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Design and simulation of efficient solar thermal water heating system for textile industries in Pakistan

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ABSTRACT

Pakistan is facing a severe crisis of energy since 2004. The core causes behind this crisis of energy are the lack of usage of advanced tools in policy development and planning, poor governance and dependency on other sources of energy which are also limited. In this research the design of a solar thermal system to produce hot water at a specified temperature has been presented as solar energy is available in abundance. A flow rate of 80 tons per day of hot water has been assumed. This system may run for 16 hours a day and it will require 5 tons of water per hour at the input. Water at ambient temperature of 25℃ enters the system and hot water at 75℃ is produced by the system. This design is implemented on TRNSYS software which validates the temperature achievement of 75℃ at outlet. It is shown that the collector area of flat plate solar collectors is 600m^2. This temperature configuration is an essential requirement for textile industry and it is achieved efficiently. It is a good replacement for the industry working with expensive energy sources like diesel, gas or furnace oil.

1. Introduction

Pakistan currently grappling with a severe energy crisis, with various factors contributing to this pressing issue [1]. The reasons behind this crisis are the ever-increasing demand for energy due to population growth and rapid urbanization. The population explosion in Pakistan has led to a surge in energy consumption, overwhelming the existing infrastructure and causing frequent power outages. Another crucial factor contributing to the energy crisis is the inefficiency and outdated technology used in power generation and distribution. Many power plants in Pakistan are outdated, resulting in high transmission losses and low energy efficiency. The outdated infrastructure not only increases the cost of energy production but also leads to frequent breakdowns and blackouts [2].

The above-mentioned reasons are leading to the fact that there is a link between the major energy crisis and the lack of usage of advanced tools in policy development and planning, poor governance and dependency on limited sources of energy [3].

Usage of solar energy for thermal applications is not very widespread in Pakistan unlike photovoltaic systems. Various systems are available internationally to provide hot water and steam through solar collectors, but they are unaffordable for local industry and a consistent supply of high-quality steam at required flow rates calls for scalability which is unfeasible for many reasons. With a lot of work already done in solar thermal domain and a certain level of maturity achieved in the technology, this research work focuses on development of a system for solar thermal hot water to fulfil the need of local industry. With engagement of industrial partner, a fresh insight is gained to allow development of system which facilitate penetration of solar thermal energy systems to supply growing needs of our urbanizing society. This essentially means analysis of their hot water requirements for the design as well as operation of the system. This will consolidate government's current efforts to reduce carbon footprint by moving towards green technologies. A hybrid operational design as well as real time operation of such system is expected to reduce capital cost and at the same time could bring an attractive saving with a feasible return of investment (ROI) period. This will consolidate government's current efforts to reduce carbon footprint by moving towards green technologies. Since the thermal and mechanical design for industrial applications is vastly more challenging than domestic requirements [4], we focus to this direction in this research.

A considerable share of research to fulfil energy requirement in the domestic and industrial region is for process heating. But it is depending upon the requirement of the industry, products and processes being used.

For the current project, Industrial companion is a textile group which deals in international and local market. Their process needs large quantity of hot water and steam which presently they provide using biofuel through boiler along with a backup by using natural gas.

1.1 Harvesting from the solar system

To harvest solar thermal energy, various technologies exist with a wide spectrum of characteristics. Concentrating collectors used with sun-tracking technology having more concentration ratio and can achieve more thermodynamic efficiency and working fluid temperature than non-concentrating collectors. There are four major categories of Concentrating Solar technologies used to collect sunlight and concentrate in order to convert it into heat named as central receiver collectors or solar tower collectors, parabolic dish, parabolic trough collectors and linear Fresnel [5]. These systems are used to generate the steam from water.

The research starts with the study of different styles of collectors for the required application and the design is developed by using Flat Plate Collectors as we need the hot water not the steam.

The TRNSYS software used for the analysis of solar thermal systems which gives a better opportunity to optimize and analyze the assumptions according to the design. This design is implemented on TRNSYS software to calculate the temperature of outlet from the system.

2. Literature Review

The air contains CO_2, CO, NOx, particulate matter and formaldehyde [6]. Global warming caused by carbon dioxide has become a serious problem that needs to be addressed. The effective usage of renewable energy, especially produced form solar system, is an encouraging solution to the global warming problems and a means to achieve viable human development. The sun emits a lot of energy into the atmosphere: the energy in Earth's upper atmosphere is 174 PW where, 1 PW = 1015 W. When the energy reaches the Earth's surface, the total solar radiation falling from the atmosphere (16% total absorption and 6% reflection) and clouds (3% absorption and 20% reflection) is halved, and other solar radiation i.e: 51% (89 PW) reaches to the oceans and land [7].

The cost of energy is growing day by day due to increase in utilization of the energy. The energy requirements can be fulfilled by creating new sources of energy and by increasing the efficiency of current available sources. By 2050, renewable energy is expected to require 85 percent of the total energy [8]. The conventional solar systems are having some technical and economic problems. To reduce these problems, the heat pipes used in conventional solar systems are under consideration [9]. A significant portion of the ultimate energy of the industrial sector utilization is for process heating systems, these systems requires medium and low temperatures. Solar thermal heating systems are the cleanest and renewable energy generation opportunities in countries where sun-shines most of the time all over the globe [10].

After conduction of an experimental study in which fixed 40 degree tilted angle towards south and biaxial parabolic solar tracking are compared. The results showed that up-to 46.64% energy can be generated with solar tracking instead of fixed sunlight collection. This is significantly greater energy production from the same size of solar concentrated system [11]. Shafien has experimentally investigated the effects of solar tracking with electromechanical systems using different solar tracking systems on the voltage and current characteristics of flat plate photovoltaic systems (FPPVs): Two axes, a north-south axis, horizontal axis and, an east-west axis, vertical axis. The results show that the measuring properties of the volt-ampere on the tracking surface are much higher than the fixed one, which increases the electrical power by 43.87%, 37.53%, 34.43% and 15.69%, respectively [12]. In addition, the maximum tilt angle is determined from 13° in summer to 61° in winter [13].

Over the last three decades, a large volume of research published on PVT (PV-Thermal) collectors is carried out. Historic and thematic overview of PVT is presented in a research and it also discussed various research issues. This research concluded that PVT liquid is suitable for domestic and PVT air is suitable for large scale buildings [14].

Compound parabolic collector (CPC) systems are fabricated for practical steam generation applications, are easy to operate, have a lesser cost than other existing concentrating solar collectors (CSC) available and have a greater opportunity to reduce costs. About 30 m2 aperture area experimental unit for steam generation was installed, which conducted steam production tests. System performance analysis shows that thermal efficiency can be increased by up to 71%. Based on the geometry, this proposed compound parabolic collector system requires a much smaller mirror area than the conventional compound parabolic collector design and requires tilt adjustment once per day during 6 hours of daily operation. [15].

Design, evaluation and evaluation of parabolic trough concentrator (PTC) having length of 4.88 m, rim angle of 45°, and 5.8 m2 aperture area. It is made of aluminum, and the assembly processes or production don`t require skilled labour or complex technology. Since parabolic trough concentrator is designed to produce hot water and steam with low enthalpy, it structures an exposed receiver design without a glass-cover to decrease transportation and production costs. After determining the mechanical behaviour of parabolic trough concentrator in structures under different artificial wind loads through stress analysis of finite element, the solar thermal tracking system is calculated when the sun tracking system faces the sun from north to south. The theoretical characteristics of the parabolic collector depend on the optical properties of the material used, geometrical calculations of the parabolic collector, and several defects caused by the design of the parabolic collector system. The thermal efficiency of parabolic trough concentrator is determined according to the international ASHRAE Standard. Achieve peak efficiency of approximately 60% [16].

The fabrication of parabolic trough collectors with low cost for processing industrial heat from temperature range 70°C to 250°C is critical for the technology of solar thermal system. This can be achieved through a design called UNIVPM.01. This is a parabolic concentrator prototype with 9.25 concentration ratio and 90 degree rim angle, made of extruded polystyrene and fiberglass. [17]. A model of a steam-generating heat exchanger was developed and tested to power a 3 kW generator. Based on the test results, a set of three steam heat exchangers was developed to power a 50 kW steam turbine. [18].

The thermo-photo-voltaic (TPV) devices and the radiant burner is used for heating purposes. The mini co-generator (self-powered-heater) is experienced to test the performance in a research, this indicates that the combustion parameters affect the performance of the radiant burner. Surface burners should be used with a high degree of care. Determine the power density of the stove and maximum radiant efficiency. The combustion variables can be affected by the radiant burner performance [19]. Scheffler concentrator are able to reach temperatures of up to 200°C. It is used in the cooking food and production of solar thermal power [20].

A rooftop-mounted hybrid PV/solar thermal water system used for power generation is linked to a circulating liquid flow heat retrieval system, while hot water supply can be heated by extracted heat from the system. Photovoltaic equipment and are traditional solar thermal systems are less efficient than latest hybrid systems, while during the production and installation stages, they tend to be less environment friendly [21].

Concentrating PV thermal power (CPVT) produced from solar collector system is most widespread in both industrial and domestic solar energy. Compared to standalone photovoltaic or hybrid PVT or PV systems, CPVT collectors provide much higher thermal and electrical energy as the solar input into the unit is maximized through energy-efficient concentrators. CPVT collectors are highly capable tools in the market and in the near future they are having higher ability to lesser the share of previously used old power production systems [22]. Concentrated photovoltaic-thermal systems use optical filters based on liquid nano-materials that can absorb heat from sun and produce electricity and have not been examined in home applications. The small-scale CPV-T dynamic simulations having spectral filtration systems under climatic conditions were conducted in Tucson, Arizona. After multiple simulations in a long time, it is calculated that CO2 can be reduced from the environment for a family up-to 1,317 tons in year by this CPV-T proposed system. Furthermore, if this system is applied to ten percent American homes, total compensation is equivalent 3.19 million automobile`s emission of greenhouse gas annually [23].

In many solar applications, space heating, water heating and cooling are using substantial energy. The energy requirement for hot water production is a major part of the today`s energy requirement. Collectors are a key aspect of meeting the energy efficient requirements of the required applications. Evacuated tube collectors provide excellent performance, especially for normal temperature requirements. Many researchers around the world have studied heat pipes usage to overcome this problem of inefficient evacuated tube collectors. This is one of the most important developments in the region. Another major advancement in phase-changing materials with evacuated tube collectors has had a major influence on the performance. This technology is reliable, efficient and easy to use [24].

The requirement of thermal energy is in the temperature range of about 250°C, but for the development of applications for heating processes at industrial level, these systems are rarely used in the industrial and domestic sector. Moreover, the benefits of laboratory-based solar water heaters can be misleading, so site measurements are important for assessing the financial stability of the system [25].

Implementation of the Sustainable Development Goals (SDGs) in Pakistan's industrial sector is essential for growth of economy, innovation, industrial sector and energy sector of Pakistan. Integrating solar parks will play a vital role in implementation of SGDs with textile industry. With the limited means of resources, it is becoming increasingly difficult to achieve these goals in the Pakistani thermal sector [26].

In the textile industry, a grand total of 14 systems known as Solar heating for industrial processes (SHIP) are utilized. Among these systems, four are situated in European countries, specifically, Spain, Greece and Germany. Three of these systems employ a flat plate collector to produce hot water, ranging from 33°C to 90°C, which is utilized for different tasks such as painting, drying and washing. One of these systems uses parabolic trough collector to produce heat at 140°C for unspecified processes. [27]

Solar heating is a proven technology for producing hot water [28]. This technology is rarely used especially in Pakistan. The requirement of the textile leather processing is 75 °C of hot water, but unfortunately there is not a suitable system available in Pakistan`s market. For meeting the requirement of the leather processing industry of Pakistan, it is required to make a system to produce 75 °C of hot water. The novelty of this research is to develop a system of hot water for the leather processing industry in Pakistan.

3. Design of the System for Water Heating

The requirement of the leather processing industry for hot water is 80 tons per day of hot water which means if the system is running for 16 hours a day it will consume 5 tons of water per hour. The inlet temperature is 25 °C which is also called ambient temperature and outlet temperature is 75 °C per hour.

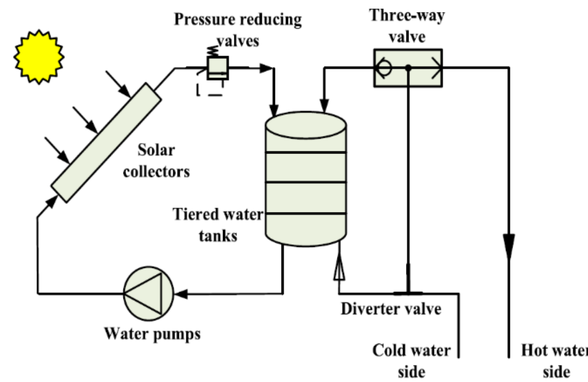

Fig. 1. Solar thermal collector system

Fig. 1 shows a solar thermal collector system for water heating [29].

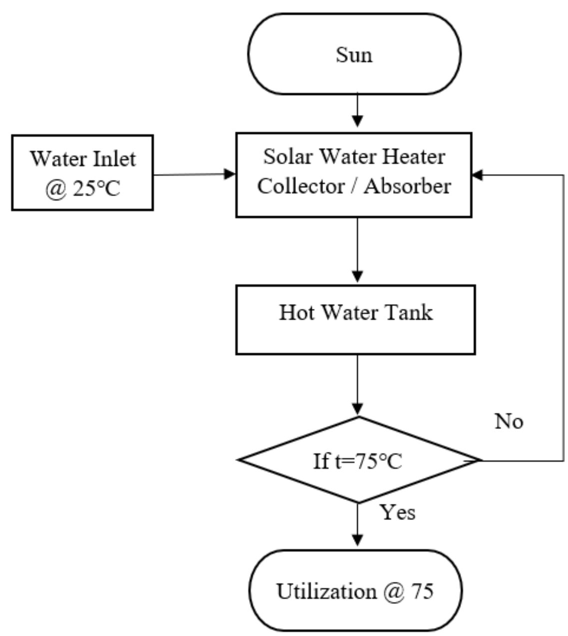

Fig. 2. Flowchart of solar thermal collector system

The flowchart of the system is shown in Fig. 2. So, if the system working for 365 days, the annual load is calculated in the form of energy by using the equation of specific heat capacity,

$$Q_L = m\, C_P (T_L - T_a) N \quad (1)$$

Where,

$Q_L =$ *Annual load in the form of energy*

$Q_{LS} =$ *Annual load in the form of energy available from solar*

$Q_{AUX} =$ *Annual Duty*

$m =$ *Mass flow rate*

$C_P =$ *Specific heat capacity*

$T_L =$ *Required fluid temperature*

$T_a =$ *Ambient temperature*

$N =$ *Number of days*

Now, put the required values in Eq. (1)

$$Q_L = 80{,}000 \times 4.18\,(75 - 25)365$$

$$Q_L = 334400 \times 50 \times 365$$

$$Q_L = 6102.8\ GJ/Year$$

If we assume the sun is available for 265 days, then the energy will be as,

$$Q_{LS} = 80{,}000 \times 4.18\,(75 - 25)265 \quad (2)$$

$$Q_{LS} = 334400 \times 50 \times 265$$

$$Q_{LS} = 4430.8\ GJ/Year$$

So, the annual solar fraction, the ratio between Q_{LS} and Q_L will be as,

$$\frac{Q_{LS}}{Q_L} = \frac{4430.8}{6102.8}$$

$$\frac{Q_{LS}}{Q_L} = 0.762$$

And annual duty auxiliary is, the difference between Q_L and Q_{LS} will be as,

$$Q_{AUX} = Q_L - Q_{LS} \quad (3)$$

$$Q_{AUX} = 6102.8 - 4430.8$$

$$Q_{AUX} = 1672\ GJ/Year$$

The major changes to make an accurate design are energy collected and energy supplied are functions of solar radiation, the ambient temperature and other atmospheric parameters such as humidity, wind, speed and clearness index.

Solar radiation intensity varies over the day and as well as over the year. As our solar thermal system design parameters are 80,000 liters of hot water at 75 °C from initial temperature of 25 °C in 16 hours. This is an open loop system.

Suppose the global radiation is, G,

$$G = 750\ {}^{W}\!/_{m^2}$$

By using Hottel-Whillier-Bliss equation,

$$Q_u = A_c[I_T F_R(\tau_\propto) - F_R U_L (T_i - T_a)]W \quad (4)$$

Where,

$Q_u =$ *Useful heat gain rate* (W)

$A_c =$ *Collector area*

$I_T =$ *Solar radiation intensity on inclined system*

$F_R =$ *Collector heat removal factor*

$U_L =$ *Overall loss coefficient*

$Q_u = A_c[I_T F_R(\tau_\propto) - F_R U_L (T_i - T_a)]W$

$F_R(\tau_\propto) =$ *Characteristics of collector*

$F_R U_L =$ *Characteristics loss coefficient of collector*

$T_i =$ *Inlet fluid temperature entering the collector*

$T_a =$ *Ambient temperature*

In this system which is open loop system, the fluid which is entering the collector is at the atmospheric temperature. So, in this system,

$$T_i = T_a$$

Also,

$$F_R U_L (T_i - T_a) = 0$$

Put this value in Hottel-Whillier-Bliss equation. So, the equation becomes,

$$Q_u = A_c[I_T F_R(\tau_\propto)]W \quad (5)$$

Let us consider the winter temperature and global winter radiation.

Where,

$$G = 750\ {}^{W}/_{m^2} = I_T$$

$$F_R = 0.65$$

So, the useful energy can be calculated by using equation of specific heat capacity as,

$$Q_u = mc_p(T_L - T_\alpha) \qquad (6)$$

$$Q_u = 80{,}000 \text{ X } 4.18\ (75 - 25)$$

$$Q_u = 16.72\ GJ$$

Now, put this value of useful energy into Eq. (5)

$$Q_u = A_c[I_T\, F_R\, (T_\alpha)]$$

$$16.72 = A_c(750X0.65X50)$$

$$A_c = 686\ m^2$$

This is the collector area where we use solar radiation on winter basis. Now, we use solar radiation according to summer basis. Because if we use the design of winter basis it will produce excessive heat in summer and also we have a high capital cost of the system. So, we will calculate according to the solar radiation on summer basis.

Global radiation (G) on summer is 972 ${}^{W}/_{m^2}$. Now, put 972 ${}^{W}/_{m^2}$ in Eq. 5

$$Q_u = A_c[I_T\, F_R\, (T_\alpha)]$$

$$16.72 = A_c(972X0.65X50)$$

$$16.72 = A_c(31592)$$

$$A_c = 529\ m^2$$

This is collector area when we use solar radiation on summer basis.

As we know that designing with 100% solar energy becomes economically unviable. We also need a backup or auxiliary for reliability. As we already calculate solar fraction 0.762. If we design on winter basis, it will produce in summer and if we design on summer basis, it will under produce in winter. So, corresponding system size that offers the maximum economic benefits. We take a mean of summer and winter collector area so, approximate are of collector is

$$A_c = 600\ m^2$$

From the design suggested for 80 tons/day of hot water at 75°C we can summarize the calculation,

$$O/P\ \ Temp. = \ T_L = 75°\text{C}$$

$$I/P\ \ Temp. = \ T_\alpha = 25°\text{C}$$

Annual load for 365 days, using Eq. 1

$$Q_L = mc_p(T_L - T_\alpha)\ N$$

$$Q_L = 80{,}000X4.18(75 - 25)365$$

$$Q_L = 334400X50X365$$

$$Q_L = 6102.8\ \ GJ/year$$

Annual load for 265 days, using Eq. 2

$$Q_{Ls} = 80{,}000X4.18(75 - 25)265$$

$$Q_{Ls} = 334400X50X265$$

$$Q_{Ls} = 4430.8\ \ GJ/year$$

So, solar fraction will be Q_{Ls}/Q_L ,

$$\frac{Q_{LS}}{Q_L} = \frac{4430.8}{6102.8}$$

$$\frac{Q_{LS}}{Q_L} = \ 0.762$$

And annual duty on Auxiliary, using Eq. 3

$$Q_{Aux} = 6102.8 - 4430.8$$

$$Q_{Aux} = 16.72\ \ GJ/year$$

Solar thermal system design for 80,000 litres of hot water at 75°C from initial temp of 25°C in 16 hours per day. We use an open loop system. Global radiation (G) on winter basis.

$$G = 750\ {}^{W}/_{m^2} = I_T$$

By using Hottel-Whillier-Bliss Eq. 4

$$Q_u = A_c[I_T\, F_R\, (T_\alpha) - F_R\, U_L\, (T_i - T_\alpha)]$$

In our system fluid is entering at ambient temp., using Eq. 5

So, $\qquad T_i = T_\alpha$

$$F_R\, U_L\, (T_i - T_\alpha) = 0$$

$$Q_u = A_c[I_T \, F_R \, (T_\alpha)]$$

Let $I_T = 750$ and $F_R = 0.65$ for winter useful energy can be calculated as, using Eq. 6

$$Q_u = mc_p(T_L - T_\alpha)$$

$$Q_u = 80{,}000X4.18(75 - 25)$$

$$Q_u = 16.72 \; GJ$$

Putting this Q_u gives

$$16.72 = A_c(750X0.65X50)$$

$$16.72 = A_c(24375)$$

$$A_c = 686 \; m^2$$

Now, Let $I_T = 972$, $F_R = 0.65$ for summer,

$$16.72 = A_c(972X0.65X50)$$

$$16.72 = A_c(31590)$$

$$A_c = 529 \; m^2$$

So, the approximate average solar collector area:

$$= \frac{A_C \; (Summer) + \; A_C(\; winter)}{2} \qquad (7)$$

$$A_c = 600 \; m^2$$

The value of Ac is approximate average collector area.

4. Simulation for Water Heating System

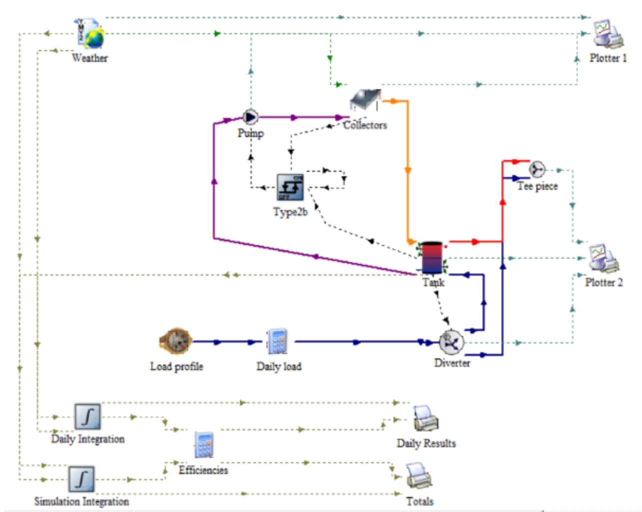

Fig. 3. The TRNSYS simulation for solar thermal for hot water

The TRNSYS simulation of solar thermal for hot water is shown in Fig. 3.

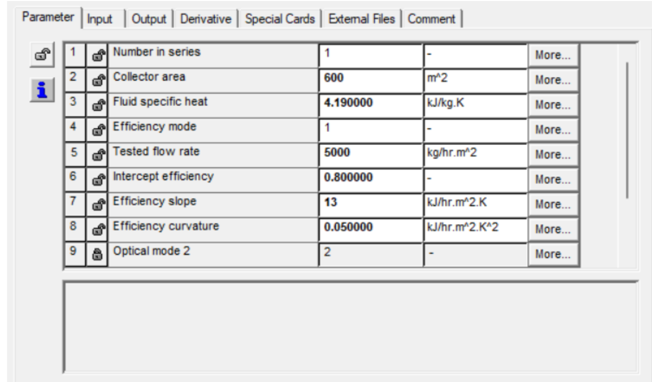

Fig. 4. Parameters used in TRNSYS

The parameters used for the manual calculation in TRNSYS is shown in Fig. 4.

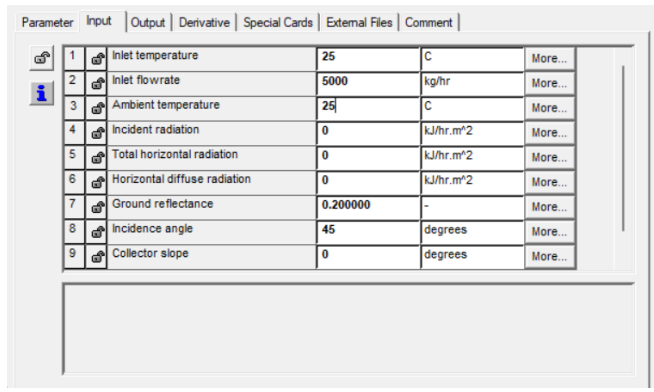

Fig. 5. Input data in TRNSYS

The input data and output for the manual calculation in TRNSYS is shown in Fig. 5. And Fig.6 respectively.

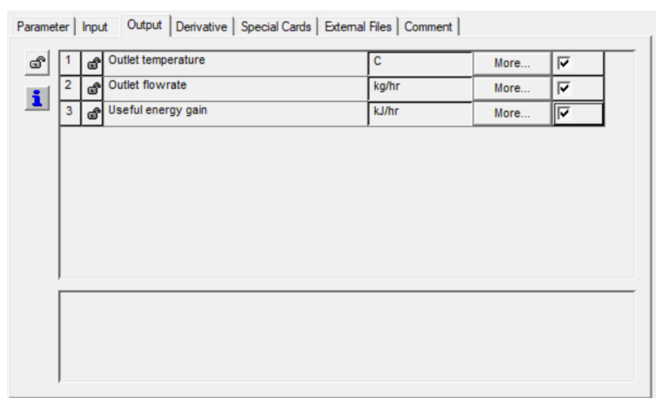

Fig. 6. Output data entry in TRNSYS

5. Results and Discussion

TRNSYS simulation was run for the said data, and the results obtained after simulation are shown in respective figures. The results are as under;

- The designed area of collector for winter season is 529 m^2 and for summer season is 686 m^2 that approximately becomes 600 m^2 which is used to concentrate solar energy to the required solar thermal system for achieving 75°C temperature of water having flow rate of 5 tons per hour.

- The obtained results from TRNSYS software shows temperature is varying from 25°C to 100°C. It is also observed that the average temperature is around 75°C achieved from collector area 600m^2.

Fig. 7. Temperature obtained from the system

The temperature we obtained from this system is shown in Fig. 7. It is observed that the obtained temperature is varying from 25°C to 100°C and average temperature is around 75°C.

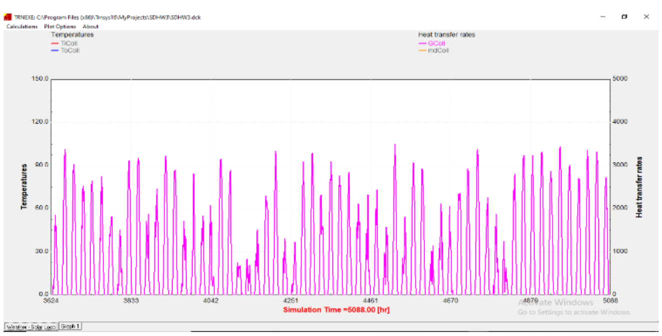

Fig. 8. The heat transfer rates obtained from this system

The heat transfer rates obtained from this system is varying between 2000 to 3000 which is against the temperatures of 60°C to 90°C as shown in Fig. 8 which is the required temperature. It is clearly observed that the heat transfer is continuously varying according to the temperature change.

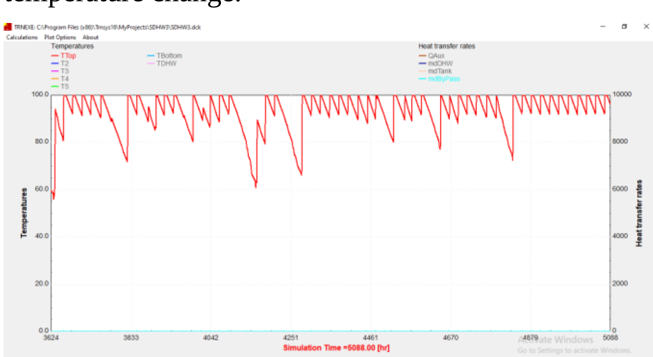

Fig. 9. The maximum temperature obtained from this system

The maximum temperature obtained from this system is 100°C shown in Fig. 9. It is clearly observed that the maximum temperature is more than 75°C, the required temperature.

Fig. 10. The bottom temperature obtained from this system

The minimum temperature level is about 40°C despite few spikes are below this level obtained from this system as shown in Fig. 10. It is already below the desired level required.

Fig. 11. The overall temperature obtained from this system

The overall temperature range obtained from this system is between 45°C to 100°C as shown in Fig. 11. It is also clearly observed that the overall temperature or average temperature is approximately 75°C which is the required temperature of the system.

Table 1

Collector areas calculation

T_L	T_i	m	Q_u	G	A_c
75	25	80,000	16.72	750	686
75	25	80,000	16.72	972	529

The overall results are shown in the Table 1. The overall collector area of the collector for summer season is 686 m^2, while the collector area for the winter season is 529 m^2. The average area for the collector is 600 m^2.

6. Conclusion

The requirement of the leather processing industry for hot water is 80 tons per day of hot water which means if the system is running for 16 hours a day it will consume 5 tons of water per hour. The inlet temperature is 25℃ which is also called ambient temperature and outlet temperature is 75℃ per hour.

After carrying out this research the following conclusions were made.

It is estimated that when properly fabricated, the solar thermal system will be more economical, environment friendly, cleaner and safer to operate than existing system. The solar thermal system for hot water is designed is a better replacement of energy source that is already used in the leather processing industry. Summer energy results are higher than the winter energy results.

The designed area of collector for winter season is smaller than the designed area of collector for winter season. The TRNSYS software used for the analysis of solar thermal systems which give a better opportunity to optimize and analyse the assumptions according to the proposed design. These conclusions are in line with the scope of research as well as requirement of textile industry and this solution will be helpful in replacement from expensive energy sources to solar energy.

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