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Design of Solar Thermal Hot Water System for Industrial Processes

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Rising sea levels, flash floods, energy crises, and increasing global temperatures are some of the side effects of the ever-increasing use of fossil fuels. The analysis of global energy resources shows a gap between fossil fuel use and renewable energy. Of these, solar energy currently ranks the lowest in usage by industry. Solar energy is abundant, non-polluting, and can satisfy the heat demand of low to medium-temperature range industrial processes, but an appropriate methodology is required for its uptake. Pinch Analysis determines the minimum hot utility required, and solar thermal energy satisfies 53 % of this requirement. Analysing the process interaction with the solar thermal fluid can give a better strategy for suitable integration. The process is analysed to determine the Heat Exchanger Network (HEN), and a solar thermal stream is introduced in the network. It becomes pertinent to see the effect on HEN and solar thermal collector areas. A single stream from the process is used to analyse and establish the interaction between the solar thermal system and the process. This analysis leads to developing a methodology for appropriately integrating solar thermal energy in industrial processes.

1. Introduction

Many industrial processes require thermal energy for production, and traditionally this requirement is met by fossil fuels. Solar thermal energy is a promising option for providing industrial thermal energy, but it accounts for just 45 GW_{th} of industrial process heat, and this is just 9 % of the installed capacity of solar thermal heat in 2021 (IEA SHC, 2022). Applying solar thermal energy for industrial process heat would contribute to Sustainable Development Goals (SDG): Affordable and Clean Energy, SDG 7, Sustainable Cities and Communities, SDG 11 and Climate Action, SDG 13. Pinch Analysis is a universally accepted method of analysing the heating requirements of industrial processes (IEA SHC, 2015). It has been extended to the domains which are relevant to the concerns around sustainability today (Tan et al., 2015). Pinch Analysis provides a framework for designing heat recovery systems by identifying processes in terms of sources and sinks (Canmet Energy, 2004), and it has resulted in significant energy savings and reduced operating costs (Klemeš et al., 2018). Several studies have used Pinch Analysis to identify potential energy savings by replacing minimum hot utility requirements with solar thermal energy. For example, Atkins et al. (2010) have used Pinch Analysis to efficiently integrate solar thermal in a dairy process plant for a constant flow rate. Similarly, Quijera et al. (2011) used Pinch Analysis in a dairy plant in a location where diffuse solar radiation is more than direct radiation and from solar thermal integration, they have shown a reduction in fossil fuel usage of 11.4 %. Nemet et al. (2012) observed that applying solar thermal energy helps achieve environmental objectives in a process plant, and solar thermal energy can be treated as a solar utility. In another study, Eiholzer et al. (2017) optimised direct heat recovery from a batch process in a brewery and identified the contribution of 7.7 % of the heat demand by solar thermal energy. Martínez-Rodríguez et al. (2022) have used Pinch Analysis to integrate solar collectors in the bioethanol and dairy industries, resulting in significant area reductions of up to 49 % and 24 %. Masera et al. (2023) assessed dairy process thermal demands, reviewed solar thermal applications, and proposed an integrated concept design with solar collectors, thermal storage, absorption chiller, and steam drum. Despite these previous studies, there needs to be more consideration of the solar thermal system, including the heat exchange with the process.

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Kulkarni et al. (2007) have determined the design space for a solar water heating system. The design space provides a practical range for the solar collector area and the hot water storage volume to provide hot water in the desired temperature range. However, the dilute and variable nature of solar energy poses a significant barrier to integrating with industrial processes, either due to the transient availability of solar energy or variable demand from the industrial process.
This work uses a case study of a dairy plant to address the following objectives:

- Identify the design space for the solar thermal collector area and the storage tank volume.
- Establish the interaction between solar thermal fluid and a single stream in the dairy process for a Heat Exchanger Network (HEN) design.
- Study the relationship between the inlet temperature, outlet temperature, and mass flow rate of the solar hot water stream during a 24 h period of operation.

2. Problem statement and mathematical formulation

Integrating solar thermal energy with industrial processes requires consideration of factors such as energy demand, availability of solar energy, and process heat requirements. These factors make integration a complex task. The design and implementation of solar thermal systems are affected by location, weather conditions, and the size of the industrial process. There is a need to develop an approach that can effectively integrate solar thermal energy into industrial processes while ensuring energy efficiency and cost-effectiveness. A schematic of a solar thermal system providing the hot utility requirements of an industrial process is shown in Figure 1a.

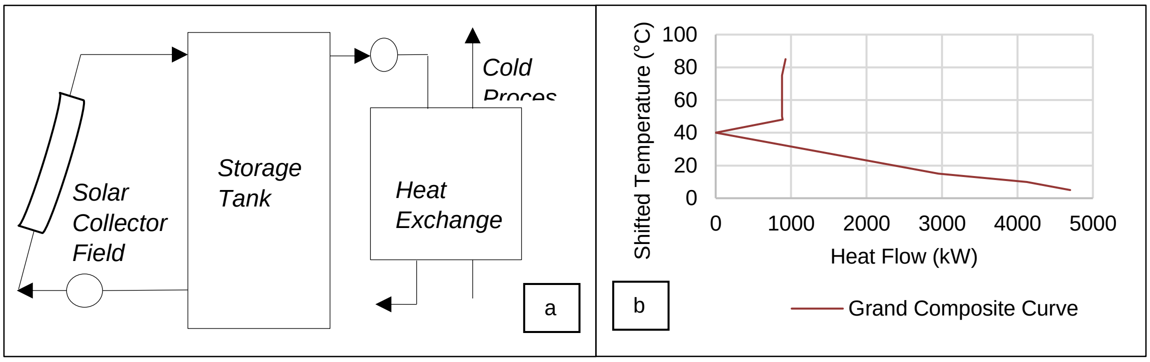

Figure 1: (a)Solar Thermal System schematic for process demand and (b)Grand Composite Curve for the process streams used in the analysis

In the schematic, the collector field is a set of parabolic trough collectors. The solar radiation is incident on the collector field, and the solar useful heat gain rate (q_u) is calculated (Sukhatme and Nayak, 2008) as:

$$q_u = F_R \cdot (W - D_o) \cdot L \cdot [S - \frac{U_l}{C} \cdot (T_{fi} - T_a)] \tag{1}$$

After passing through the collector field, the water goes to a storage tank. The relationship between the storage area, A_{st} and storage volume, V_{st} (Kulkarni et al., 2007), is given as:

$$A_{st} = 5.54 \cdot (V_{st})^{2/3} \tag{2}$$

When water attains a minimum required temperature, it is sent to a heat exchanger to supply heat to a cold process stream. This minimum temperature is calculated from the energy balance for a well-mixed storage tank. The energy balance is expressed in the form of a differential equation:

$$\rho \cdot c_p \cdot V_{st} \cdot \frac{dT_{st}}{dt} = F_R \cdot (W - D_o) \cdot L \cdot \left[S - \frac{U_l}{C} \cdot (T_{fi} - T_a)\right] - q_{Ls} - U_{st} \cdot A_{st} \cdot (T_{st} - T_a) \tag{3}$$

Where ρ is the density of water (1,000 kg/m^3), c_p is the heat capacity of water (4,180 J/(kg·K)), T_{st} is the storage tank temperature at any in a time step in °C, F_R is the collector heat removal factor (1.09), W is the aperture of the concentrator (1.25 m), D_o is the absorber tube outer diameter (0.041 m), L is the concentrator length (3.65 m), S is the absorbed flux in every time step of analysis (W/m^2), U_l is the collector loss coefficient (13.28 W/(m^2·K)), C is the concentration ratio (9.31), T_{fi} is the inlet temperature to the collector in °C and is calculated for every time step, T_a is the ambient temperature in °C, and it varies during the period of analysis, q_{Ls} is the process load/demand met by solar thermal energy in W and is calculated for every time step. U_{st} is the storage loss coefficient. The constant values of the parameters are taken from Sukhatme and Nayak (2009). The final storage tank temperature T_{stf} at the end of a time step is determined by the solution of Eq(3) which is given by Eq(4):

$$\frac{X - Y \cdot (T_{stf} - T_a) - q_{Ls} - U_{st} \cdot A_{st} \cdot (T_{stf} - T_a)}{X - Y \cdot (T_{sti} - T_a) - q_{Ls} - U_{st} \cdot A_{st} \cdot (T_{sti} - T_a)} = \exp(\frac{-(Y + U_{st} \cdot A_{st}) \cdot t}{\rho \cdot c_p \cdot V_{st}}) \tag{4}$$

where, $X = (W - D_o) \cdot L \cdot S$ and $Y = (W - D_o) \cdot L \cdot U_l / C$

The hot stream enters the heat exchanger at the initial temperature, T_{hi} and leaves at the outlet temperature T_{ho}. The hot stream inlet temperature is equal to the final storage tank temperature T_{stf} and its mass flow rate is $\dot{m}_h$. A cold stream enters the heat exchanger at T_{ci} and leaves at T_{co} with a fixed mass flow rate $\dot{m}_c$. The variation of T_{stf} and $\dot{m}_h$ with time during the day is studied to establish the interaction between the solar thermal system and the process system.

3. Methodology

This section presents the systematic approach used to analyse and design the solar thermal integration system. It begins with the selection of solar thermal collector, followed by the choice of the heat exchanger; subsequently, the identification of the optimal cold stream to be heated using Pinch Analysis is discussed. Finally, the generation of design space for further optimisation is described.

Selection of solar thermal collector

Appropriate technology is selected depending upon the desired temperature for the working fluid of the solar thermal system and allowed stagnation temperature. The line-focusing solar thermal collector, such as a parabolic trough collector, is used to achieve the temperature range of 60–300 °C (Sharma et al., 2017) and is suitable for low to medium heat application.

Selection of heat exchanger

A counter-current heat exchanger (with heat exchanger characteristic, UA = 10 kW/°C) is selected for providing heat to the process stream from the solar thermal system. A minimum approach temperature of 10 °C is to be maintained in the heat exchanger between the hot and cold streams for an efficient heat transfer.

Selection of cold stream to be heated using Pinch Analysis

Principles of Pinch Analysis are employed to select an appropriate cold stream for integration with the solar thermal stream within the industrial process. This analysis helps determine temperature profiles, assess heat availability, and identify integration potential, enhancing the efficiency of solar thermal utilisation. The most suitable cold stream is chosen by evaluating temperature ranges and heat capacity rates, resulting in optimised heat recovery and improved energy efficiency.

Design space generation

For design purposes, it is assumed that the net heat gain and loss from the storage tank over 24 h is zero, and the temperature profile obtained is a non-fluctuating curve. This is a steady state condition of heat transfer from the storage tank (Kulkarni et al., 2007) given by the equation:

$$\int_0^T \rho \cdot c_p \cdot V_{st} \cdot \left(\frac{dT_{st}}{dt}\right) \cdot dt = 0 \tag{5}$$

The solar thermal system is assumed to provide all the thermal requirements of the suitable cold process stream without any auxiliary heating unit in place. Solar fraction, F = 1 for this case. The temperature of the storage tank must be greater than 90 °C for the entire analysis period to satisfy the process demand.

$$T_{st} \geq 90\ ℃ \tag{6}$$

The solar thermal collector fluid in this case is pure water. For some application it may be appropriate to use an additive to increase the boiling temperature of the fluid. However, in this example the water is pressurised to 2 bara to suppress boiling. The maximum temperature for water is 120 °C to satisfy process requirements.

$$T_{st} < 120\ ℃ \tag{7}$$

With the conditions of Eqs(6) and (7), different designs for the combination of collector area and storage volume are obtained and form the design space. This design space is demonstrated through an example:

Table 1: Solar thermal parameters for design space

Location	Concentrator Geometry	Day	Mass flow rate in collector loop	Storage
Pune, India Latitude -18.53° Longitude -73.85°	Aperture=1.25 m Length = 3.6 m Concentration Ratio= 9.31	15 April 2012	0.5 kg/s	Glass wool insulation= 0.14 m Storage Loss coefficient, U_{st}= 0.23 W/(m^2·K)

The design space is shown in Figure 2. It is the area between the upper bound 'Minimum storage temperature constraint' curve and the limiting storage temperature line. This region satisfies the temperature constraints of the storage tank to satisfy the process requirements. The minimum collector area, the maximum storage volume, is given by 'b', and the maximum collector area, the minimum storage volume, is given by 'a'. Going below 'a' would increase the water temperature beyond 120 °C, increasing the pressurisation of the working fluid. Going to the left of 'b' will result in a storage temperature of less than 90 °C. The curve 'ab' gives the Pareto Optimal front and gives the designer a choice for optimising the cost associated with the solar thermal system by considering the collector and storage tank cost as conflicting objective functions.

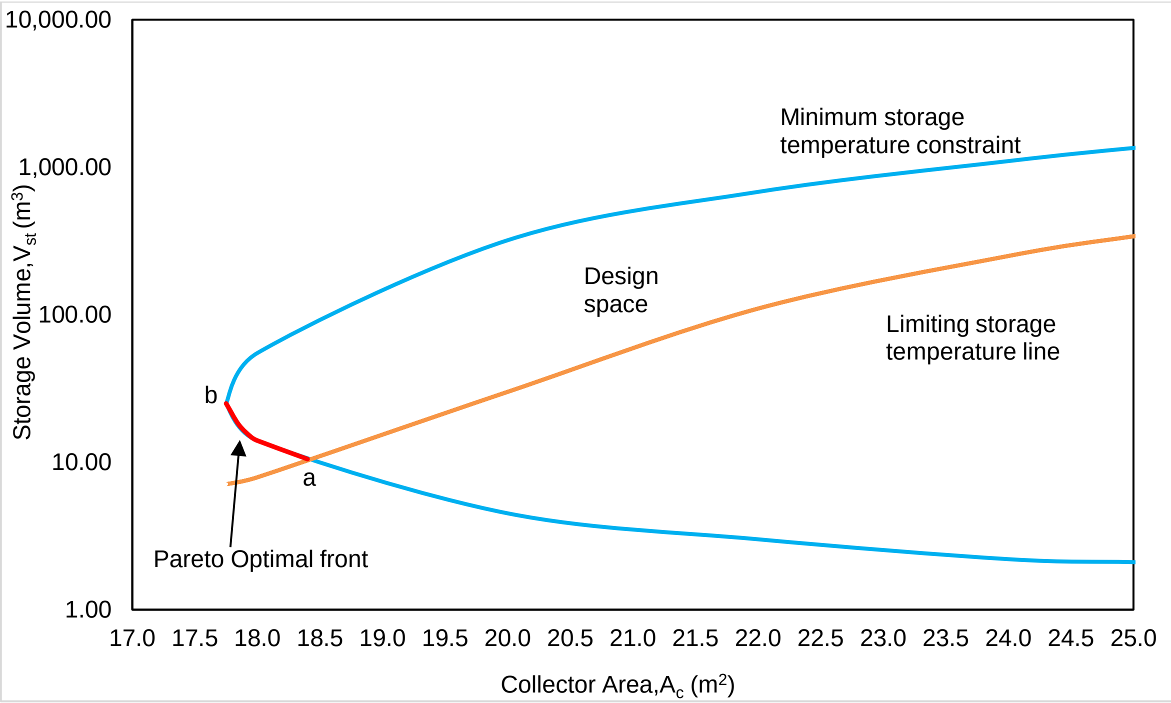

Figure 2: Design space for storage volume and collector area at unity solar fraction (F = 1)

4. Case study

Table 2: Process streams running in the dairy plant (Atkins et al., 2010)

Name of the stream	Supply Temperature, T_s (°C)	Target Temperature, T_t (°C)	Heat capacity Flow rate (kW/°C)	Type of stream
Cold Water	45	15	118.5	Hot
Cream	45	80	4.8	Cold
Skim milk	45	10	110.6	Hot
Cream A	80	10	4.8	Hot
Raw milk	10	43	115.8	Cold

To demonstrate the proposed approach, data of a dairy process plant (Atkins et al., 2010) is considered. This case study explores the possible options of retrofitting the milk powder plant with a solar thermal system. The plant operates from August to April and is non-operational for three months during the winter season in the region. Table 2 represents various process streams that are running in the dairy plant.
The temperature profiles and heat transfer characteristics of the streams are examined by conducting Pinch Analysis. The analysis gives a Pinch point of 40 °C and is shown in Figure 1b. This Pinch point is a reference for identifying potential heat recovery opportunities within the process. Based on the Pinch Analysis, the heat recovery potential of each cold stream is evaluated. For example, the "Cream" stream has a supply temperature of 45 °C and a target temperature of 80 °C, while the "Cream A" stream has a supply temperature of 80 °C and a target temperature of 10 °C. These streams and others are assessed to determine their compatibility with the solar thermal stream. The Pinch Analysis identifies the "Cream" stream as the most suitable cold stream for solar thermal integration considering factors such as temperature range, heat capacity rates, and process requirements. This stream exhibits the highest potential for effective heat recovery and alignment with the solar thermal system's energy output. After identification, analysis is done for Pune in India on 15 April. The radiation data is taken from IMD GoI (2009). Variation in outlet temperature of the hot stream and its mass flow rate in time step of 1 h is estimated and compared with storage tank temperature. The analysis is done for the minimum collector area (17.75 m^2) and maximum collector area (18.4 m^2) identified from Pareto Optimal front in Figure 2. Outlet temperature and mass flow rate can be calculated by fixing the heat duty, which is 168 kW. The results are calculated using Eqs(8) and (9) (Sukhatme and Nayak, 2009).

$$Q = \dot{m}_h \cdot c_p \cdot (T_{hi} - T_{ho}) \tag{8}$$

$$Q = UA \cdot \triangle T_{LM} \tag{9}$$

Where, $\triangle T_{LM}$ is the Log Mean Temperature Difference (LMTD) that needs to be maintained in the heat exchanger.

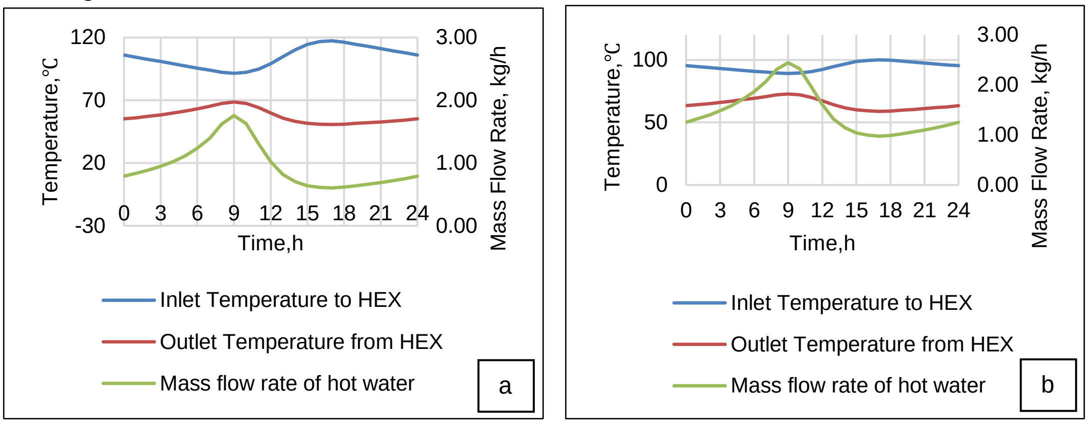

Figure 3: Variation of outlet temperature and mass flow rate with respect to inlet temperature for a) collector area of 18.4 m^2 and b) collector area of 17.75 m^2

Figure 3 shows the variation in the heat exchanger's inlet and outlet temperatures. The profiles of both temperatures follow an opposite trend during the 24 h. At 09:00 h, the least heat transfer occurs between the hot and cold fluid; at 16:00 h, the maximum heat transfer occurs. When the collector area is smaller, the solar thermal system yields a lower temperature for the hot stream than a larger collector area. Additionally, when the hot water entering the heat exchanger has a lower temperature, a higher mass flow rate is required to meet the heat duty requirement. The difference between the hot stream's inlet temperature and outlet temperature is higher in the case of a higher collector area. The temperature of hot water going in the heat exchanger is higher in the case of a larger collector area. The fluctuation in mass flow rate is lower for higher collector areas and lower storage volumes. The smaller change in the mass flow rate has implications for load pump design. When there is a narrower range of mass flow rates for the pump, the cost of operation also comes down. To satisfy the process stream requirement, the designer can make an economic decision for the process plant. Also, the optical efficiency(η_o) of the collector is calculated as 66 %, which is constant and a characteristic of the solar thermal collector. There is variation in the instantaneous efficiency(η) of the collector in the range of 7 % (when the solar radiation and useful solar heat gain rate is minimum) – 21.3 % (when solar radiation and solar useful heat gain rate is maximum). The outlet temperature of water from the collector increases with increasing efficiency. The low values of instantaneous efficiency are due to the high value of the inlet fluid temperature for the calculated value of the concentration ratio. The storage tank used in the analysis is insulated, and significant heat loss takes place from its surface after sunset when there is no solar radiation. There is a maximum drop of 10 °C in the storage tank temperature till sunrise the next day. Based on this study, a collector area of 17.75 m^2 is recommended for satisfying a selected cold stream in a dairy process plant.

5. Conclusions

The design space allows a designer to choose the combination of solar thermal collector area and storage volume from a feasible region. The minimum and maximum collector area is obtained to be 18.4 m^2 and 17.75 m^2. The corresponding variation of outlet temperature of the hot stream and its mass flow rate for a collector area of 18.4 m^2 is in the range of 54 °C – 69 °C and 1.76 kg/h – 6 kg/h. These variations in the case of a collector area of 17.75 m^2 are observed as 63 °C – 73 °C and 1 kg/h – 2.44 kg/h. These parameters are studied to satisfy the process stream requirements and establish the interaction between the solar thermal and process systems. This interaction can lead to a better pump design. This interaction is established when only one cold process stream is involved, and there is a requirement for one heat exchanger. In future work, multiple cold process streams can be included for establishing the interaction, and Pinch Analysis can better understand this interaction. When considering multiple streams, the utilisation of auxiliary heating sources such as heat pump will be explored. At present, the storage tank volume is high. There will be a focus on reducing storage volume while using external heating sources, which can add to the system's capital cost. This methodology will give a better understanding of reliability in the design of the solar thermal system.

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