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Effect of in series and in parallel flow heater configuration of solar heat system for industrial processes

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Original article

Abstract

The boiler is an enclosed vessel that transfers the energy from fuel combustion or electricity into hot water or steam. Then, this hot water or pressurized steam is used for transferring the heat to a certain heat process. Usually, the required hot water or steam keeps on varying throughout the day which also may be implied on the daily or monthly load. Therefore, several configurations of connecting the boiler into the solar heating system ensure the temperature of the final output. The boiler can be connected in series or parallel to improve the efficiency of the overall process as well as to reduce the running costs. This paper presents a simulation study of a solar heating system for industrial processes. Two flow-heater system configurations are designed for covering the heat demand of a pasteurising factory existing in Budapest, Hungary. The configuration "A" consists of a solar heating system for hot water preparation using in series flow heater configuration. While configuration "B" consists of the same solar system but with a parallel flow heater configuration. These system configurations are modelled using T*sol software for evaluating the system performance under the Hungarian climate from five different aspects: required collector area, glycol ratio, volume flow rate, relative tank capacity, and tank height-to-diameter ratio. According to the optimum design parameters, in series configuration is better than parallel by 3.14% at 45 m^2 collector area, 0.45% at 25% glycol ratio, 0.42% at 50 $l/h \cdot m^2$ volume flow rate, 2.05% at 50 l/m^2 relative tank capacity, and 0.42% at 1.8 tank height-to-diameter ratio respectively. The results show that in series configuration is better in terms of solar fractions than parallel configuration from all five aspects.

Keywords

- solar thermal
- industrial processes
- in series
- in parallel
- process heat

Authors contributions

A – Conceptualization
B – Methodology
C – Formal analysis
D – Software
E – Investigation
F – Data duration
G – Visualization
H – Writing – original draft preperation
I – Writing, reviewing & editing
J – Project administration
K – Funding acquisition

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Conflict of interest

None declared.

Introduction

In Hungary, water heating systems are mainly based on fuel such as wood and gas with 64% of the national energy share. Among these, wood is still widely used because of its low price and wide availability in the countryside while gas is mostly used in residential and industrial cities. Unfortunately, the combustion of wood and gas is the main source of air pollution during wintertime. On the other hand, the renewable energy share is growing from 2% in 1990 to 15% in 2015 showing the new trend of integrating and utilising renewable energies in national energy production. It is proven that the cost of the fuels is highly sensitive to crises like Covid 19 where the price of oil has dropped below zero in April 2020 or the oil crises back in 1973. These problems are the driving motivations to evaluate the performance of the environmental highly efficient energy alternatives like the solar thermal system which is known as Solar Heat for Industrial processes (SHIP).

Solar energy is considered one of the most sustainable energy sources since it delivers stable supply energy for both thermal applications and power generation in domestic and industrial sectors [1, 2]. Where the thermal conversion of the solar energy can have an efficiency of up to 70%. Even for power production, it has between 20–25% compared to 15–20% for photovoltaic systems [3]. Therefore, the use of solar thermal systems for industrial applications meets the increased industrial demand.

The solar heat process system consists of four main components, solar collector, buffer tank, hydraulic system (like pipes and valves), and boiler. The boiler is needed to convert the water into hot water or steam using different energy sources such as fuel combustion of electricity. This hot water or steam is needed for the vast majority of the industrial processes such as pasteurising, bleaching, paper, sugar, textile, dairy, etc. In such industrial processes, hot water or steam quality and temperature must be maintained to meet the temperature requirements of the heat process within acceptable margins. To achieve the maximum efficiency of the solar heat process, the generated hot water or steam must match the hot water or steam demand as accurately as possible and meet up with the fluctuation in the demand. As known that solar energy has a sporadic nature, because it fluctuates on an hourly, daily, and monthly basis, thus a backup system has to be connected to ensure the temperature of the final supply. In most of the scenarios, the backup system is a boiler with effective controlling being needed since the boiler's efficiency varies with the load condition. In the case of a single boiler system, the controlling process is relatively easy compared to the facilities where more than one boiler is on-site running so that it requires upgrading to the controlling system to ensure the final output. In the case of a multiple boiler system, demand-load management is needed to get the optimum results [4]. Since there are no clear strategies to maximise the efficiency of the boiler system, the decision of the operation and load distribution among the boiler rely on the expertise of the boiler operator. This decision can result in significant efficiency loss and operating costs. When the hot water of steam demand is low the efficiency of the boiler decreases. So that, it is suggested to use multiple small boilers with proper demand load management to save the consumed fuel as well as the required space for installation.

With a significant share of the final energy demand and mainly for processes below 250°C, solar heating for industrial processes is considered as one of the best renewable energy solutions under several atmospheric conditions. These processes have around 35% of the world's growth [5] so that they significantly influence the national economic growth. These industrial shares may vary between growing economics and developed ones depending on the industrial level of the country. For example, Germany has 28% [6] and the united states of America has 33% [7], compared to India 47% [8] and China 70% [9]. In each industrial sector, there is a demand for both electrical and thermal forms of energy. The electrical energy is needed for operating the electrical machines such as the motors, lights, and air conditioning system. While thermal energy is needed for heat processes such as dyeing, bleaching, drying, etc. So that, a substantial share of the industrial demand is needed for heat processes. According to the available statistics, a major fraction of around 60% of the solar fraction is reported in the temperature interval of 30–250°C [10].

Generally, and in all industrial firms, all the hot water demand is generated by a heating element that generates heat such as a boiler. Then, it is transferred from the heating source to the needed heat process by a transferring mechanism (piping system) which serves as a distribution system. The transfer mechanism is not needed in all cases since the heat can be generated into the heating process such as hardening and tempering. While indirect heating is typically generated for duties such as drying and washing [11]. The boiler mechanism can be electrical-based or combustion-based. In combustion-based systems, the heat is produced by the combustion of different types of fuels or gas (available in solid, liquid, and gas form) and then it is transferred to the heat process. While in electrical-based boilers, the heat is produced by electromagnetic fields or electrical currents such as infrared emitters [12].

The use of liquid fuels and coal accounts for about 50% of the total share of fuels used in the industrial sector. In 2020, the share of renewable energy (solar and biomass) accounts for 6.6%, while electricity, natural gas, liquid fuel, and coal account for 16%, 22%, 27%, 28.4% respectively [13].

The heat transfer medium may or may not be in direct contact with the under-manufactured products. Because it depends on the process itself and the end-use requirements. Generally, heat transfer mediums must have high heat capacity, low viscosity, low corrosiveness, low vapour pressure, and high thermal stability [14–16]. While steam is the most used medium in industries accounting for 37% and 33% for the USA and the UK respectively [17] because it has high energy density and can be stored in large quantities. For example, in the dairy, chemical, and pulp and paper industries, it accounts for 50–60%, 47%, and 84% of the needed demand in steam form. On the other hand, oil can be used in industries due to its ability to operate under very low pressure. However, it costs more and has a low specific heat capacity than water [18].

The International Energy Agency (IEA) has established a program of solar heating and cooling (SHC) back in 1977 aiming to promote the utilisation of all forms of solar thermal energy. Those activities involve experts from EU and IEA member countries. For example, Task 33 (2003–2007) aimed to show the huge potential of using solar heat in industry and the importance of creating a new market sector to integrate solar thermal systems into different industrial processes [10]. While Task 49 (2012–2015) reported after analysing more than 120 operating solar thermal systems, that worldwide around 30% of the industrial heat demand is needed at a temperature below 100°C. While in the EU27 28% of the overall energy demand is for heat below 250°C [19]. Finally, Task 64 (2020 – ongoing) aims to help solar technologies to become a reliable solution for industrial duties up to 400–500°C [20].

For selecting appropriate solar collectors for industrial duties, it is important to meet the following criterion: 1. To harvest the accepted range of solar yield, 2. To meet the operating temperature needs, 3. To have high efficiency, and 4. To have a realistic cost [21, 22]. Currently, three different types of solar collector types are being used in the industrial sector mainly: flat-plate collector (FPC), evacuated tube collector (ETC), and concentrated ones. Where mostly water and air are the most used mediums in the collector loop, while in some cases water has to be mixed with propylene glycol (where the ambient temperature falls below 0°C) in order to avoid freezing and burst failures. Generally, FPCs and ETCs are being used for low-temperature industrial processes [23], and concentrated collectors for medium to high temperature (> 300°C) and it is available in several designs like parabolic troughs, dishes, and linear Fresnel reflectors [24].

In the literature, the reported potential of using solar energy in several industrial processes is enormous, while worldwide, the actual installed capacity in the industrial sector is below 1%. That is due to several reasons such as lack of governmental subsidies, lack of awareness, and most importantly that every case is a unique case (retrofit project or a new project). Even though, it has never been studied before as a comparative analysis to determine which boiler configuration would be the best to achieve the highest solar yield and the highest solar fraction. The current study focuses on two different boiler configurations, in series and parallel, from five different aspects. The study factors are required collector area, glycol ration, flow rate, relative tank volume, and tank height-to-diameter ratio.

Materials and methods

An indirectly forced circulations solar thermal system for heat process applications with external heat exchanger integration and antifreeze fluid in the primary flow loop is modelled in this study. The secondary loop is the process heat section where the boiler is connected to the process either in parallel or series. The parallel connection can be used by attaching the boiler's input and output directly into the buffer tank as in Figure 1a, while in series connection is by installing the boiler directly into the piping system between the process heat and the buffer tank as in Figure 1b.

When the primary loop receives the solar irradiation then it transports it from the solar collectors to the primary side of the external heat exchanger (hot side). Since the study is in a relatively cold climate, where the ambient temperature falls below zero degrees during wintertime, the fluid used in the primary loop is a solution of glycol in water where the conducted simulations measure the performance of both systems under different volumetric glycol ratios to avoid freezing in the primary loop. To allow the absorbed energy to be transferred to the buffer tank, the external heat exchanger does not only do this but also separates the glycol in the primary loop from being mixed with the duty water in the buffer tank in the secondary loop. Before the process heat, the output hot water temperature is checked by the temperature sensor if it matches the needed temperature. If not, the auxiliary heater (which can be gas, pallet, oil-fired boiler, or even a heat pump) runs to warm up the output water to the desired level and this occurs mainly on overcast days where the solar irradiation is not sufficient. On the contrary, when the produced water exceeds the desired temperature, a 3-way valve adds more cold water to adjust the output temperature.

According to the recent literature reviews and to optimise the performance of the solar system, two sets of simulations are conducted. The first one is to perform then optimise the system performance (considering the solar fraction as the key factor) for given characteristics of a solar collector. While the second type is to optimise the efficiency of the solar collectors. Nevertheless, most of the studies are done using MATLAB or TRNSYS software.

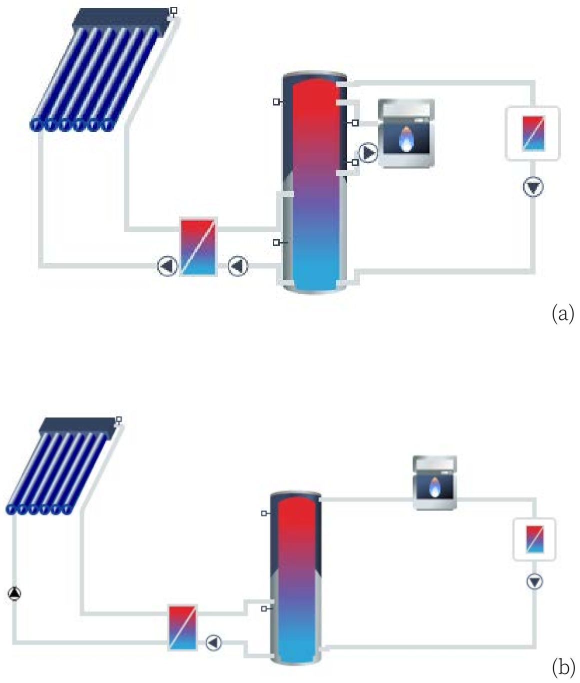

Figure 1. Solar thermal system for heat process (a) parallel boiler connection (b) series connection

The working profile of a pasteurising plant generally continues during the whole year with short breaks, for example during Sundays with half working days, Christmas, and summer holidays. Since the pasteurising process starts every early morning from 6 AM till 4 PM when the cleaning process starts with 100% capacity since it needs water at 90°C or steam compared to 20% capacity and around 73°C for the pasteurising heat process as in Figure 2. The cleaning process is preferable at a higher temperature to clean all the possible residuals in all system components such as pipes or heat exchangers which may cause serious health issues due to the existing pathogens in all dairy products. Indeed, not all pasteurising plants have the same working profiles since they may have extra processes such as cheesing, or packaging. However, this study is concerned with the main process of all pasteurising plants.

The solar thermal system is simulated using the following parameters:

- **Different sets of Evacuated-tube collectors**
  To choose the optimum collector number, an Evacuated-tube collector (ETC) is chosen with an 87.8% conversion ratio and 1.43 $W/m^2 \cdot K$ and 0.0038 $W/m^2 \cdot K^2$ simple and quadratic heat transfer coefficients. The gross area and the active area of the collector are 2.14 m^2 and 1.31 m^2 respectively with 8000 $J/m^2{\cdot}K$ specific heat capacity. Since the study is in the upper hemisphere, the solar collectors are facing the south with a tilting angle (β) of 72° which is the optimum angle for Budapest under winter weather conditions according to the solar electricity handbook.
- **Collector loop heat exchanger**
  The maximum heat transferred by the heat exchanger depends on the size of the system such as the collector area and the process heat demand. For our study, the mean logarithmic temperature difference (MLTD) is considered to be at 5°K for all scenarios.

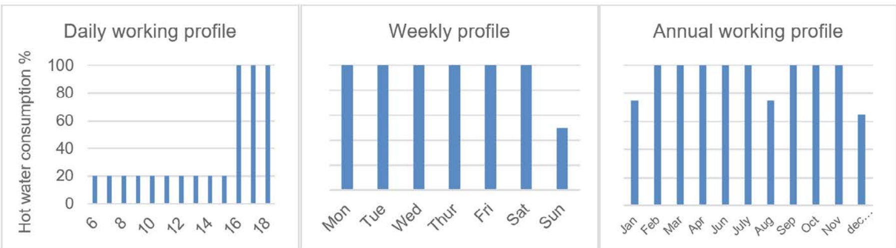

Figure 2. Daily, weekly, and monthly pasteurising profiles

- **Buffer tank**
  The buffer tank is an unstratified tank with 100 mm insulation thickness, 0.065 W/m · K thermal conductivity, and the expected average daily heat loss to be at 7.10 kWh/day. The studied variable considering the buffer tank is the height-to-diameter ratio HT/D.
- **Auxiliary heater**
  53.1 kW gas-fired boiler is connected in parallel with the buffer tank or series with the secondary loop before the process heat section. The capacity of the auxiliary heater is oversized since it is not only needed for the process heat demand but also space heating and domestic hot water supply. The efficiency of the boiler is 85% measured based on the low heat value. The studied variable here is the connection type, in series or parallel.
- **Flow circulation pumps**
  There are several pumps mounted in the system which are needed for circulating the running medium fluid. The first one is mounted in the primary loop in two places, the first one between the solar collector and the external heat exchanger and the second one circulates the fluid between the buffer tank and the external heat exchanger. While in the secondary loop there is a circulating pump between the process heat and the buffer tank, in addition to an extra pump needed in the parallel mode between the boiler and the buffer tank. For each pump, there is an on/off controlling system that generates the signals for each pump. In the primary loop, the controlling system generates an on signal if the collector's output temperature is above the reference temperature of the tank by $+8^0$K and generates an off signal if it is +3°K. Two variables are studied in this section, which is the glycol volumetric ratio and the volume flow rate.
- **Internal and external piping system**
  The external piping system is the piping parts that exist between the buffer tank and the solar collectors. While the internal ones are between the buffer tank and the process heat. The sizing of the pipes is chosen relatively based on 0.5 m/s fluid velocities. The piping system is surrounded by a thermal insulator which has 0.045 W/m · K thermal conductivity and 100% relative thickness to the nominal pipe's diameter.
- **Weather and meteorological data**
  T*sol uses an external weather acquisition program as an external Typical Meteorological Year (TMY) file for the studied location. In our case study, Budapest is the chosen city, and the weather data are acquired between 1986 and 2005.

Results and discussion

Required collector area

The modelling is studied for 20 collector areas varying from 5 to 100 m^2 with an incremental step of 5 m^2. To make the comparison, both in series and parallel systems were modelled while fixing the other variables at 50 l/m2 tank volume to solar collector area which is recommended for solar heat for industrial processes under the climate of central Europe [25]. The relative volume flow rate to each square meter of the collector area is at 50 l/m^2·h as recommended by the literature [26]. In the primary loop, the volumetric glycol ratio is 30% that has 3736 J/kg · K specific heat capacity, and it can stand −13°C freezing temperature till −30°C for burst protection according to the Hungarian climate. Finally, the height-to-diameter ratio of the buffer tank chosen to be 1.8 m/m. Above this value, the daily heat losses from the tank will be relatively higher due to the larger exposed surface to the ambient.

The results show, as in Figure 3, that in general in series boiler connection has higher results than in parallel configuration. It is noted that the difference reaches its maximum value of 5.8% when the collector area is at 65 m^2. At this value in series connection delivers 65.48% solar fraction while in parallel delivers 59.68% only. According to the designing recommendations from financial aspects, the best feasible design should deliver between 40–60% solar fraction in winter and summer conditions, respectively. As average design value, 50% annual solar fraction is the optimum which stands for 40–45 m^2 which equals 20 ETC collectors. This design is considered an adequate design since it provides more than 50% monthly solar fraction between April to October, nevertheless, it does not fall below 25% monthly solar fraction for the rest of the year. Taking into consideration the required space, costs, and the potential reliability issues which are attributed to large systems (in our case between 40–45 m^2), this system is an adequate design for the studied pasteurising plant located in Budapest, Hungary. For the assumed recommendations, the solar thermal system consists of a 40 m^2 solar collector filed provides 49.05%, 51.72% in parallel and series configuration, respectively. While a system consisting of a 45 m^2 solar collector field provides 52.27% and 55.41% in parallel and series, respectively. In conclusion, the differences for 40 m^2 and 45 m^2 solar collector fields are 2.67% and 3.14% more solar fraction in series mode than in parallel one.

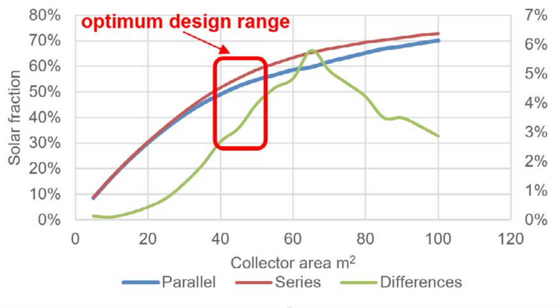

Figure 3. Collector area versus solar fraction

Figure 4. Glycol ratio effect on the solar fraction

Glycol ratio configurations

In the primary loop of the solar thermal systems, the solution of a polypropylene glycol-water mixture is used to avoid burst and freezing situations in relatively cold climates. As the glycol volumetric ratio increases in water, the specific heat decreases of the whole mixture since the specific heat of the glycol is less than the water. For the comparison, the other variables were set at fixed values similar to our first model while changing the glycol volumetric ratio. The fixed variables were 50 l/m^2 tank volume to solar collector area, 50 l/m^2 · h relative volume flow rate, and finally, the height-to-diameter ratio of the buffer tank chosen to be 1.8 m/m and 35 m^2 collector area. The glycol ratio varies from 0% (fully water solution) to 60% with an incremental step of 5%.

The results show, as in Figure 4, that in series boiler configuration has a higher solar fraction compared to in parallel one. Nevertheless, the difference does not exceed 0.5% solar fraction at the best scenarios. This concludes that the glycol ratio does not affect severely the solar fraction in both modes, in parallel and series. Anyhow, using glycol mixture in cold climate conditions is a must to avoid freezing and burst problems which may stop the entire system. From an energetic aspect, we can say that the glycol ratio does not affect the results, but we still have to take into consideration the mechanical and hydraulic aspects. For the 30% glycol volumetric ratio, we noted that the solar system provides 40.07% solar fraction in parallel mode compared to 40.48% in series mode. This concludes that in series configurations has 0.42% solar fraction than in parallel one. Also, it is noted that the maximum difference is at 15% glycol ratio 0.5% more solar fraction, but this is below the recommended values from hydraulic and mechanical aspects.

Collector flow rate configuration

The effect of the relative flow rate in the collector varies between 5 to 100 litres per hour for each square meter of the collector gross area with an incremental step of 5 l/h · m^2. The annual and monthly solar fraction was modelled for both systems, in series and parallel, to conduct the comparison. The other variables were fixed at 35 m^2 solar collector area, 50 l/m^2 relative tank volume to solar collector area, 30% volumetric glycol ratio, and finally, the height-to-diameter ratio of the buffer tank chosen to be 1.8 m/m.

The results show as in Figure 5, that in series boiler connection generally provides a higher annual solar fraction. The differences are bigger between the two systems when the relative flow rate is significant 5–15 l/h · m^2, while it is almost constant between 20–90 l/h · m^2. The difference in the results is more than 2.05% when the flow rate is 5 l/h · m^2, while it is around 0.5% in the range of 20–90 l/h · m^2. According to the recommendation of using 50 l/h · m^2 in the central European climate, we see that the difference is 0.42–0.56%.

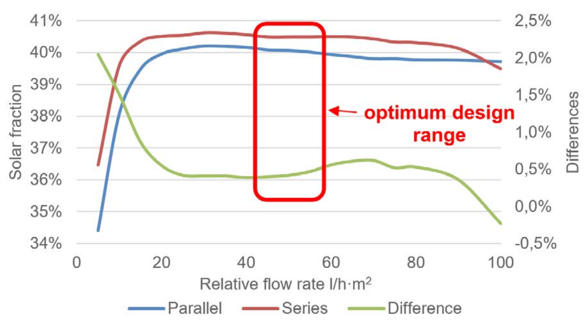

Figure 5. Relative flow rate effect on the solar fraction

Relative tank volume configuration

Considered as one of the most influential factors in the solar system, relative solar tank volume VC/AC is measured at different ratios from 10 to 300 litres buffer tank volume for each collector's gross square meter area. In the meanwhile, the other variables were fixed at a 35 m^2 solar collector area, 50 $l/h \cdot m^2$ relative volume flow rate, 30% volumetric glycol ratio, and finally, the height-to-diameter ratio of the buffer tank chosen to be 1.8 m/m.

The results show, as in Figure 6, that in general in series boiler configurations provides higher solar yield than parallel connections. The maximum difference occurs when VC/AC equals 20 litres/m^2 with a 5.1% annual solar fraction difference. According to the central and southern Europe recommendations for industrial heat process, 50–75 litres/m^2 is an adequate design. For this range, we notice that in series connection provides between 0.93–2.05% annual solar fraction.

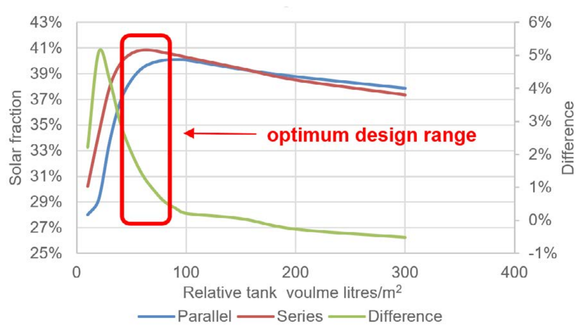

Figure 6. Relative tank volume effect on the solar fraction

Tank height-to-diameter configuration

To compare the two configurations, both systems were studied from the aspect of tank height-to-diameter ratio as the variable. While the other parameters were fixed at 35 m^2 solar collector area, 50 $l/h \cdot m^2$ volume flow rate, and 30% volumetric glycol ratio.

The results show, as in Figure 7, that in general in series connection delivers more solar yield than in parallel connection. The variations between the two configurations are 0.44% on average. For recommended designs at a 1.8 m/m tank height-to-diameter ratio, the difference is 0.42% annual solar fraction. While for horizontal design at 0.2 m/m, which is not common because it utilises more space to mount, the difference is 0.57%.

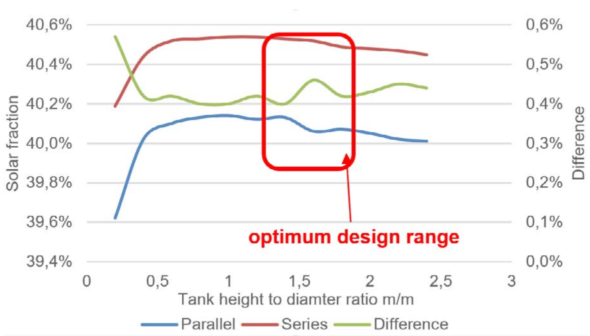

Figure 7. Tank height-to-diameter ratio effect on the solar fraction

Conclusions

Several industrial processes such as food processing require massive thermal energy demand to generate the final product. By utilising solar energy systems, this demand can be partially or totally covered with high solar fraction where more than 60% of the energy demand temperature is needed below 250°C. Nevertheless, the utilisation of solar thermal energy in the industrial sector is still below 1% worldwide due to several barriers. It means that any improvement in the designing stage can afford better solar fraction and thus wider usage. The boiler has a major role in any solar thermal system since the solar energy can't afford the total demand due to the sporadic nature of the solar radiation and the boiler compensate the rest of the demand and provide a stable flow rate at the required temperature. In the paper, we analysed two different boiler configurations for solar heat for industrial process systems to check which is the better design, in series or parallel design. The results were measured from five different aspects using T*Sol software which are: required collector area, glycol ratio, relative flow rate, relative tank volume, and tank height-to-diameter ratio. All those aspects showed that in series boiler configurations provides higher solar fraction than parallel configurations. According to the recommended designing parameters in central Europe, in series configuration are better than parallel by 3.14% at 45 m^2 collector area, 0.45% at 30% glycol ratio, 0.42% at 50 $l/h \cdot m^2$ volume flow rate, 2.05% at 50 l/m^2 relative tank capacity, and 0.42% at 1.8 tank height-to-diameter ratio respectively.

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