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Targeting the Maximum Outlet Temperature of Solar Collectors

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The aim of this work is to show the construction and application of design curves for solar collector networks of the flat plate type. The design curves display two important design parameters: delivery temperature and the minimum number of solar collectors in series to achieve that target temperature. Given the complex nature in which the various ambient and operating parameters interact to determine the thermal performance, it is justifiable to develop quick and reliable design methodologies to estimate the collector surface area required for a given industrial application. Since a solar thermal plant operates under intermittent conditions, it recognised that it must exhibit a flexible design to allow it to deliver the required thermal duty (load and temperature) under any set of ambient conditions. When establishing the number of collectors required for a given duty, the question to answer is if the system should be sized based on the most favourable ambient conditions or on the least favourable. This problem becomes an optimization problem but before such an approach is undertaken, some design and operating criteria must be established. This paper seeks to establish these criteria based on the concept of maximum outlet temperature attainable with the minimum number of solar collectors. A graphical representation of these two parameters is presented and a design approach of solar collector networks taking advantage of the manipulation of inlet temperature is demonstrated. The plots are derived for design parameters such as solar radiation, mass flow rate and inlet temperature using an experimentally validated thermal model. The approach is demonstrated on flat plate collector technology, but it can be extended to any other type of low temperature solar technology.

1. Introduction

The design of networks of solar collectors for the integration of solar thermal energy in industrial processes has still many challenges to solve. For instance, it is desirable to maximize the time for the supply of the heat load at the fixed temperature considering the daily and seasonal variability of the solar radiation bearing in mind the need to maintain the costs at a minimum. The specification of a network structure of solar collectors is not a simple task. The surface area for capturing the incoming solar energy is a critical parameter since this determines the actual heat load and temperature to be delivered to the process. Also, specification of a network of solar collectors demands the combination of series and parallel arrangements (Garg,1973). When determining the maximum temperature that can achieved by solar collectors positioned in series, a point is reached where it is unjustifiable the increase the number of collectors since the temperature increment keeps reducing such that the investment does not justify the heat load gain (Martínez-Rodríguez et al., 2018). Therefore, there is a maximum attainable temperature for a certain number of collectors placed in series. During the design of solar thermal plants to fully or partly supply the process heat duty, the size of the network must be fixed so that the system will be able to operate satisfactorily during periods of time when solar radiation is at its highest and large periods of time where solar radiation is at medium or low levels (Walmsley et al., 2014).

Various design approaches for solar collector networks have been proposed in the open literature. The main feature behind these methods is that they are based on fixed operating conditions but that still lack analysis of its operation. Among these approaches is the one presented by Picón-Núñez et al. (2013) who used the concept of thermal length and hydraulic length to create a graphical design tool to determine the arrangement and the number of collectors that meet the heat duty and temperature level at a given allowable pressure drop. Other methodologies for the design of networks of solar collectors based solely on thermal needs are the ones

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published by Oonk et al. (1979), the F-Chart by Klein et al. (1976) and the methodology developed by Li et al. (2010). The size of a collector network also depends on the mass flow rate of the thermal fluid which determines the amount of heat that will be delivered to the process. Overall, as presented by Picón-Núñez et al. (2014), the larger the mass flow rate the larger the number of parallel arrangements whereas the higher the delivery temperature, the larger the number of collectors arranged in series. However, the selection of the design conditions in the first place is a problem that must be based on costs and operability aspects. For decision making, it would be useful to have at a glance an overall picture of the range of options to identify the maximum temperature that can be achieved, and the number of collectors required considering the operating and ambient conditions, the collector technology, the working fluid and the time spam of the day for actual operation of the network. The aim of the present work is to show the construction and application of design curves that relate the specified network delivery temperature to the minimum number of collectors in series required to achieve the target. It also shows the determination of the operating conditions to achieve the heat load targets maintaining investment at low levels. Although the work focuses on flat plate collectors, the approach can readily be extended to other type of low temperature solar technology such as evacuated-tube collectors (Picón-Núñez et al., 2016).

2. Solar thermal networks

The basic design equations for the prediction of the thermal performance of flat solar collectors are shown in Eq(1) to Eq(3). The main considerations in the development of such model are: a) steady state conditions, b) solar radiation perpendicular and homogeneous to the tube surface, c) uniform flow distribution per tube inside the collectors, e) one-dimensional heat flux, and f) uniform inner tube wall temperature. The final expressions to determine the flat collector outlet temperature are:

$$mCp(T_{out} - T_{in}) = A_{abs}\,[G\tau\alpha - U_L(T_s - T_a)] \tag{1}$$

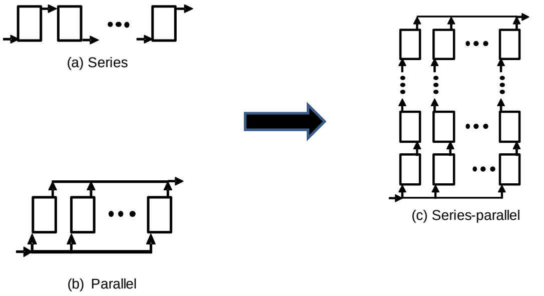
$$h_{c+r}(T_s - T_c) = U_L(T_s - T_a) \tag{2}$$

$$mCp(T_{out} - T_{in}) = hA_{abs}\,LMTD \tag{3}$$

Where: T_s is the surface temperature (°C), T_a is the ambient temperature (°C), T_{in} is the fluid inlet temperature (°C), T_{out} is the collector outlet temperature (°C), T_c is the transparent cover temperature (°C), G is the solar radiation, τ is the transmittance of the transparent cover, α is the absorptivity of the selective layer and A_{abs} is the surface area for the absorption of solar energy (m^2), LMTD is the logarithmic mean temperature difference (°C), h is the heat transfer coefficient between the fluid and the surface (W/m^2 °C), U_L is the coefficient of thermal losses (W/m^2 °C), h_{c+r} is heat transfer coefficient for the combined convection-radiation between the surface and the transparent cover, m is the fluid mass flow rate (kg/s) and Cp is the heat capacity (J/kg °C). The heat transfer coefficient (h) can be obtained from an expression of the following form (Munz et al., 1983):

$$Nu = bRe^{x}Pr^{y} \tag{4}$$

The network arrangement refers to the specific structure that will meet the required design specifications and is composed of sets of collectors in series and rows or branches of collectors in parallel. The number of collectors in a set is fixed by the temperature the system is to deliver; whereas the number of rows or branches in parallel is determined by the required mass flow rate. Figure 1 depicts a typical network structure.



(a) Series

(b) Parallel

(c) Series-parallel

Figure 1: Structural components of a network of solar collectors

Overall, the thermal integration of a solar system into a processing plant contains some basic elements: a solar collector network, a storage system and temperature control system, as shown in Figure 2. As the present work focuses only on the solar collector network, the following section shows the validation of the thermal model against experimental data. Then the model is used to graphically determine the maximum temperature that can be reached for given solar radiation, inlet temperature and mass flow rate.

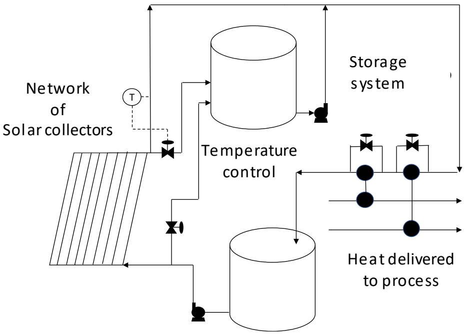


Figure 2: Basic components of an integrated solar thermal system into processing plants

2.1 Flat plate collector

The theoretical model of a flat solar collector broadly described above is validated against experimental data. The geometrical specifications of the flat plate collector used for the experimental measures are: 8 tubes 1.97 m long and 0.54 cm external diameter; clearance between tubes: 11.25 cm. The transparent cover is made of tempered glass 4 mm thick. Glass fiber is used as thermal insulation. Table 1 shows the comparison between the experimental ($T_{out\ exp}$) and theoretical outlet temperature ($T_{out\ theo}$). Since the results show that the maximum error is 4.5 %, the theoretical model is considered robust enough and later is used to predict the thermal performance of sets of collectors arranged in series as shown in Figure 3. The experimental curve was obtained as follows: from the experimental data, the efficiency curve is produced, this curve is used to extrapolate the outlet temperature of sets of collectors in series.

Table 1: Validation of the theoretical model for flat plate collectors

Irradiance (W/m^2)	T_a (°C)	T_{in} (°C)	T_s (°C)	T_c (°C)	$T_{out\ theo}$ (°C)	$T_{out\ exp}$ (°C)	% Error
924.20	26.60	56.30	73.66	44.88	60.69	61.00	0.50
925.40	26.60	56.50	74.35	46.99	61.02	61.20	0.30
925.30	26.40	56.50	73.82	44.84	60.88	61.30	0.68
928.40	26.70	56.70	74.21	45.61	61.13	61.50	0.60
949.20	28.00	47.00	67.00	42.79	52.06	52.90	1.59
948.20	27.90	47.10	67.33	43.96	52.22	52.80	1.10
945.40	28.00	47.10	66.99	42.78	52.13	52.70	1.08
943.90	28.20	47.00	66.91	42.87	52.04	52.70	1.26
957.80	22.00	34.00	55.70	34.42	39.49	40.20	1.77
956.10	21.90	34.00	55.72	34.67	39.49	40.10	1.51
956.00	22.20	34.10	55.77	34.57	39.58	40.20	1.54
956.10	21.70	34.00	55.73	34.71	39.50	40.00	1.26
937.70	19.10	20.00	43.24	27.60	25.88	27.10	4.50
938.90	19.00	20.00	43.34	27.90	25.90	27.00	4.06
940.10	19.10	20.10	43.44	27.89	26.00	27.00	3.69
941.80	19.00	20.00	43.59	28.74	25.97	26.90	3.47

3. Targeting for maximum temperature

Knowledge of the maximum outlet temperature that a solar collector or series arrangement of solar collectors can reach for a given mass flow rate, solar radiation and inlet temperature, is a fundamental output that determines the feasibility of the application of low temperature solar plants. The procedure for its determination and the minimum number of collectors required is as follows:

1.- Equations (1) to (3) are solved for a single collector for a fixed solar radiation intensity, mass flow rate and inlet temperature.

2.- The outlet temperature of the collector is used to solve the model again using this value as inlet temperature of the next collector.

3.-The process is repeated until the difference between the inlet temperature and outlet temperature of the next collector is lower than 1.

The targeting curves for flat plate collectors are shown in Figure 4. Figure 4a shows the curves for winter, a mass flow rate of 4.3 l/min and an inlet temperature of 20 °C. The bars at a given time indicate the targets for that time of the day. At the highest radiation level during the day, a maximum temperature of 97.50 °C is obtained with 36 collectors in series and a solar intensity of 808.37 W/m^2. Figure 4b, shows the targeting curve for summer, where the maximum outlet temperature reached is 126.87 °C with 40 collectors. The effect of mass flow rate is analyzed, and the results presented in Figure 4c. A mass flow rate of 15 l/min for summer conditions reveals that the maximum temperature that can be reached is 77.82 °C with 45 collectors. Additionally, the effect of inlet temperature upon the targeting curve is shown in Figure 4d where a temperature increment of 10 °C is analyzed. The results show that for a typical winter day and an inlet temperature of 30 °C, the maximum temperature that can be reached is 97.3 °C with 33 collectors.

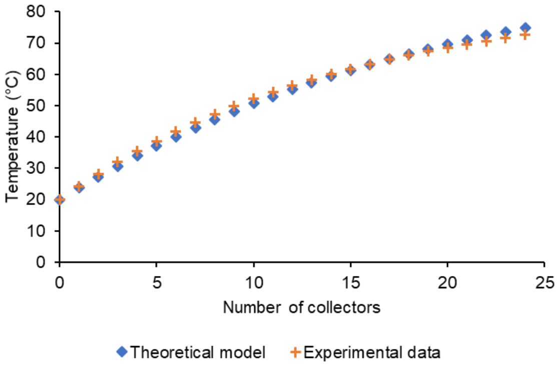


Figure 3: Prediction of the outlet temperature using the theoretical model and the experimental efficiency curve for a flat plate solar collector

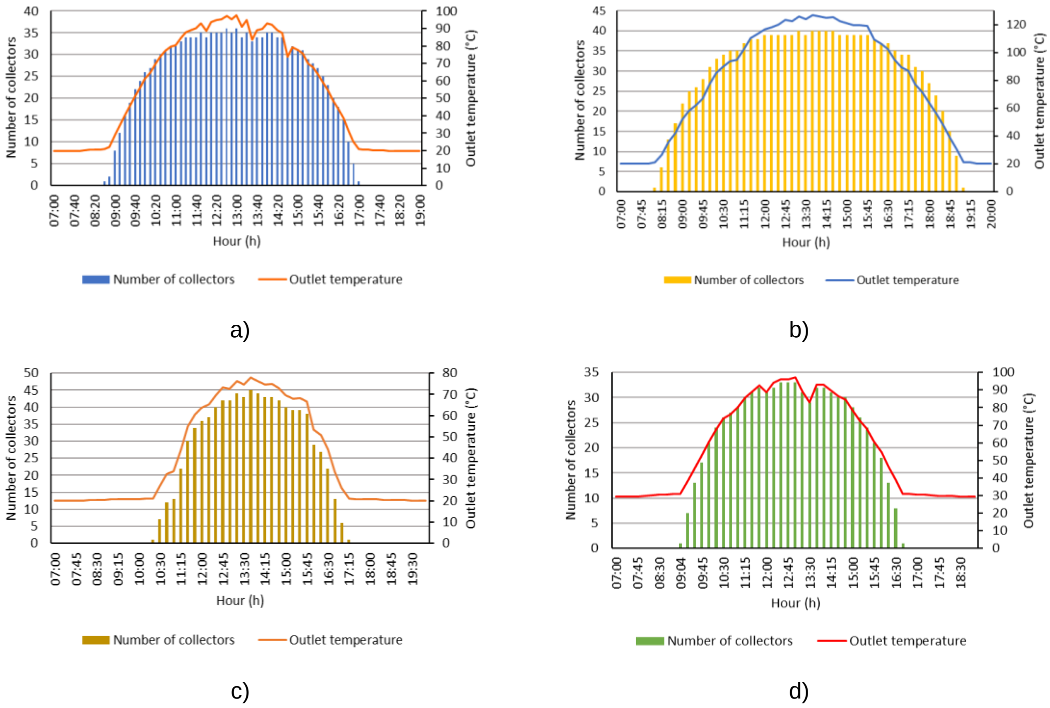
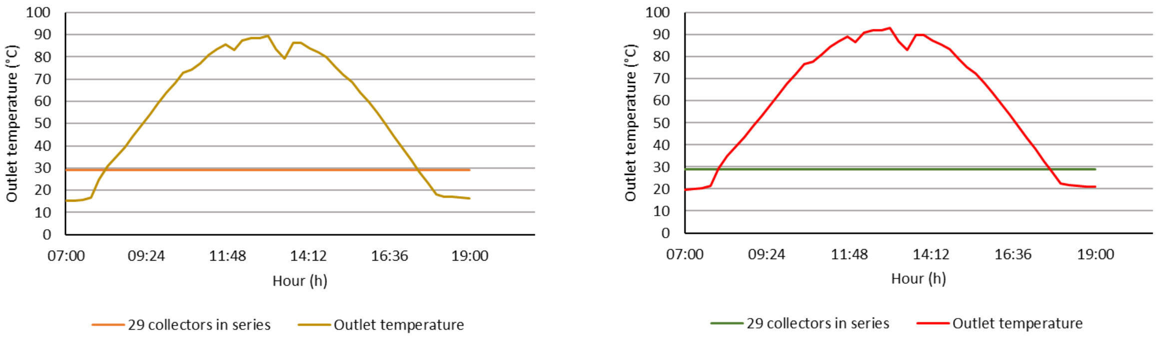


Figure 4: Design curves for maximum outlet temperature and minimum number of collectors: a) Design for winter, inlet temperature of 20 °C and mass flow rate of 4.3 l/min; b) Summer conditions, inlet temperature of 20 °C and mass flow rate of 4.3 l/min; c) Summer conditions and a mass flow rate of 15 l/min; d) Winter conditions, mass flow rate of 4.3 l/min and inlet temperature of 30 °C

4. Network selection procedure

The selection of the network structure must be based on a trade-off between investment and operating time. Therefore, the first set of values identified through the targeting plots must be followed by an analysis of performance using the thermal model. Two extreme design options are those derived from the plots generated for the winter and for the summer seasons. The main difference between these two options is the number of collectors and the time interval over which the target temperature can be reached. The decision of using the design for winter conditions means larger investment and larger amount of energy collection for storage when the solar irradiation increases. On the other hand, the design for the summer season, means a reduced number of collectors and shorter period of operation in less favorable ambient conditions. However, inlet temperature is a degree of freedom that can be manipulated for improved performance. Energy stored can be used to increase the inlet temperature and so counteract the lower surface area to recoup the temperature potential. So, in a second stage of the network selection process, the thermal model is applied to achieve two purposes: 1.- asses the performance of the network with lower number of collectors during the low irradiation seasons, and 2.- to determine the impact of the increase of inlet temperature upon the performance of the network. Figure 5a shows the case for winter operating with only 29 collectors in series and an inlet temperature of 20 °C, and Figure 5b shows the same conditions but with an inlet temperature of 30 °C.



a) b)

Figure 5: Thermal performance curves for a network of 29 collectors in series: a) Performance over winter with an inlet temperature of 20 °C and a mass flow rate of 4.3 l/min; b) Performance over winter with an inlet temperature of 30 °C and a mass flow rate of 4.3 l/min

4.1 Application

A typical low temperature food process in Mexico is the nixtamalization, a chemical process whereby maize undergoes a thermal treatment in an alkaline medium using calcium oxide. After the reaction, a lump of natural polymers and starch is obtained. Water is added in a 3:1 ratio with respect to the grain weight. Cooking time varies between 20 to 50 minutes depending on the hardness of the grain, with harder grain requiring the longest time. Cooking temperature ranges between 85 °C and 92 ºC, which is enough to gelatinize the starch. For a daily throughput of 6,000 kg and considering a water feed temperature of 85 °C, the amount of water required per day is 18,000 l/day. A water supply temperature of 20 °C is assumed. Using the design plots, it is found that in winter a network comprising 20 sets of 34 collectors in series each (680 collectors in total) operating with a flow rate of 4.3 l/min and a total of 3 h 20 min (from 11:10 to 14:30 h) would be enough to supply the needs of the process. If the design was carried out using the summer plot, a new network using 29 collectors in series is needed. This means a saving of 14.7 % of surface area. The operation time of this new network in winter goes from 11:45 to 14:15 (2 h 30 min). However, operating the new network with an inlet temperature of 30 °C results in an operating time between 11:15 and 14:45 (3 h 30 min).

This example shows that inlet temperature is a key variable that determines the performance of a network. Although the operating time shrinks a bit as the smaller network is analyzed, this can be compensated for by increasing the inlet temperature during the seasons with lower solar irradiation. To this end, the storage and the temperature control systems of the solar thermal plant play an important role in the conditioning of the inlet temperature and the delivery of the thermal load.

5. Conclusions

There are various aspects that need to be solved for the thermal integration of low temperature systems to become the first choice of energy source in low temperature processes. Despite being mature enough, solar collector technology is not seen as reliable and cost effective compared to conventional sources of energy. This should not be the case. The thermal integration of low temperature solar plants must be flexible enough to accommodate the variation of the ambient conditions and even the variations in the process needs to deliver the process temperature and heat load targets. The work presented in this paper has set the basis for a flexible design able to absorb the typical disturbances a solar network is bound to encounter through the year, maintain the investment at low levels and guarantee the supply of the required heat duty. It is also shown that the flexibility in the operation can be achieved by the manipulation of operating parameters, particularly inlet temperature. For design purposes it can be concluded that subject to the process needs and keep investment and solar plot area at low levels, a solar network must be designed for the most favorable ambient conditions found in the summer and manipulate the inlet temperature to compensate for a low solar radiation intake during the winter.

Apart from solar radiation, other variables that have an impact upon the size of a network of solar collectors are: the collector technology, the mass flow rate and the inlet temperature. In design, another important parameter is the time spam where the required temperature can be achieved. All this information is available on the target plots presented in this work, where the maximum achievable outlet temperature linked to the minimum number of solar collectors in series are displayed. However, it is important to emphasize that for this information to be generated, the use of a reliable and simple thermal model is fundamental.

This paper has dealt with the design of solar collector networks; however, the future work will be focused on the analysis of the whole solar collector system which, apart from the collector network, is made up of other components that are needed to provide the required plant operability. These components are: the heat storage system and the temperature control system.

References

Garg H.P., 1973, Design and performance of a large-scale size solar water heater, Solar Energy, 14, 303-312.

Klein S.A., Beckman W.A., Duffie J.A., 1976, A design procedure for Solar Heating Systems, Solar Energy, 18, 113-127.

Li Z., Chen C., Lou H., Xue Y., 2010, All–glass vacuum tube collector Heat Transfer model used in Forced-Circulation solar water heating system, Solar Energy, 84, 1413-1421.

Martínez-Rodríguez G., Fuentes-Silva A. L., Picón-Núñez M., 2018, Solar Thermal Networks operating with Evacuated-tube Collectors, Energy, 146, 26-33.

Munz B.B, B.J. Gandy, L. Lankenbach (Eds), 1983, Heat Exchanger Design Handbook, Forced convection in ducts, Hemi- sphere Publishing Corporation, New York, USA.

Oonk R., Jones D., Cole-Appel B., 1979, Calculation of performance of N collectors in series from test data on a single collector, Solar Energy, 23, 535-536.

Picón-Núñez M., Martínez-Rodríguez G., Fuentes-Silva A. L., 2013, Thermo-hydraulic Design of Solar Collector Networks for Industrial Applications, Chemical Engineering Transactions, 35, 457-462.

Picón-Núñez M., Martínez-Rodríguez G., Fuentes-Silva A.L., 2014, Design of solar Collector Networks for Industrial Applications, Applied Thermal Engineering, 70, 1238- 1245.

Picón-Núñez M., Martínez-Rodríguez G., Fuentes-Silva A. L., 2016, Targeting and design of evacuated-tube Solar Collector Networks, Chemical Engineering Transactions, 52, 859-864.

Walmsley M. R. W., Walmsley T. G., Atkins M. J., Neale J. R., 2014, Options for Solar Thermal and Heat Recovery Loop Hybrid System Design, Chemical Engineering Transactions, 39, 361-366.