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Targeting and Design of Evacuated-Tube Solar Collector Networks

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In this work the structure of solar collector networks for the supply of thermal energy to low energy intensity industrial processes is determined. For a given solar radiation intensity it is shown that the inlet temperature is the design variable that has a major impact upon the surface area. Typically a solar collector network exhibits a structure which is a combination of series-parallel arrangement. In design, the number of lines in parallel is determined based on the total mass flow rate required and pressure drop specified while the number of collectors in series is established by the target temperature. The achievement of the process thermal requirements depends on the thermal performance of the collector technology as well as the availability of the solar radiation. This work focuses on the use of evacuated-tube solar collectors and presents an approach for the specification of the network structure required. The approach is demonstrated on a case study.

1. Introduction

The supply of the thermal needs of low intensity processes through the absorption of solar energy and its conversion into thermal energy is achieved by means of a network of solar collectors. The size and arrangement of such networks to accomplish this task depends on the amount of solar energy received and the type of technology to be used. For processes where the target temperature is lower than 100 °C, the evacuated tube collector is the current most efficient technology available. The structure and the total surface area of the network to be installed depends on the design variables, such as process temperature needs, water inlet temperature, solar radiation and ambient conditions of the location where the plant operates. This paper discusses the various options and considerations for the design of these systems.

In terms of the definition of the network structure for a given application, one of the first approaches was introduced Oonk (1979), who developed a methodology to predict the thermal performance of n solar collectors arranged in series based on experimental data. The collector field or network is defined based on the heat load, the temperature level, the mass flow rate and the thermal fluid. Reports of cases where solar energy is used to supply part or the totality of the heat loads of process plants where the temperature levels range between 40 °C and 80 °C were presented by Walmsley at al. (2014) but the reports do not contain information regarding the actual network structure. The solar energy absorption area of a solar collector network strongly depends on the process thermal needs and the ambient conditions. Other examples of applications of solar energy to process plants is the case reported by Quijera et al. (2011) where it was reported that a network of 1,000 m² can supply 50 % of the thermal load of a dairy plant during spring and summer. Among other cases reported is the sea water desalinization where 1,064 evacuated tube solar collectors arranged in parallel are used (El-Nashar, 2009). Some works that look into the thermal integration of solar energy in process plants report on the total surface area required and the number of collectors but only a few describe the actual network structure (Quijera, 2011). SO far, no consideration has been given the actual consumption of pressure drop as a design parameter. A methodology that makes this consideration for the case of flat plate collectors was presented by Picón Núñez et al. (2013).

This work shows the approach for the design of networks of evacuated tube collectors considering: the effect of the heat load, pressured drop, ambient conditions and the collector logarithmic mean temperature

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difference upon the network structure. Since the work at this stage focuses on the network structure the case study is defined only on the basis of the actual thermal needs and temperature level requirements.

2. Arrangement of a network of solar collectors

A network of solar collectors can exhibit different arrangements: cascade, parallel, series and series-parallel. In design the structure can be specified by means of two dimensions, a thermal and a hydraulic dimension. The thermal dimension which in this work is termed: thermal length (Lt), refers to the total collector length that is required to supply the process heat duty, while the hydraulic length (Lh) is the total collector length required to fully absorb the available pressure drop. The ideal design corresponds to the point where for a given network structure both dimensions equate (Picón Núñez, 2014). The operating parameters that modify the thermal length are the inlet, outlet and fluid velocity according to:

$$L_t = \frac{Q}{\pi\, d_i N_t U_p h\, LMTD} \tag{1}$$

Where: Q is the heat load, di is the tube inlet diameter, Nt is the number of tubes of the collector, Up is the number of parallel arrangements, h is the heat transfer coefficient and LMTD is the logarithmic mean temperature difference given by:

$$LMTD = \frac{T_{in}-T_{out}}{ln\left(\frac{T_p-T_{out}}{T_p-T_{in}}\right)} \tag{2}$$

Where:Tp is the plate surface temperature. The hydraulic length depends on the velocity, the inlet diameter of the tube, and the number of parallel arrangements of the network. ∆P is the available pressure drop and f is the friction factor which depends on the flow regime:

$$L_h = \frac{\Delta P\, \rho\, d_i^5\; N_t^2\, U_p^2\, \pi}{32\, f\, \dot{m}} \tag{3}$$

2.1 Evacuated tube solar collector

Despite the fact that evacuated tube solar collectors cannot operate with pressures above 1 kg/cm² and cannot withstand thermal shocks during operation, their thermal performance is superior to other technologies such as flat plate collectors (Morrison et al., 2005). A thermal model for this type of technology is developed in this work considering the following assumptions: 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 total amount of energy received on the collector surface is:

$$q_t = A_{abs}\, G\, \tau\alpha \tag{4}$$

The heat losses by radiation in the tube are represented by:

$$q_r = A_{abs}\, \varepsilon\, \sigma\left(T_p^4 - T_a^4\right) \tag{5}$$

The useful heat (q_u) that is transferred from the surface to the thermal fluid is given by:

$$q_u = A_{abs}\, \left[G\tau\alpha - \varepsilon\, \sigma\left(T_p^4 - T_a^4\right)\right] \tag{6}$$

Where: T_p is the surface temperature, T_a is the ambient temperature, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^4), ε is the emissivity of the selective surface layer, G is the solar radiation, τ is the transmittance of the glass tube, α is the absorptivity of the selective layer and A_{abs} is the surface area for the absorption of solar energy. In terms of the logarithmic mean temperature difference, the useful heat can be calculated from:

$$q_u = h\, A_{abs}\, LMTD \tag{7}$$

The heat transfer coefficient can be obtained from an expression of the form (Gnielinski, 1983):

$$Nu = bRe^x Pr^y \tag{8}$$

From the energy balance, we have that:

$$q_u = mCp(T_{in} - T_{out}) \tag{9}$$

Combining Eqs(6), (7) and (9) gives:

$$mCp(T_{in} - T_{out}) = A_{abs}\left[G\tau\alpha - \varepsilon\,\sigma\left(T_p^4 - T_a^4\right)\right] \tag{10}$$

$$mCp(T_{in} - T_{out}) = hA_{abs}\,LMTD \tag{11}$$

The two unknowns (T_{out} and T_p) can be found solving Eqs(10) and (11). The value used for the product $\tau\sigma$ is 0.837 (Li et al., 2010). Figure 1 is a flow chart of the solution of the model.

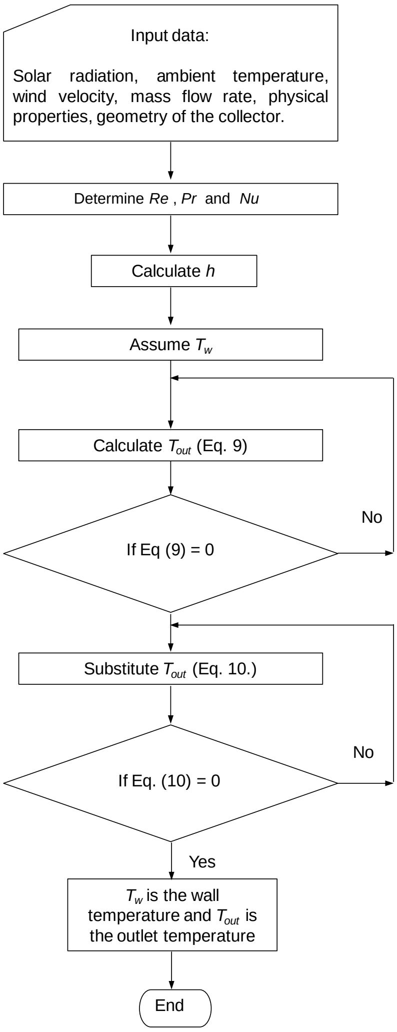

Figure 1: Flow diagram for the determination of the fluid outlet temperature.

3. Design considerations

For the scope of this work, the main information of the process pant to be considered is the thermal duty and the temperature level required. Such data is taken from a dairy factory and the information is: operation during 360 days a year seven days a week. In normal operation, the plant consumes hot water at 85 °C which is produced by the operation of a boiler that heat water up from 19 °C to target. The total energy consumption is 4,401.01 kWh/d.

The solar radiations and ambient conditions are taken as those found in the state of Guanajuato in Mexico which is located between the parallels 19°55’08’’and 21°52’09’’ north latitude and between the meridians 99°41’06’’ and 102°09’07’’ of west longitude. From historical data, the weather conditions for this region are: maximum temperature, 26.2 °C; minimum temperature, 11.3 °C; mean temperature, 18.7 °C. The mean solar radiation in the country is 5.5 kWh/d, and for the state of Guanajuato is 6 kWh/d. Figure 2 shows the solar radiation for a typical clear day and for a cloudy day for the year 2010. In January the duration of a day is approximately 11 h with the lowest solar radiation causing also the lowest collector surface temperatures. The shadowed area under the curve represents the irradiation, defined as the total amount of solar energy available at a certain location. Typically, a cloudy day represents 50 % of the irradiation of a sunny day.

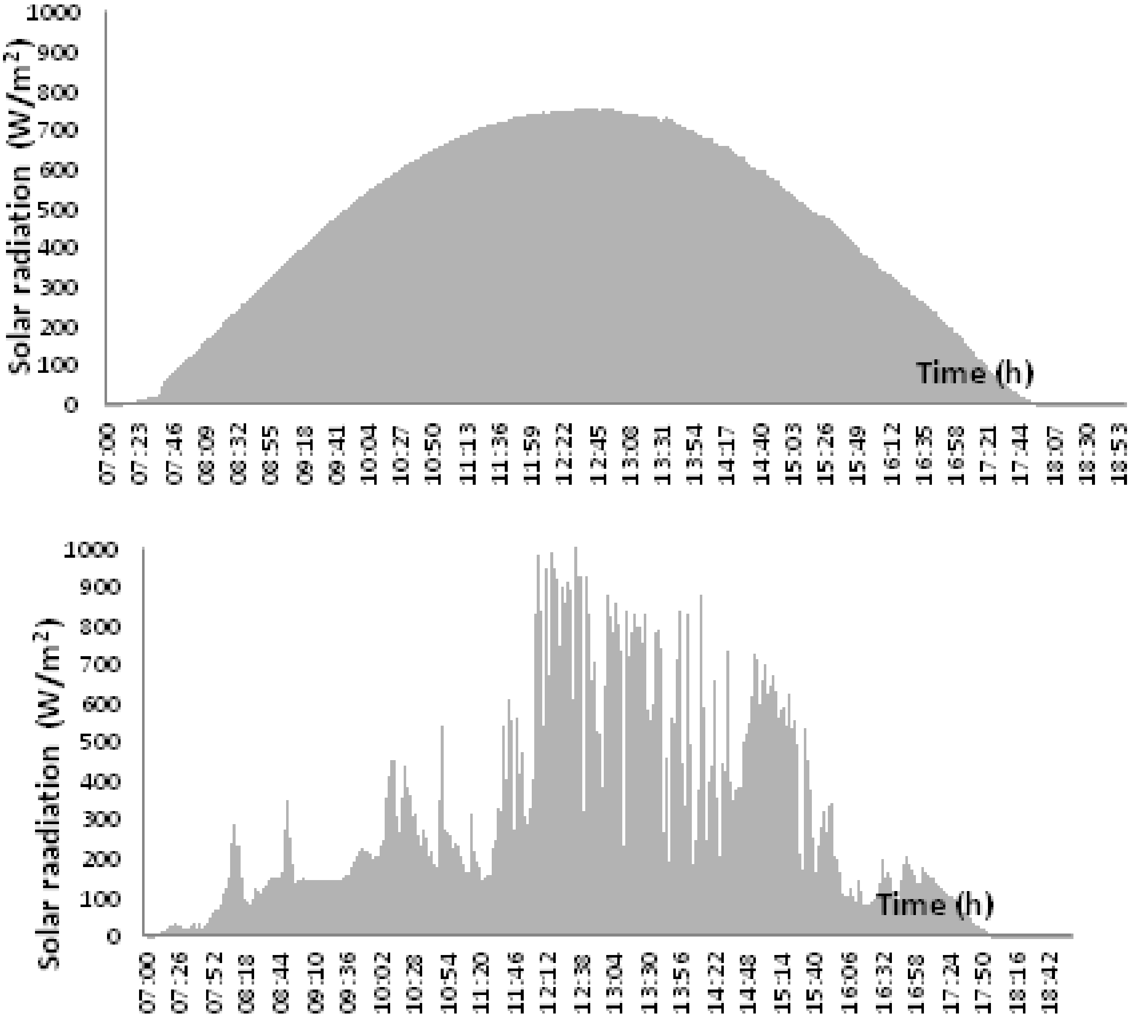

Figure 2: Solar radiation on a horizontal surface in a sunny day and a cloudy day.

4. Results and discussion

Figure 3 shows a design pictorial tool for networks of evacuated solar collectors that results from the solution of Eqs(1) and (3) for a range of Up values. The “y” axis is the number of collectors in series and the “x” axis represents the number of parallel arrays. The number of thermal and hydraulic collectors is obtained from the corresponding lengths and the length of a single collector. As described above, the intersection between the thermal and the hydraulic dimensions is the ideal design option. The region to the right of this point is an acceptable design region. The hydraulic dimensions were determined considering an available pressure drop of 101.3 kPa. It is assumed that the network is to start operation at 10:00 a.m. Under the operating and ambient conditions prevailing at this time, the design shows that three lines in parallel are required; each one containing 105 collectors in series. This is a total of 315 collectors with a total surface area of 799.0 m^2. In the following section, a set of design scenarios are considered.

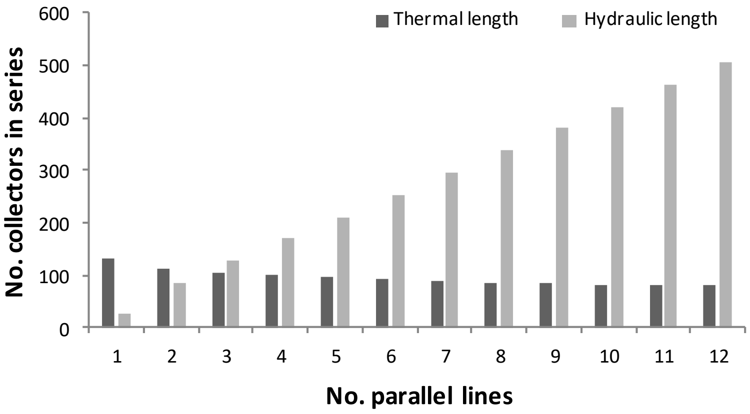

Figure 3: Graphical tool for the design of evacuated tube solar collectors.

4.1 Scenario 1

In this scenario the network of collectors is designed for the more critical ambient conditions found in January. Another design condition that has an effect upon the final network structure is the time of the day when the system is to be designed for. Since the LMTD varies with time, this parameter influences the surface area requirements. Table 1 shows the network structure required for different radiation levels. The operating conditions are as follows: water inlet temperature 19 °C; process heat duty, 4401.01 kWh/d; water outlet temperature, 85 °C. With the radiation level at 08:30 h, a single solar collector exhibits a temperature rise of 1°C.

Table 1: Solar collector network design for different LMTD values.

Time (h)	G (W/m^2)	LMTD (°C)	Series-parallel arrangement	No. of collectors
08:30	187.88	1.43	206-6	1,236
09:00	292.45	1.97	162-4	648
09:30	397.53	2.49	128-4	512
10:00	493.58	3.20	100-4	400

4.2 Scenario 2

In this scenario the effect of the inlet water temperature and the target temperature upon the network structure is analyzed. Table 2 shows that as the water inlet temperature increases the number of collectors decreases. For instance, for a target temperature of 85 °C, if the inlet temperature is 19 °C, 648 collectors are required whereas if the inlet temperature was 25 °C, the requirement is 438. If the inlet temperature is maintained at 19 °C but the target temperature is required at 95 °C, the number of collector increases from 648 to 744.

Table 2: Solar collector network design considering different operating conditions..

Inlet Temperature (°C)	Outlet Temperature (°C)	Series-parallel arrangement	No. of collectors	Area (m^2)
19	95	186-4	744	1,888.27
25	95	161-4	644	1,634.47
19	85	162-4	648	1,644.62
25	85	146-3	438	1,111.64

4.3 Scenario 3

This scenario considers an inlet temperature of 66 °C with an outlet of 95 °C. From 11:00 h, a single collector exhibits water temperature increments of 1 °C. The number of collectors to supply the heat load within the specified pressure drop is 48 collectors in series.

It can be seen from the results above that inlet temperature has a major impact upon the surface area requirements. Higher inlet temperatures can be achieved if surplus thermal energy is stored and later used raise the temperature of the incoming fluid. Since the network is designed for the critical conditions, the outlet temperature rises as the solar radiation intensifies during the day. A control strategy has to be implemented; the development of such strategy is beyond the scope of the present work.

5. Conclusions

Among the main design variables a designer has to consider in the application of solar thermal energy to supply part or the totality of the heat duty of industrial processes is the water inlet temperature, the process heat load, the fluid outlet temperature, the available pressure drop, solar radiation at the site and ambient conditions. Out of these variables, fluid inlet temperature has a stronger impact upon the size of the collector network, with higher inlet temperatures resulting in smaller surface areas. However, for practical heat recovery, the operation with higher inlet temperatures causes the reduction of the period of time for solar energy collection since during the first hours of the day, solar radiation may not be enough for effective temperature increments on the fluid. The consequence of this is that solar energy can only be recovered in a shorter period of time. On the other hand lower inlet temperatures will require larger surface areas but will cause the system to operate during a longer period of time. Determination of the optimal inlet temperature through optimization is the necessary next step and this must be followed by an operating strategy linked to a control system.

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