Dynamic Modelling and Experimental Analysis of Tankless Solar Heat Process System for Preheating Water in the Food Industry

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Abstract: Worldwide, industrial process heat accounts for over two-thirds of global industrial energy consumption. Wherein solar thermal systems are expected to be a reliable alternative solution. The temperature output of the flat-plate collector (FPC) is enough to serve specific industrial applications where low temperature is needed for heat processes, as in the food and beverage sector where nearly all the demand is needed heating and more than 40% is below 100°C. This work presents a tankless solar heat for industrial process (SHIP) system using FPC to produce low temperature for process heat of a food factory in the climate of central Europe. The modelling system is developed based on heat transfer and thermodynamics phenomena, and it is resolved mathematically and validated experimentally onsite. Moreover, this study considers the Budapest region (47.50° N, 19.04° E- Hungary) as a case study. The metrological data is extracted by MeteoSyn software. The objective function is to meet the set temperature requirements for preheating water for food factories to minimize the annual energy costs by saving more fuel. The heat exchanger secondary loop's six different temperature configurations were used as 60, 55, 50, 45, 40 and 35°C, respectively, and each measurement was tested for several summertime days. Results show that tankless SHIP can help preheat water for temperatures below 100°C. By comparing the different configurations, they are acierating that all set temperature combinations can be achieved at a lower mass flow rate of 60 litres per hour for the primary and secondary loops. The obtained outcomes of this work show that integrating solar thermal systems into industrial processes for low-to-medium temperatures is a very economical and promising solution to replace fossil fuels.

Keywords: tankless system; solar heat; flowrate; food processing

1 Introduction

Solar radiation can be utilized directly by photosynthesis or by converting the radiation into electricity. While indirectly heating a particular medium using low-to-medium temperature solar collectors for heating applications such as solar cooking, solar dryer, or solar water heating systems. Also, solar thermal energy for low-temperature applications such as domestic or industrial water heating is the most common around the globe. There are significant differences between the SHIP and domestic hot water (DHW) systems. Firstly, using the solar tank is a must for the DHW, while it is not an obligation in the SHIP systems. Secondly, the required temperature in the case of DHW is permanently fixed at around 60°C, while for SHIP, it varies between 40°C to 600°C. Finally, the DHW system can have a simple configuration and integration, while the SHIP has more sophisticated and complex to integrate into the heat process due to the sensitivity of each industrial case study. Also, integrating SHIP into the industrial process is times harder and more complicated than a simple DHW system, but since industrial demand accounts for a significant portion of the national and global demand, it will result in significant savings in fuel and natural gas. There are different types of solar collectors for water heating applications flat-plate collector (FPC), evacuated tube collector (ETC), and compound parabolic collector (CPC). Several researchers have designed and analyzed FPC using exergy analysis to obtain the optimal thermal energy conversion [1], [2]. At the same time, other researchers have studied the thermal performance of the energy storage tank in the solar heating system [3]. As a result, It is reported that using solar energy in the industrial sector can enormously reduce CO_2 equivalent emissions by 65-75% [4].

Globally, energy is essential in industrial processes and used for economic growth and continuous development. To assess the sustainability of any energy source, the availability, security, and environmental effect are critical parameters. Therefore, scientists and researchers focus on these concerns to achieve a sustainable and secure energy future. In the most recent literature, global energy consumption is expected to increase by 33% from 2010 to 2030, and the industrial sector will take a big part in this upsurge [5]. The average energy consumption in the industrial sector is higher than any other sector, estimated at 35% globally [6] and 30% in the southern Mediterranean European countries. 78% of this energy is needed for heat processes and 22% for electricity [7]. Nevertheless, it varies by economic activities, regional location, and modernization. Solar thermal energy would significantly contribute to industrial energy systems by tapping into this worldwide potential.

Potential studies were carried out for different regions and countries to use SHIP systems. A comprehensive study was performed for the USA, Spain, Portugal, Austria, Australia, Italy, Netherlands, Sweden, Cyprus, Tunisia, and Germany to analyze the industrial heat demand below 300°C [8]-[11]. At first, suitable sectors were selected to determine a theoretical potential. Therefore, high waste heat or low heat demands were excluded. As a result, sectors of chemicals, food, beverages, and textiles are suitable for using solar heat. The low-to-medium temperature heat demand in those sectors is suitable for drying, cleaning, washing, and surface treatment. Then, the theoretical potential was divided into a short-therm (<100°C) and mid-therm (<250°C) because the solar collector's technology for heat process above 100°C is not readily available in the market, so it did not reach a mature level by the time of the study. As a result, the food and beverages sector is considered suitable for using solar heat in all potential studies. Within food and beverage factories, a significant share of the heat demand accounts for 58% and 42% for low and medium temperatures. It is noteworthy that more than 50% of the installed solar heating systems were used for washing or water heating processes. In 2006, more than 40% of it was used for processes in 60-100 °C, which is a very suitable range for commercial solar collectors [12].

Using a boiler as a process heating device to generate hot water or steam in the industrial sector is expected, which consumes significant energy. Fossil fuel is used in all major industries to produce hot water or steam for industrial processes. This consumption results in greenhouse gas emissions that cause climate change, where CO_2 emission alone involves 76% of global warming [13]. Since fossil fuels play a significant role in meeting the required energy for different heat processes, renewable energy sources for process heat generation are more suitable due to their sustainability. For example, solar thermal collectors directly convert the solar energy into heat compared with 3-4 times higher energy efficiency than the photovoltaic powered electrical heater. Also, storing electrical energy using batteries is very expensive and still under development, making the PV system less favourable in the heating energy market [14].

Nevertheless, the current status of implementing solar heat for SHIP is still at an incentive stage of commercialization due to several barriers: relatively high upfront costs, low awareness of policymakers, and the need to develop more suitable solar technologies for medium and high-temperature processes [15]. According to the most recent published reports, solar energy will afford 45% of the global energy requirements by 2050. Many strategies and projects have been launched to fulfill this target.

Milk, fruits and vegetable production have a considerable heat demand, and it is a promising sector for integration with solar heat systems. In contrast, the sugar industry has the highest energy demand, where production mainly occurs in winter and autumn. Furthermore, some subsectors that appear suitable for solar heat are mineral water, feed and malt, where standard processes such as pasteurizing liquid goods at 65-100 °C and cleaning production facilities and products in all subsectors at 60-90 °C.

In many industries, integrating solar systems does not require a storage tank. Because either the heat provided by the solar system is higher than the heat needed, or the solar system will be integrated into the processing system as preheating water before entering the conventional boiler or steam generator.

In other words, this system can be used when the heat process requires a continuous operation and a load, such as in food processes, where the load is always higher than the supplied heat from the solar system. In this case, the integration of solar thermal systems remains low to avoid high costs related to the storage system. In such a configuration, the hot water supplied from the solar heat system will be fed directly to the existing heat supply or the heat process, as shown in Figure 1.

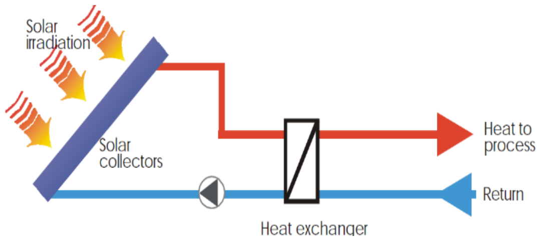


Figure 1
Tankless solar heat for industrial process system

Although many experimental and simulation studies on FPC and SHIP systems have been reported in the literature, detailed simulation for tankless solar heat systems in central Europe with real-time experiments is yet to be carried out. Many types of research were focused on SHIP systems in central Europe to highlight the massive energetic potential in the literature. In central Europe, acceptable solar radiation levels are available, which can meet the low to medium temperature requirements in several industrial sectors. Preheating water in those industries can account for significant fossil fuel and natural gas savings annually. In the V4 group, Hungary has the highest solar energy potential compared to the other bloc countries.

Nevertheless, no actual experiment was conducted to prove those hypotheses regarding SHIP. Also, no dynamic system simulation with T*sol is available to perform parametric analysis of different parameters of a tankless solar system for the industrial heat process considering parameters like water inlet temperature, mass flow rate, ambient temperature, outlet temperature, solar thermal heat gain, and so forth. The present work focuses on T*sol software to analyze a tankless solar heat for an industrial process system used to preheat water for the food industry in Budapest, Hungary, at different output temperatures. This research includes a comprehensive statistical study of the temperature profiles to meet the needed set-temperature values. Then, the simulation and the actual results were evaluated regarding the temperature and weather parameters. The well-engineered tankless SHIP can supply industrial heat processes per the required outlet temperature range.

2 Method

2.1 Hungarian Energy Status

All over the Europe Union (EU), solar water heater systems are given financial incentives to encourage the usage of renewable energy, except for Finland, Greece, and Denmark. While in Hungary, which is part of the "Visegrád group - V4 group", currently solar capacity has increased tenfold in the past three years (2017-2020) due to the favourable investment environment and the lower cost of solar technology [16]. Hungary also has ten solar power plants with more than 10 MWp, and five solar power plants under 10 MWp spread all over the country [17]. Moreover, 40% of the total consumed energy goes for heating and cooling purposes [18]. Since energy security is a worldwide concern, all nations have framed energy policies in contrast with sustainable growth.

Similarly, the EU framed two targets (by 2030 and 2050) to reduce greenhouse emissions by at least 55% compared to 1990 [19]. Reducing carbon emissions is a significant challenge in all EU and especially V4 countries due to the dependency on conventional energy sources. The EU aims to increase the renewable energy share to 32% by 2030, while Hungary plans for 21% by 2030, and the current status reports that the renewable energy share will be 12% in 2019 [20]. According to the available records, solar, biomass, biogas, hydro, and wind are the most significant resources in Hungary, as in Figure 2. Biomass was the primary renewable energy source for energy production, and it was reduced drastically in less than ten years from 67% to 48%.

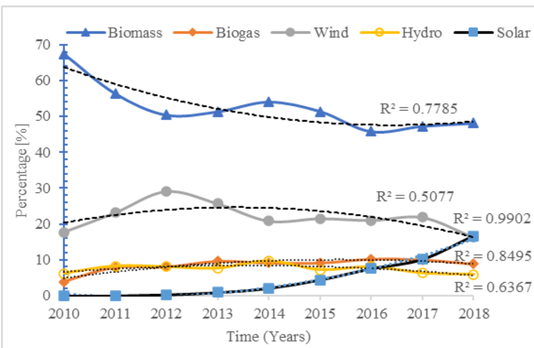


Figure 2
Regression line analysis of various renewable energy sources in Hungary using poly trendline (2010-2018)

On the other hand, bio-based sources have increased slightly, and wind and hydropower maintained their share. In contrast, solar energy has the most extensive share growth in the last decade, from almost 0% to 16% (coefficient of determination R^2=0.9902). If the trendline and conditions remain the same, it can reach more than 30%. Consider that the new technological advancements can positively affect the long-term aims.

Several solar parks with small to high-power capacities were installed in the last decade throughout Hungary. According to the Hungarian solar Association, the growth parameters have doubled in the last few years. Comparing it with the neighbourhood countries is essential to unfold the potential capacity. For example, Germany has the highest number of solar panels, though Hungary has 50% more solar radiation than Germany throughout the year. Moreover, in Vienna, Austria, the annual sunshine hours are around 1850 hours, while in Budapest, Hungary, there are 2000 hours.

Nevertheless, Austria is the world-leading country in solar water heating systems regarding the thermal energy produced (kWh) per one thousand capita [21]. Based on the growth data, the regression analysis was depicted in Excel. The two lines represent the solar growth potential in the Hungarian region. The coefficient of determining the solar energy growth prediction has a linear value. While for determining more accurate results, two clusters were studied with more significant and lesser than 10 MWp solar park capacities. The graph confirms that the expected growth of solar parks is more significant than 10 MWp if further developments are achieved in this technology.

The regional map analysis is helpful for visualizing the region's current falling and irradiance scenario. The recorded global irradiance data is a powerful tool to predict solar potential [22] accurately. According to the regional maps, Hungary receives the highest region V4 in annual irradiation of 1200-1400 $kWhm^{-2}$. So, the annual energy generation prediction was the highest, with a range of 900-1050 $kWhm^{-2}$. While the optimally inclined collectors can harvest a sum of irradiation in the range of 1300-1600 $kWhm^{-2}$, and the energy production potential is 975-1200 $kWhm^{-2,}$ as in Figure 3.

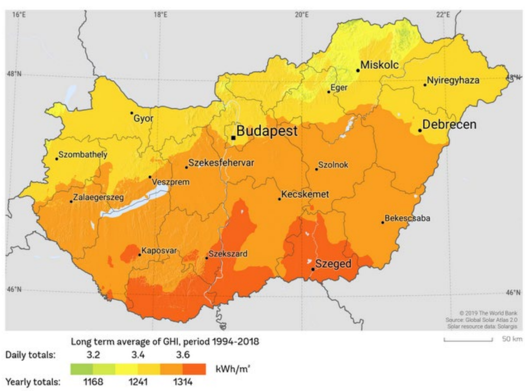


Figure 3

Global solar radiation in Hungary on a horizontal surface

2.2 Model Development and Simulation

A dynamic analysis tool is needed to accurately describe the system's response to the rapid environmental change in weather conditions to study the SHIP system's performance [23], [24]. T*sol software is a professional simulation program for designing solar thermal systems, including domestic hot water (DHW), swimming pool heating, district heating, and heat process systems. It calculates and simulates the thermal process in these systems by providing the components and tools of the solar systems and all relevant data [25]. This software enables the engineers to design the system optimally at a low cost and time. The calculations are based on the energy balance flows and provide predictions according to the hourly metrological data [26].

This section develops the comprehensive models of the tankless SHIP system by collecting the meteorological data for an entire year and comparing it with the average data records between 1995-and 2012 with a deeper focus on the summertime results.

2.2.1 SHIP Concept

The SHIP comprises a solar collector integrated with an external heat exchanger in a closed loop. In this external loop, a water and propylene glycol mixture runs in the piping system to convey the absorbed energy from the solar collector to the heat process using a heat exchanger. The concept assumes that the flow goes out of the solar collector at a specific temperature (denoted by T Pr In) which is the same input temperature of the primary side of the heat exchanger since the piping system is well-insulated. Moreover, the output temperature from the heat exchanger in the primary loop (denoted by T Pr Out) is the same temperature that flows in the collector for the same reason. On the secondary side of the heat exchanger, there is an open loop that warms up the network water (denoted by T Sec In) by exchanging the heat with the fluid on the primary side so it can be ready for the heat process at the required temperature (denoted by T Sec Out).

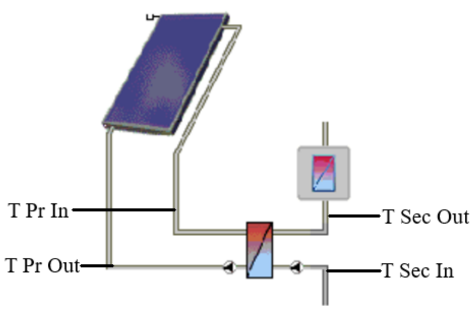


Figure 4
A tankless solar system with heat exchanger and FPC collector schematic

The schematic concept of the system is shown in Figure 4. The concept assumes no possibility of mixing between the fluid on the primary and the secondary side to avoid mixing the antifreeze liquid with the process heat, which can be risky for human health, mainly in food processing like pasteurizing.

2.2.2 Modelling in T*sol

The simulation is carried out for six different configurations of a food process industry to assess and optimize the working parameters. The following assumptions and inputs are considered:

- The weather data is used for the geographical location of Budapest (KMI weather station), Hungary.
- The solar fraction can reach up to cover the whole required energy during certain weather conditions. However, central Europe's annual feasible solar fraction is 40-60%. Therefore, an auxiliary heating system is considered in natural systems to cover the rest of the demand and ensure a continuous supply of the process heat.
- The efficiency of the solar thermal collector is dependent on the ambient temperature. Therefore, an average ambient temperature of 25 °C is the relevant temperature for the modelling analysis.
- The examined case study of the food process requires several temperatures for processing and cleaning.
- The temperature of the network water is taken from the data records

3 Experiment

The components used in the T*sol model configuration are (1) single FPC. (2) external heat exchanger transfers the absorbed energy from the primary loop to the secondary one. (3) heat exchanger. The water flows in the pipes using an active circulation pump in a closed loop in the primary loop. The flow rate of the primary loop is 60 litres per hour. The fluid is a mixture of glycol and water with an 18% volumetric percentage to avoid freezing and bursting during low-temperature. The intended experimental setup consists of several primary data logging and instrumentation components: (1) IMRe, and (2) data logger (ALMEMO® 2890-9) in a universal input data logger that connects nine sensors through multiple channels, (3) pyranometer, (4) mechanical flow meter, (5) temperature sensor (k-type). (6) Open Energy Monitor is monitoring, modelling, and assessment tool to monitor live data and records. (7) TECH controller to adjust the working schedule of the process heat. The measurement ranges and the accuracy of each instrument are shown in Table 1.

The experiment set up has been installed in the Hungarian University of agriculture and life sciences renewable energy laboratory, Gödöllő, Hungary. Experiments were carried out 24 hours a day during August and September 2021, when the weather was relatively stable, with rain interruption for a few days during the whole period. All the data have been recorded persistently by the data logger every minute.

The actual experiment (mainly the solar collector) was mounted on a metallic structure and directed at an angle of 33º facing the south to harvest the maximum radiations throughout the day. Knowing that this angle is the optimum angle for Budapest during the summer climate was recommended by the solar electricity handbook 2019.

Table 1
Measurement tools and measuring range

Instrument	Type	Measuring range	Accuracy
Data logger	ALMEMO® 2890-9	over 70 measuring ranges	-
Pyranometer	THEODOR FRIEDRICHS 6003.000 BG	0 - 1300 [Wm^{-2}]	< 10%
Mechanical flow meter	Zenner DE-07-MI001-PTB010 (R80HR40V) with impulse output	0.05 [l] to 10,000 [m^3]	Cold water ± 5 % hot water ± 3 %
Thermocouple (k-Type)	Programmable Resolution 1-Wire Digital ThermometerDS18B20	-55 to +125 [°C]	0.5 [±°C]
IoT device	IMRe	Relative to each sensor	

As in Figure 5, the IMRe system is an internet of things (IoT) device that collects the energy usage data of a specific case and uploads the sensor data directly to the internet [27]. A single user can collect data using one or more devices, which provides higher scalability and flexibility if required. The collected data can be viewed and evaluated using an internet browser. The monitoring system has two main parts, the local group, which contains IMRe hardware and sensors. The second group is the cloud, where a server runs Emoncms framework processes for all raw signals and then converts them into their corresponding physical values [28]. It should be mentioned that it is possible to build and generate additional calculated values in the server. All these data are stored in the cloud database and can be easily visualized to the end-user.

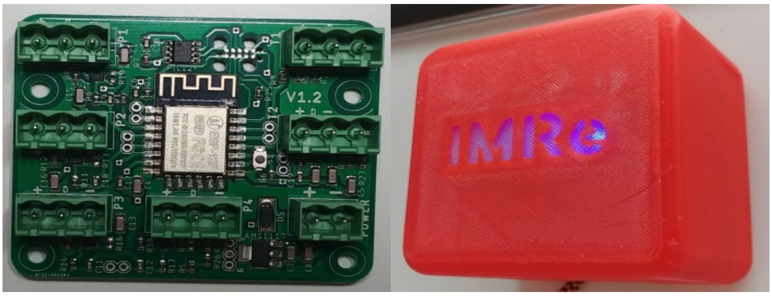


Figure 5
IMRe controlling system

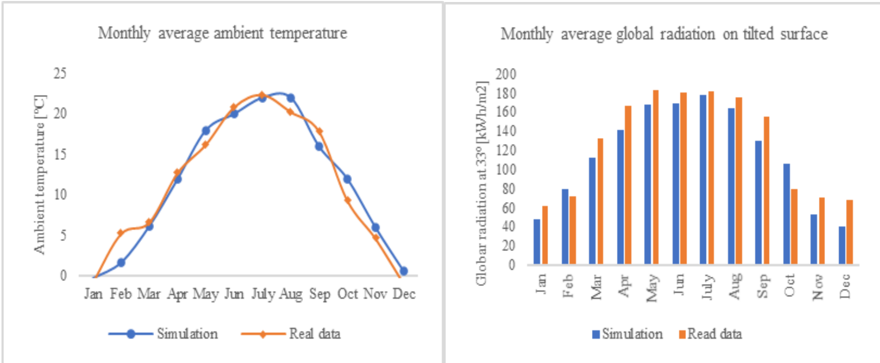
4 Results

The outcomes of this research, along with the corresponding physical explanations, are described in this paragraph. Data were collected for the continual flow of hot water at different process heat temperatures 35-60℃ for preheating water and 60/60 litres per hour configurations of flow rates in the primary and secondary loop and actual solar radiation from the sun.

4.1 Hungarian Weather Profile

The Hungarian climate is continental, with cold, snowy and frigid winters and low humid hot summers. The average annual temperature is 9.70℃ based on long-term statistics and 11.25℃ based on the software outputs. In comparison, temperature extremes are 42℃ in summer and -29℃ in winter. The minimum and maximum variation of the annual ambient temperatures obtained from the T*sol simulation compared to the actual data shown in Figure 6 (a). In the same plot, the solar radiation's annual variation is also portrayed to show the interactive pattern between the two parameters, as in Figure 6 (b). It is evident from the graph that the ambient temperature varies with the solar radiation, and the ambient temperature profile varies between -1 and 23 ℃ in average monthly rates.

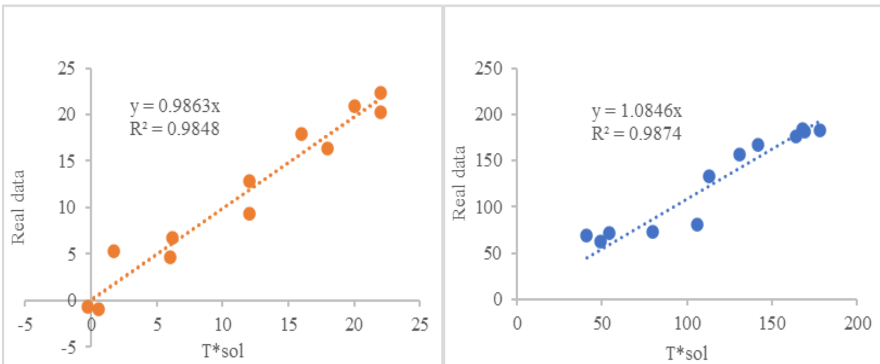
The comparison is conducted between the T*sol weather data file, TMY, an average recorder between 1995 and 2012, and the actual experiment data at the site location. As a result, the average differences are more than one hundred $kWhm^{-2,}$ and the error is 10% between the two yields, as in Figure 6 (b). While for the ambient air temperature profiles, the average difference is less than 0.1℃, approximately 0.8% error.



(a) *(b)*

Figure 6
Monthly average a) ambient temperature b) solar radiation

A comparison analysis was conducted to understand this difference. It was found that there is a linear correlation using (0,0) set intercept between the two ambient temperature profiles and the determination coefficient R^2= 0.9848. Similarly, for the global radiation profiles, it was found that the two profiles have a linear correlation with a determination coefficient R^2= 0.9874, as in Figure 7.



(a) *(b)*

Figure 7
Coefficients of determination for linear weather data a) ambient temperature b) solar radiation

4.2 Model Validation

The authenticity of the dynamic simulation model using T*sol software of the tankless SHIP has been examined experimentally by real-time measurement for three months at 60/60 litres per hour for both loops (primary and secondary).

Figure 8 shows the black dashed line, representing the heat process set temperature. It is pretty apparent from the graph that the orange line (representing the secondary output temperature) is always nearby the set temperature. Hence, the simulation model is appropriate to carry on further to predict system performance.

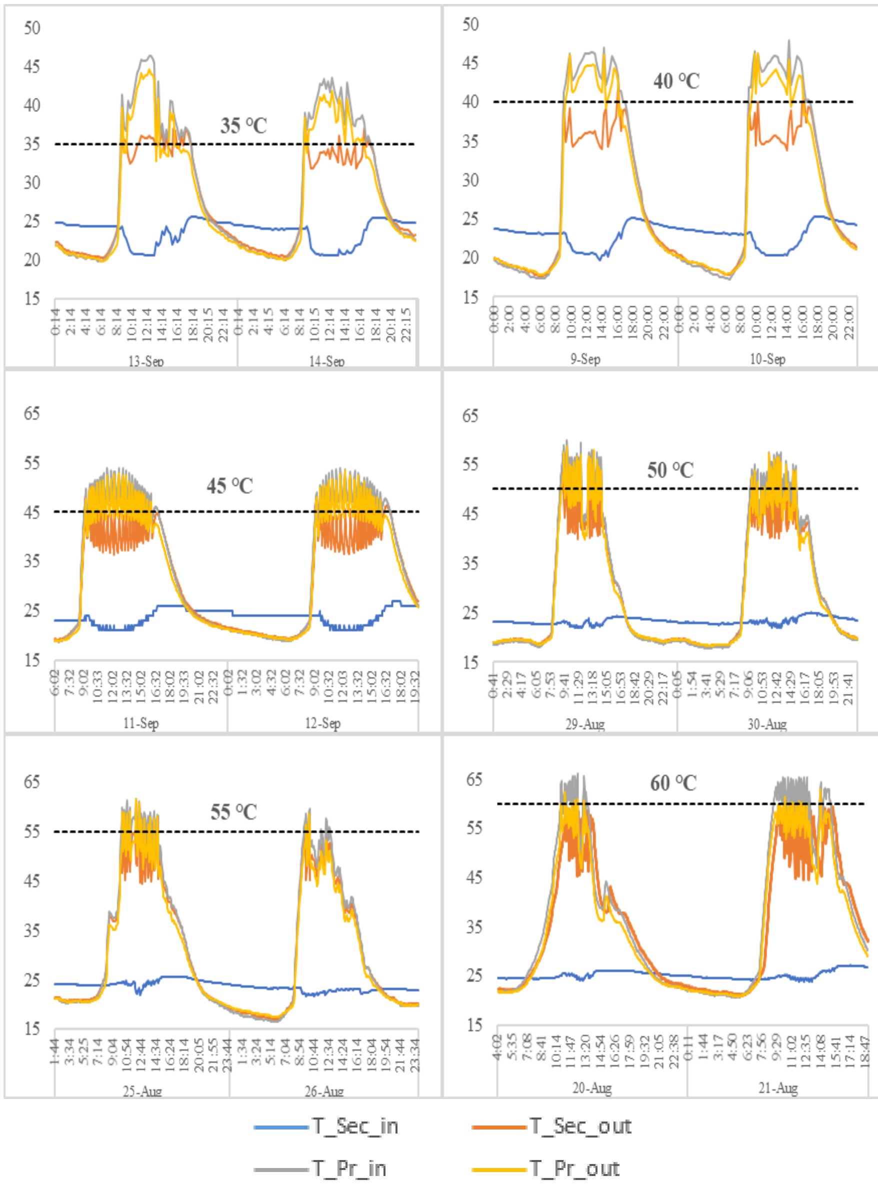


Figure 8
Actual experiments for a different set of output temperatures

The heat exchanger's secondary side output temperature as a function of the primary side input temperature was conducted in a linear correlation with a (0,0) set intercept to estimate the strength of the connection between the most critical parameters of the heat exchanger. As a result, in Figure 9, the coefficients of determination are always higher than 0.9863, indicating the performance of the heat exchanger. It shows that the differences between the two parameters are as low as possible.

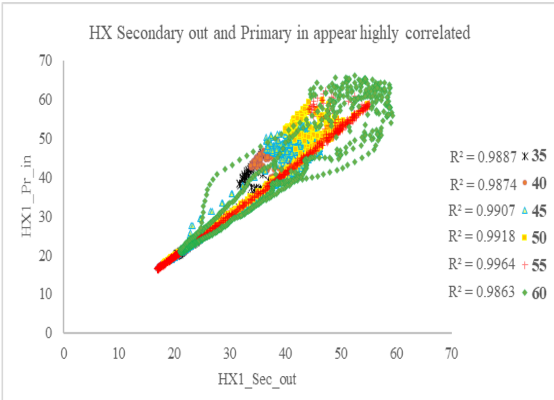


Figure 9

Heat exchanger primary input versus secondary output temperature

In addition, the logarithmic mean temperature difference (LMTD) is a tool in flow systems, most notably in heat exchangers, to determine the temperature driving force for the heat transfer process [29]. For a heat exchanger with a specific heat transfer coefficient and constant area, the larger the LMTD, means more heat is transferred. For a generic heat exchanger with two ends at which the cold and hot streams enter, the LMTD is defined by the following equation:

$$LMTD = \frac{\Delta T_p - \Delta T_s}{\ln\left(\frac{\Delta T_p}{\Delta T_s}\right)} \tag{1}$$

Where ΔT_s are the temperature changes in the heat exchanger's primary and secondary sides, respectively. In our case, the heat exchanger is a counter-current where the streams enter from different ends. It should be noted that the LMTD is a steady-state concept, and it cannot be applied to a dynamic analysis [30].

Figure 10 shows the LMTD of all real cases to estimate the average value. As LMTD is higher, we have better performance of the heat exchanger. It is noted that all cases have average LMTDs higher than eight, while the higher the value means more heat has been transferred between the two sides.

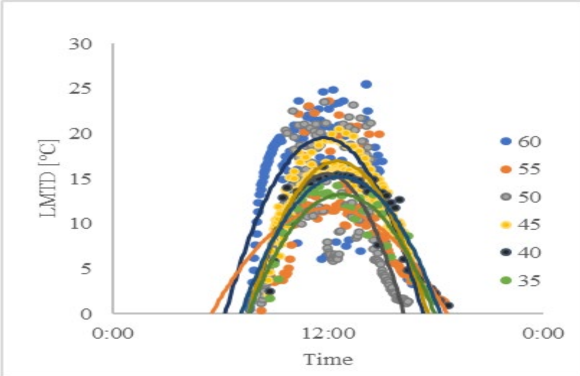


Figure 10
LMTD performance of the heat exchanger

4.3 Parametric Analysis

4.3.1 Effect of Solar Radiation and Mass Flowrate on the Outlet Temperature

Figure 11 shows the outlet temperature variation under varying solar radiations for three different configurations, 30/30, 60/60 and 90/90 litres per hour per square meter mass flow rate. In contrast, the inlet water temperature of the secondary loop was relatively constant at 25°C return temperature. The simulation was conducted in July, and the results show that the 30/30 configuration has the highest output temperature for summertime compared to 60/60 and 90/90 $l/h^{-1}m^{-2}$.

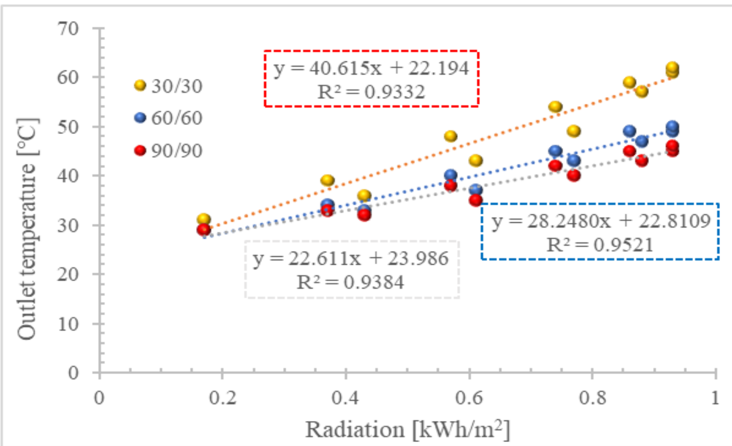


Figure 11
Effect of solar radiation on water outlet temperature for tankless SHIP system at different flowrates

4.3.2 Effect of Solar Gain under Different Mass Flowrate

Figure 12 illustrates the variation of the generated thermal energy fraction from the tankless SHIP system for the specific industrial process under varying solar radiation and mass flowrate. Results show that the 30/90 configuration has the highest annual energy yield by 638.79 $kWhm^{-2}$ and 1,226 kWh for the whole system. In the second place, the whole system has a 30/60 configuration of 604.05 $kWhm^{-2}$ and 1,160 kWh. It is noted from the graph that the second loop must have a higher flow rate compared to the primary loop, which is a result of choosing a closed loop on the primary side. At the same time, the open loop on the secondary side shows that a higher flow rate results in higher yields if we consider a fixed flow rate at the primary loop.

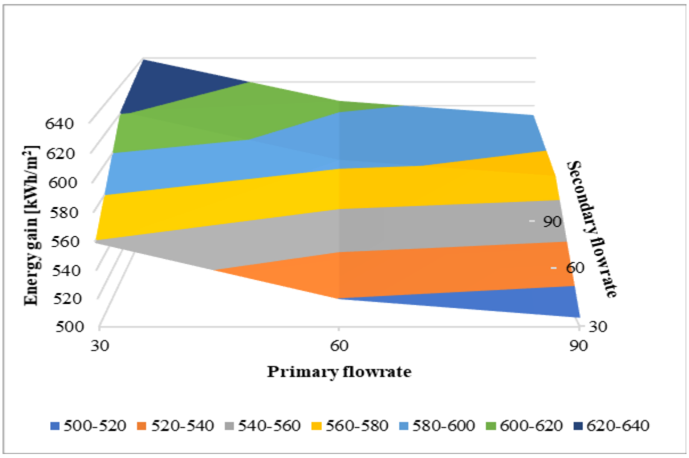


Figure 12

Annual energy yield considering different flowrate configurations

Conclusion

A novel tankless solar heat for industrial process (SHIP) system comprising FPC and an external heat exchanger has been designed. A dynamic simulation model has been developed in T*sol software, which is thus authenticated using prototype implementation. The proposed tankless SHIP system can fulfil the low to medium heat demand for pasteurizing process heat demand. This work's primary objective is to study the possibility of affording solar energy for an industrial process requiring low to medium temperatures at different output temperatures. The case study is considered for a food processing plant in Budapest, Hungary.

The modelling system has been tested experimentally based on the thermodynamics and heat transfer phenomena. The meteorological data has been used from MeteoSyn software in the T*Sol program. Moreover, six different temperature configurations were chosen as a set temperature of 35, 40, 45, 50, 55, and 60°C, respectively. Each measurement took several days during the summertime of 2021. The meteorological data have been examined between average aggregated data between 1995-2012 and one-year actual experiment weather data. Results show less than 10% difference between the two solar radiation profiles and less than 1% in the ambient air temperature profiles.

On the other hand, a narrower comparison was conducted during the three months of the experiment. The results show a high correlation with more than $R^{2,}$ more significant than 0.7500 for the coefficients of determinations for both solar radiation and ambient temperature profiles. In practice, this methodology and the IMRe controlling system met all set temperature configurations. After that, all coefficients of determination of the primary input temperature and the secondary output temperature have been examined. The results show that R^2 is higher than 0.9800 for all scenarios. Also, the performance of the external heat exchanger was measured by the logarithmic mean temperature difference LMTD, and the results show high performance with bigger than 7.9°C for all scenarios. The root means squared error RMSE was evaluated for the ambient temperature and was around 5%, proving the proposed methodology. Finally, parametric analysis has been evaluated to determine the best flow rate configuration on the primary and secondary sides. The results show that 30/90 has the best performance with 638.79 $kWhm^{-2}$ and 1,226 kWh for the whole system. In conclusion, tankless SHIP systems can serve as a considerable solution for low to medium heat temperatures in the industrial sector and under central European weather conditions.

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