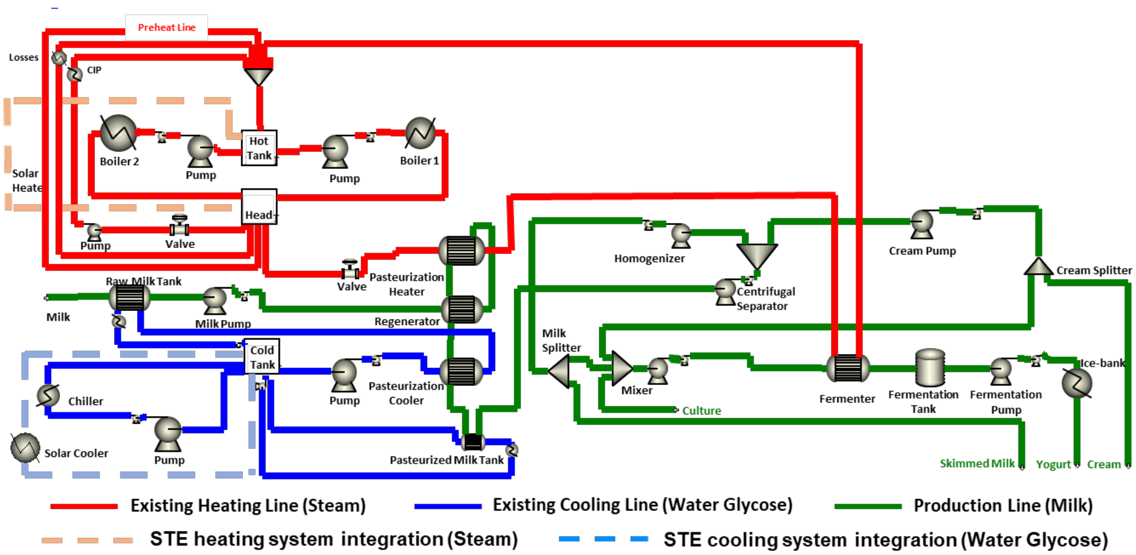

FIGURE 3. Schematic of integration Scenario C which provides steam to pasteurizer and fermenter in series.

Table 2 presents the nominal capacity requirement for Scenario A, Scenario B and Scenario C. It can be seen that the capacity of the conventional heating and cooling systems in Scenario A were 641.4 kW$_{th}$ and 206.2 kW$_e$, respectively, and an additional electric load of 142.8 kW$_e$. The integrated STEn system in Scenarios B and C reduced the capacity of the conventional heating system to 401.2 kW$_{th}$ and 220.9 kW$_{th}$ and the capacity of the conventional cooling system to 128.6 kW$_e$ and 128.6 kW$_e$., respectively. According to the results, Scenario C showed to be the more technically efficient due to the rearranging of the pasteurizer and fermenter on a single heating line and utilizing of the excess heat.

TABLE 2. Nominal capacity requirement for different scenarios

	Scenario A	Scenario B	Scenario C
Electric Load [kW$_e$]	142.8	142.8	142.8
Conventional heating [kW$_{th}$]	641.4	401.2	220.9
Solar thermal heating [kW$_{th}$]	0	240.2	133.3
Conventional cooling [kW$_e$]	206.2	128.6	112.1
Solar thermal cooling [kW$_{th}$]	0	77.6	93.4
Solar contribution (%)	0%	32%	32%
Total capacity - solar system [kW$_{th}$]	0	317.8	226.6
Total capacity - conventional systems [kW$_{Total}$]	847.6	529.8	332.9
Total capacity required [kW$_{Total}$]	990.4	990.4	702.3

Table 3 presents the SEC per kg of milk, yogurt and cream. It was found that the Scenario A had the SEC of 0.339 MJ per kg of milk, 0.659 per kg of yogurt and 0.390 per kg of cream. Those results showed to be consistent with the literature that presented the overall SEC for milk to be 0.3-0.8 MJ/kg, yogurt 0.47-1.2 MJ/kg; and cream 0.18-1.0

MJ/kg (15). Scenario B had the same SEC as Scenario A as they had the same operational conditions with 32% replacement of conventional with solar energy. Scenario C reduced SEC to 0.218 MJ per kg of milk, 0.576 MJ per kg of yogurt and 0.268 MJ per kg of cream, which resulted with the reduction of up to 36% compared to the Scenario A and Scenario B.

TABLE 3. Specific energy consumption per product for different scenarios

SEC [MJ/kg]	Scenario A	Scenario B	Scenario C	Literature (12)
Milk	0.339	0.339	0.218	0.3-0.8
Yogurt	0.659	0.659	0.576	0.47-1.2
Cream	0.390	0.390	0.268	0.18-1.0

CONCLUSIONS

In conclusion, thermal processes in a dairy plant were analyzed and simulated for STEn integration with developing of two new scenarios presented as B and C. The current dairy process presented as Scenario A showed a thermal and electric load of 847.7 kW and 142.8 kW, and a SEC per kg of milk, yogurt and cream of 0.339 MJ/kg, 0.659 MJ/kg, and 0.390 MJ/kg, respectively. Scenario B demonstrated that the conventional thermal load could be reduced to 529.8 kW within the same SEC compared to Scenario A. Scenario B demonstrated that the conventional thermal load and the specific energy consumption per kg of milk, yogurt and cream can be reduced to 332.9 kW, 0.218 MJ/kg, 0.576 MJ/kg and 0.268 MJ/kg. It can be seen that Scenario C was up to 36% more efficient compared to the other two scenarios due to the re-use of any excess heat that eliminated heat losses.

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