Article

Journal of Chemical and Physical Energy

June 2023, Vol.10 No.28 16-24

Consideration of fouling by scaling in the sizing of flat plate solar collector networks

Consideración de ensuciamiento por scaling en el dimensionamiento de redes de colectores solares de placa plana

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DOI: 10.35429/JCPE.2023.28.10.16.24

Received March 20, 2023; Accepted June 30, 2023

Abstract

In this work, the effects of fouling on the performance of flat plate solar collector networks that operate with water as the thermal fluid are studied, and design considerations are put forward to be used in the sizing of these systems from the thermal and hydraulic points of view. The quantification of the effects produced by scaling is carried out through a mathematical model that predicts the deposition on the walls of the tubes. The model considers that $CaCO_3$ is the only compound present in the fouling layer. Results indicate that for a volumetric flow rate of 3.78 l/min and assuming a $CaCO_3$ concentration of 250 ppm, in a period of six months, the maximum outlet temperature that can be obtained in a day falls 1.5 °C and the pressure drop increases four times. It is shown that it is advisable to design a network of solar collectors considering scaling. The case study indicates that to supply a total flow rate of 48 l/min at a temperature of 70 °C, the design considering scaling requires 220 collectors and a volumetric flow rate of 4.8 l/min per line with a total annualized operating cost of $343,300 Mx.

Design, Flat plate, Solar collectors, Networks, Thermal-hydraulic performance, Scaling, Pressure drop, Mathematical model, Fouling prediction

Resumen

En este trabajo se estudian los efectos del ensuciamiento por scaling en redes de colectores solares de placa plana que operan con agua como fluido de trabajo y se plantean consideraciones que se utilizan en el dimensionamiento de estos sistemas tanto desde el punto de vista térmico como hidráulico. La cuantificación de los efectos ocasionados por el ensuciamiento se realiza a través de un modelo matemático que predice la deposición en las paredes de los tubos. El modelo considera al $CaCO_3$ como el único compuesto presente en la capa de ensuciamiento. Los resultados indican que para un flujo volumétrico de 3.78 l/min y suponiendo una concentración de $CaCO_3$ de 250 ppm, en un periodo de seis meses, la máxima temperatura de salida que se puede obtener durante el día se reduce 1.5 °C y la caída de presión aumenta cuatro veces. Se demuestra que es más recomendable diseñar una red colectores solares considerando scaling. El caso de estudio indica que para suministrar un flujo total de 48 l/min a una temperatura de 70°C, el diseño considerando scaling requiere 220 colectores y un flujo volumétrico de 4.8 l/min por línea con un costo total de operación anualizado de $343,300 Mx.

Diseño, placa plana, Colectores solares, Redes, Desempeño termo-hidráulico, Scaling, Caída de presión, Modelo matemático, Predicción de ensuciamiento

Citation: LUGO-GRANADOS, Hebert Gerardo, CANIZALEZ-DÁVALOS, Lázaro and PICÓN-NÚÑEZ, Martín. Consideration of fouling by scaling in the sizing of flat plate solar collector networks. Journal of Chemical and Physical Energy. 2023. 10-28: 16-24

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Introduction

Scaling fouling is a common phenomenon in thermal equipment using water as the working fluid. Sometimes, scaling can lead to severe thermal and hydraulic problems characterised by a loss of heat transfer capacity and increased pressure drop. High water hardness, high temperatures and low flow velocity are factors that favour the formation of scaling. Proper control of these variables can reduce the problems caused by this type of fouling [I].

There are several methods to reduce scaling fouling. Among the most commonly used are treating water to reduce its hardness and replacing the use of water with mixtures of ethylene glycol and water as working fluids. These methods have additional costs associated with them, tend to contaminate the water and can cause corrosion problems by changing the pH.

Some authors have used coatings to inhibit scaling scale deposition on solar collector tubes. The use of anti-scaling coatings can extend the life cycle and cleaning period of the equipment. Although coatings can inhibit the deposition process of CaCO3 and oxide scale, they also tend to increase the resistance to heat transfer due to the thickness of the coating itself [II].

Another way to prevent fouling is through corrective cleaning techniques. These techniques could be implemented more effectively if the speed at which the fouling layer forms were known in order to determine, in advance, the appropriate time to clean the equipment. On the other hand, from an operational point of view, a factor that has been shown to have an important effect on the speed of scaling is the velocity of the working fluid. This parameter is defined at the design stage of the equipment, which means that fouling can be reduced from this early stage.

The aim of the work presented here is to demonstrate how to design to reduce fouling and predict the appropriate time to carry out cleaning activities on the equipment. In this context, this work introduces a study to quantify the effects of scaling on solar collectors by determining the amount of mass deposited on the surfaces over time. In this analysis, geometrical data are taken from a real solar collector plant used in food dehydration processes [III].

There has been published work addressing the design and optimisation of flat-plate solar collectors and collector fields; however, there is limited information on the incorporation of fouling effects into the design and operation of these systems. Some of the notable work is that of Hajabdollahi *et al* [IV], who developed a study to model and optimise a flat-plate solar collector array based on an equation relating the cost of the collector array and the conventional heating system. In the cost model, the authors incorporate the energy efficiency variable. Some geometrical parameters such as length, collector width, pipe diameter and collector arrangement are involved in the work. It is concluded that the cost-effectiveness of a solar system decreases when high thermal efficiencies are sought.

From the point of view of collector field operation, Weinstock and Appelbaum [V], investigated the performance of a solar plant considering intermittent effects on radiation absorption caused by shading on the collector. In addition, the system design was optimised to minimise operating costs as a function of the annual amount of energy produced. The authors concluded that, for an optimal operation of the plant, it is necessary to determine: the daily energy demand, the cost of the area where the collectors will be installed, as well as the efficiency of the solar collector [VI.

Given that most of the work on solar collector networks focuses on aspects of operation, sizing and optimisation, without considering the effects of fouling, the work introduced here aims to fill this gap. To this end, the starting point is the design of solar collector networks to supply part or all of the thermal load of an industrial process. For the purpose of this work, a solar collector network consists of a structure of parallel collector lines, where each line consists of a certain number of collectors in series.

The structure of a flat plate solar collector network is such that the number of collectors in series determines the temperature level that can be achieved, while the number of collector lines in parallel is determined by the total thermal load to be delivered to a process. If it is known how scaling deposition evolves over time, it will be possible to define the number of collectors that will allow operation to be maintained at a target time.

In this work, a period of six months is set as the desirable operating horizon for the network. Since the appropriate oversizing is that in which the fluid velocity is maintained, oversizing is considered by adding collectors in series at the cost of increasing the pressure drop. The evolution of the pressure drop with increasing fouling is analysed and an economic analysis is carried out to determine the ideal conditions for reducing investment and operating costs. The results of this work establish the basis for optimisation studies.

Methodology

To determine the scaling fouling, a mathematical model developed by Lugo and Picón [I] is used. The model is used to determine the amount of $CaCO_3$ deposited on the inner walls of the tubes.

$$\dot{m}_d = \frac{\beta}{2}\left(\frac{\beta}{\alpha\, k_r} + (C_1 + C_2) - \sqrt{\frac{[\beta+(C_{1+}C_2)\,\alpha\, k_r]^2+4\,\alpha^2\, {k_r}^2\left(K_{sp}-[C_1][C_2]\right)}{\alpha^2\, {k_r}^2}}\;\right) \tag{1}$$

The model determines the mass flux $\dot{m}_d$ (kg/m^{2}s) of $CaCO_3$ that is deposited inside the tubes and considers the parameters involved in scaling formation such as pH, Ca^{2+} (C_1) (kg/m^3) and CO_3^{2-} (C_2) (kg/m^3) concentration, which affect the solubility K_{sp} (kg^2/m^6) of CaO_3 in water. The model includes design variables such as temperature, which impacts the rate at which the chemical reaction for crystal formation takes place (defined by the reaction constant, k_r (m^2/kgs). Another variable is the fluid velocity, which directly affects crystal deposition and is quantified by the mass transfer coefficient β (m/s). A dimensionless parameter α is included, which depends on the viscous and inertial stresses that affect crystal deposition on the surface. Over time, fouling increases leading to changes in pipe roughness and diameter, which in turn leads to higher pressure drop.

The calculation of the mass flux, $\dot{m}_d$ (kg/m^{2}s) that is deposited, allows the determination of the thermal resistance generated by the fouling during the operation of the solar collectors by means of Eq.(2). According to this expression, the thermal resistance due to fouling, Rs (m^2 °C/W) is also a function of the mass flux that is removed, $\dot{m}_r$ (kg/m^2 s) [VII]; the density ρ_f (kg/m^3) and thermal conductivity λ_f (W/m °C) of $CaCO_3$.

$$\frac{dR_s}{dt} = \frac{\dot{m}_d - \dot{m}_r}{\rho_f \lambda_f} \tag{2}$$

To determine the amount of heat Q_u' (W/m^2) per unit length (Eq.(3)) that reaches the working fluid, it is necessary to take into account the resistance to heat transfer from the surface of the fin connecting the plate to the tube and from the tube to the fluid (Figure 1). These resistances occur through the junction between the plate and the tube, R_k (m^2 °C/W), the tube wall, R_t (m2 °C/W), the fouling layer, R_s (m^2 °C/W), and from the inner wall to the centre of the tube by conduction, R_h (m^2 °C/W), Eq.(4). It is common to find that solar collector models do not consider the resistance generated by fouling.

$$Q_u' = U_f\left(T_{pm} - T_f\right) \tag{3}$$

$$U_f = \frac{1}{R_h + R_k + R_t + R_s} \tag{4}$$

The thermal resistance due to fouling directly affects the thermal performance of solar collectors, since the amount of heat Q_u (W) absorbed by the working fluid (Eq.(5)) is only a fraction of the net heat absorbed by the plate (Eq.(6)) due to thermal and optical losses [VIII].

$$Q_u = \dot{m}_f\, C_p (T_i - T_o) \tag{5}$$

$$Q_u = F_R A_s\left[I_G(\tau\alpha_c) - U_c A_s\left(T_{pm} - T_a\right)\right] \tag{6}$$

In the above equations, A_s (m^2) is the area of the plate, $\dot{m}_f$ (kg/s) is the mass flow inside the tubes, C_p (kJ/Kg°C) is the specific heat, T_i and T_0 (°C) are the inlet and outlet temperature in the tubes respectively, T_f is the average temperature of the working fluid, (F_R) is the heat removal factor from the plate to the fluid, (T_{pm}-T_a) is the temperature difference between the plate and the environment (°C), (α_c and τ) are the absorbance and transmittance of the cover and the I_G term (W/m^2) is the radiation intensity. This last parameter is fundamental to determine the efficiency (η) of solar collectors (Eq.(7).

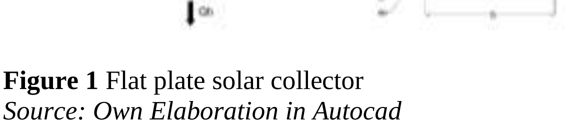


Figure 1 Flat plate solar collector
Source: Own Elaboration in Autocad

$$\eta = \frac{Q_u}{I_G A_s} \tag{7}$$

The thermal resistance generated by fouling directly affects the hydraulic resistance, since according to Eq.(8), the fouling thickness x_f (m) generated by $CaCO_3$ deposition is proportional to the fouling resistance and the thermal conductivity. The thickness of the deposit causes a decrease in pipe diameter and increases the roughness of the pipes, so that the flow and pressure drop are affected.

$$x_f = R_s \lambda_f \tag{8}$$

From Eq.(9) the pressure drop within a solar collector network can be known [VIII]. The pressure drop is proportional to the sum of the hydraulic resistances, K_i (kPa s^2/m^6) and the square of the volumetric flow rate $\dot{V}$ (m^3/s).

$$\Delta P_T = \dot{V}^2 \sum_{i=1}^{n} K_i \tag{9}$$

The main hydraulic resistances are due to the friction, K_1 (kPa s^2/m^6) generated by the flow of the fluid through the length of the pipe and that generated by the fittings K_2 (kPa s^2/m^6), among which are elbows, valves, unions, etc.

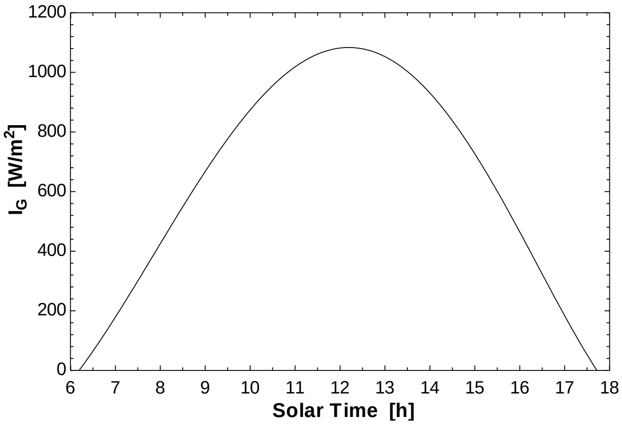
$$K_1 = \frac{8L}{\pi^2 d^5} f \tag{10}$$

$$K_2 = \frac{8\rho}{\pi^2 d^5} k_r \tag{11}$$

From Eq.(10) and (11) it can be seen that, as the diameter is reduced, the flow resistance increases, so the pressure drop also increases, Eq.(11). The term f is the friction factor generated along the pipe, k_r is the resistance factor for each of the fittings, L (m) and d (m) are the length and internal diameter of the pipe.

Results

To demonstrate the application of the fouling model, the operation of a single collector within a collector network is analysed [III]. The characteristics of the flat plate solar collectors are shown in Table 1. The solar hour is considered during a typical day in September from 6 h to 18 h, the maximum radiation is reached at 12 h with a value of 1067 (W/m^2), see Graph 1.

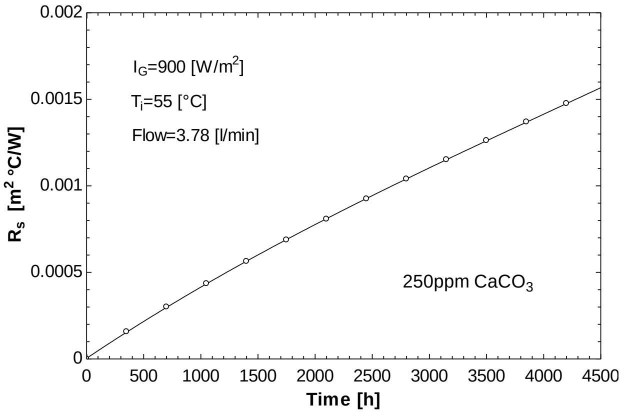


Graph 1 Solar radiation vs. time of day

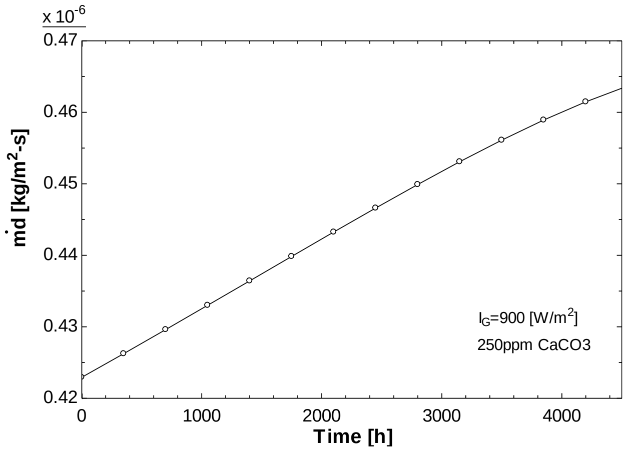
Dimensions	Length	Width	Absorbent area
	2099 [mm]	1196 [mm]	2.311 [m^2]
Absorbent tubes	Number of tubes	External diameter	Inner diameter
	11	10 [mm]	8 [mm]
Cover	Material	Transmittance	Thickness
	Solar tempered glass	0.91	4 [mm]
Absorption	Absorption surface	Thickness	Emissivity surface
	0.95	0.4 [mm]	0.05
Collector pipes	Number of tubes	External diameter	Inner diameter
	2	22 [mm]	20 [mm]
Housing and insulation	Thickness of bottom insulation	Side insulation thickness	Material
	44 [mm]	25 [mm]	Poliuretano + lana mineral

Table 1 Technical characteristics of the solar collector

The study of the thermal and hydraulic effect generated by fouling in the collector is carried out under the following operating conditions: inlet temperature of T_i=55 (°C), radiation of I_G=900 (W/m^2) and volumetric flow of $\dot{V}$=3.78 (l/min). The thermal resistance due to fouling with respect to the operating time is shown in Graph 2. It is observed that, as time goes by, the fouling resistance increases reaching a value of 1.5x10-3 (m^2K/W) in a period of 6 months. Graph 3 shows the mass flux deposited on the pipe wall with respect to the operating time under the same conditions.



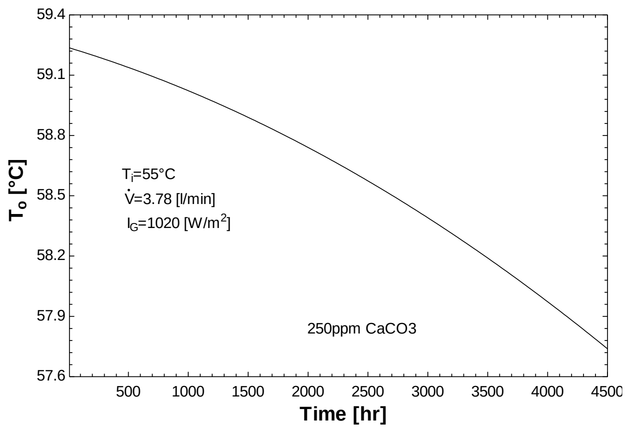
Graph 2 Thermal resistance due to fouling versus operating time



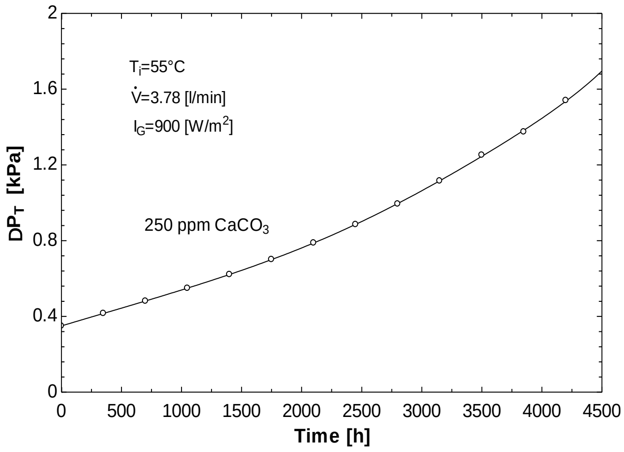
Graph 3 Deposited mass of $CaCO_3$ by fouling vs. time.

Graphs 4 and 5 show the variation of the maximum daytime outlet temperature with respect to the operating time and the increase in pressure drop. In Graph 4, it can be seen that the maximum temperature obtained over time decreases, becoming 1.5 (°C) lower over a period of just over half a year (4500 h). On the other hand, the pressure drop increases with time (Graph 5), reaching a pressure drop of more than 1.6 (kPa), which represents an increase of 4 times the original pressure drop in an operating time of 4,500 hours. From these results it can be seen that the fouling of the solar collectors has a greater impact on the hydraulic part.

Graphs 6 and 7 show the curves of collector outlet temperature and collector efficiency versus time of day after 4,500 h of operation with and without fouling (blue and black line respectively). Graph 6 shows that, when there is no fouling, the collector outlet temperature increases throughout the day reaching a maximum outlet temperature of 59.3 (°C), while when there is fouling, the maximum outlet temperature is 57.8 (°C).



Graph 4 Output temperature versus time



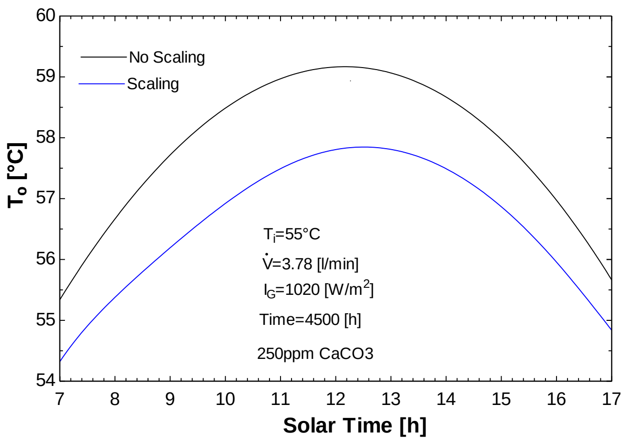
Graph 5 Pressure drop vs. time

The behaviour of the thermal efficiency is presented in Graph 7. A typical trend of decreasing over the course of the day is observed. Since this parameter increases when the fluid temperature is lower, it is observed that, for the case with fouling, the efficiency values with respect to time are higher by up to 8.5% with respect to clean operating conditions.

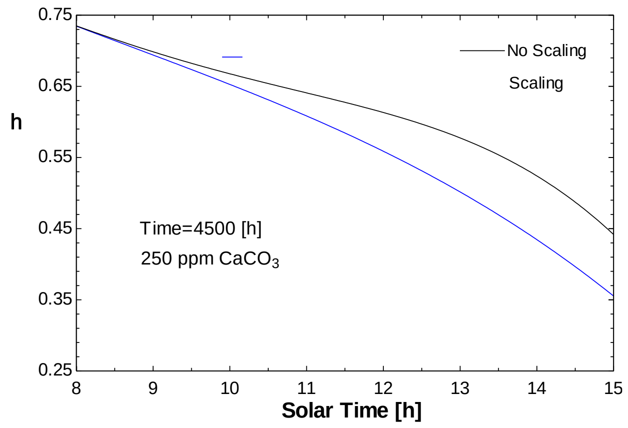
Solar collector network

In the design of a solar collector network, the volumetric flow and radiation are parameters that determine the number of collectors needed to reach the target temperature.

As higher temperatures are required, the number of collectors in series increases, while as the thermal load to be supplied to the process at that temperature is increased, the number of parallel lines must be increased. To exemplify, assume that you have a line of 5 collectors in series operating at 3 (l/min) and delivering a certain target temperature (Figure 2a). If you want to triple the heat load at that temperature, you must add two more 5-collector lines to the network as shown in Figure 2b.



Graph 6 Departure temperature vs. time of day



Graph 7 Thermal efficiency versus time of day
Source: Own Elaboration in EES Software

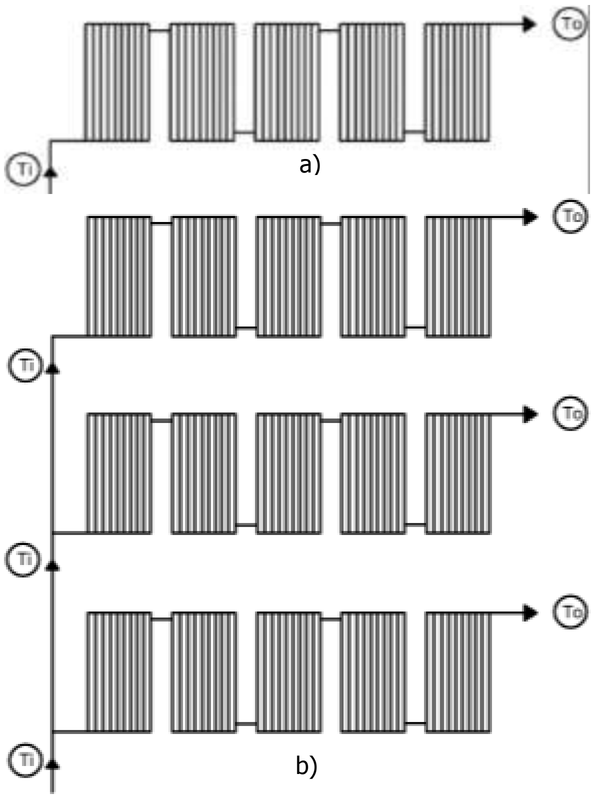
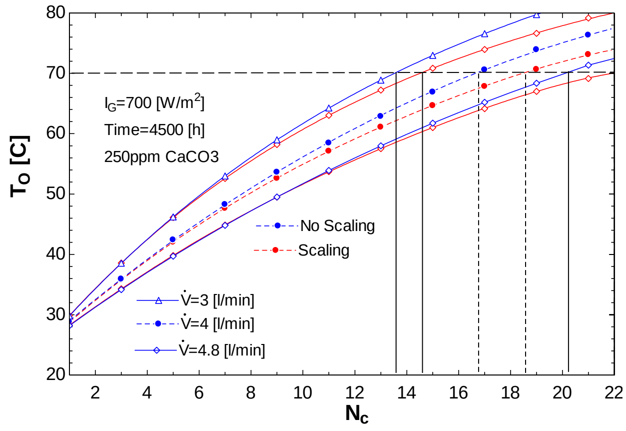


Figure 2 Solar collector network: a) 5-collector row in series, b) 15-collector network with three rows of 5 collectors each
Source: Own Elaboration in Autocad

Graph 8 shows sizing results assuming a desired temperature of 70 (°C). For the purpose of the analysis, the design is carried out under an irradiation of 700 (W/m^2). The design is carried out under clean and fouling conditions. The design is presented for three volumetric flow conditions: 3 (l/min), 4 (l/min) and 4.8 (l/min). In clean conditions (blue lines), a total of 14 collectors are required for a flow rate of 3 (l/min), while 17 collectors are required when operating with a flow rate of 4 (l/min) and 21 for 4.8 (l/min). This shows that when operating with lower volumetric flow, fewer collectors are required to reach the target temperature.



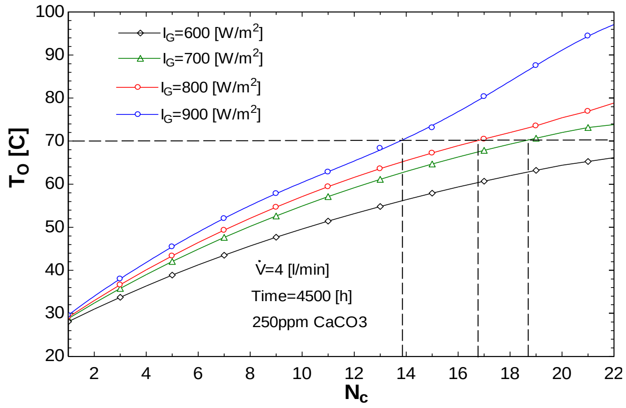
Graph 8 Output temperature versus number of exchangers in the network, with and without scaling
Source: Own Elaboration in EES Software

In fouling conditions (red lines) under the same flow and solar radiation parameters, it can be seen from Graph 8 that with a flow of 3 (l/min), 15 collectors are required to reach a temperature of 70 (°C). While for a flow rate of 4 (l/min) 19 collectors are required and for 4.8 (l/min) 22 collectors are required.

This means that, if a temperature of 70 (°C) is still expected to be delivered in a period of six months under the solar radiation conditions of 700 (W/m^2), considering scaling originating from a hardness of 250 ppm, a higher number of collectors is required. In the case of operation with a volumetric flow rate of 4 (l/min), if only 17 collectors are installed, after six months, the presence of fouling will cause the outlet temperature to be 67.3 (°C). This means that, if two more collectors are installed in series, after six months the target temperature is 70 (°C). This means a 12 % increase in heat transfer area.

Design considerations

The changing conditions of solar radiation throughout the day and over the days of the year necessarily imply that a design basis must be taken. If the objective is for the system to be able to deliver the thermal load at the required temperature on any given day of the year, the minimum level of radiation can be specified as the design basis. This will result in a network that is oversized on all other days of the year. However, this means that energy can be stored for later use [VI]. In Graph 9, the design is presented considering different radiation levels. For an irradiation of 600 (W/m^2), 700 (W/m^2), 800 (W/m^2) and 900 (W/m^2), 25, 19, 17 and 14 collectors in series are required under fouling conditions, respectively.

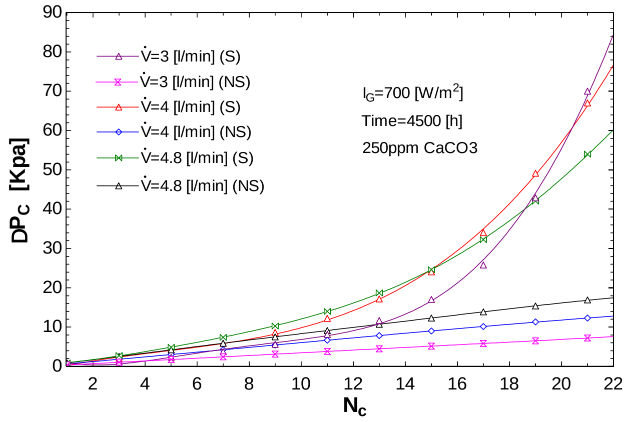


Graph 9 Number of collectors required for different radiation levels considering fouling conditions
Source: Own Elaboration in EES Software

Graph 10 shows the behaviour of the pressure drop in a network of solar collectors operating under different flows in clean and fouled conditions. It can be seen that the pressure drop is directly proportional to the number of collectors, presenting a logarithmic behaviour. With the presence of scaling, the pressure drop in the network increases considerably. It is important to note that in the case of the design with the lowest volumetric flow (3 l/min), the rapidity with which fouling occurs causes the pressure drop growth to be higher than in the other cases. The implication of this is that pumping costs grow faster when operating at low volumetric flow rates. With these elements, the design with a higher flow rate, e.g. 4.8 (l/min), allows to compensate the higher cost due to the higher number of collectors needed, with lower costs due to pumping.

Cost estimation

In this section an economic analysis is performed based solely on the total annualised cost of operation which is the sum of annualised collector field costs plus the annualised cost of pumping.



Graph 10 Pressure drop vs. number of collectors
Source: Own Elaboration in EES Software

Eq. (12) shows the pumping power as a function of pressure drop:

$$\dot{w} = \frac{\dot{V}\Delta P}{\eta_b} \tag{12}$$

Where $\dot{V}$ is the volumetric flow (m^3/s), ΔP is the pressure drop (kPa) and η_b is the pump efficiency.

The operating cost is obtained from:

$$Cos\_b = cost_u \dot{w}\ t \tag{13}$$

Where *Cos_b* is the cost of operation ($), *cost$_u$* is the unit cost of electricity ($/kWh) and t is the time of operation (h).

To determine the unit cost of operation, the GDMTH tariff with a variable peak charge of 2.13 ($/kWh) for the month of April in the municipality of Calera, Zacatecas in the Bajío subdivision, published by the Comisión Federal de Electricidad [X].

The commercial cost of a solar collector is estimated at $13,800.00 Mx. To obtain the annualised cost of a solar collector network, Eq.(14) is used, which requires an annualization factor defined by Eq.(15). The useful life of the equipment is considered to be 20 years and the annual interest rate is 8%.

$$Cos\_A = C\_u \cdot Fac\_A \cdot Tot\_col \tag{14}$$

$$Fac\_A = \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{15}$$

Where C_u is the unit cost of the solar collector, Fac_A is the annualisation factor, Tot_col is the total number of solar collectors, i is the annual interest and n is the number of years of equipment life.

To incorporate the economic analysis into the design of a collector network taking into account the existence of fouling, the results of Graph 8 are used. It is assumed that 48 (l/min) of water at 70 (°C) needs to be supplied to an industrial process. To supply this flow it is necessary to increase the number of parallel lines in the network. With the total flow and the flow per line, the total number of parallel lines is calculated, resulting in 16, 12 and 10 lines required for a flow of 3, 4 and 4.8 (l/min) respectively.

To find the total number of collectors, the number of lines is multiplied by the number of collectors in each line.

The annualised total cost of operation is obtained from:

$$Cos\_T = Cost\_A + Cost\_b \tag{16}$$

A comparative analysis is made between the scenarios with and without fouling. Table 2 shows the results obtained for the case without fouling. Under these conditions it is observed that the design with a flow per line of 4 (l/min) has the lowest total annualized operating cost ($320,376 Mx) and requires the lowest total number of solar collectors (204).

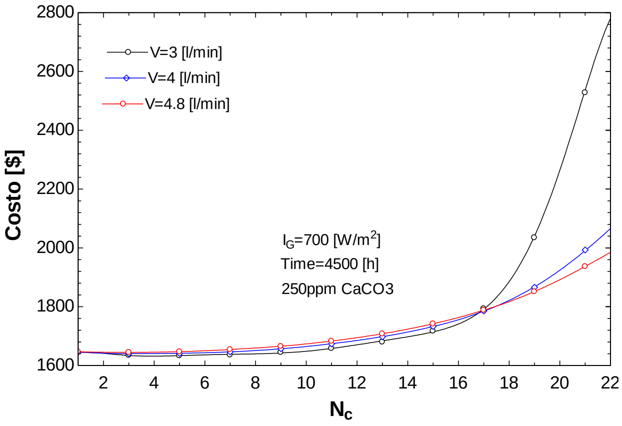
Flow per line (l/min)	Colec per line	No. Line	Total colec	Cost colec ($)	Cost bomb ($)	Cost Total ($)
3	14	16	224	3091200	51040	360160
4	17	12	204	2815200	38856	320376
4.8	21	10	210	2898000	33000	322800

Table 2 Cost analysis of the network with different design without scaling

The scenario under fouling conditions is now analyzed and the results are shown in Table 3. It is observed that with a volumetric flow of 3 (l/min) per line, 15 manifolds in series per line are required to reach the target temperature, and a total of 16 lines are needed to achieve the total flow required by the process. This means that the total number of manifolds the network needs is 240, resulting in an annualized cost including pump operation of $386,144 Mx. On the other hand, when operating with a flow rate of 4 (l/min) and 4.8 (l/min), the total annualized operating costs are $359,424 Mx and $343,300 Mx respectively. As shown in Table 3, each of these designs require fewer collectors (228 and 220, respectively), and the operating costs per pumping are also lower compared to the design with 3 (l/min) and 4.8 (l/min), respectively).

Flow per line (l/min)	Colec per line	No. Line	Total colec	Cost colec ($)	Cost bomb ($)	Cost Total ($)
3	15	16	240	3312000	54944	386144
4	19	12	228	3146400	44784	359424
4.8	22	10	220	3036000	39700	343300

Table 3 Cost analysis of the network with different design considering scaling



Graph 11 Cost per pumping with respect to the number of collectors in series
Source: Own Elaboration in EES Software

Graph 11 presents the pumping costs for each of the operating cases of 3 (l/min), 4 (l/min) and 4.8 (l/min) per line under conditions of accumulated fouling in six months. It is observed that starting at manifold 17, the pressure drop of the network operating at 3 (l/min) grows faster compared to the other systems. This occurs for two reasons: a) the number of collectors is greater, so the length of the fluid flow is greater, and b) this system, which operates at a lower speed, tends to generate more fouling, which over time forms a larger layer that reduces the diameter of the pipes and increases the resistance to flow and the pressure drop.

Conclusions

This paper demonstrates the importance of considering the effect of scaling fouling in the design and operation of flat plate solar collector networks. Taking as a basis the total annualized operating cost, which includes the investment cost in equipment and the operating cost by pumping, the difference between the design that would be obtained if scaling is considered or not considered in this stage is clearly observed. It can be seen that it is advisable to design with a higher volumetric flow of operation per line, because with the passage of time, not only will the operating costs be lower, but it will also be feasible to achieve the target temperature in the time in which the cleaning of the equipment can be planned. The main conclusions of this work are:

1. The sizing of a solar collector network to supply low temperature thermal load to industrial processes must consider the adverse effects, both thermal and hydraulic, that scaling fouling produces.

2. To incorporate the fouling phenomenon in the design process it is essential to have a mathematical model to predict the deposition on the surfaces of the tubes. The model presented here can be used satisfactorily for this purpose.
3. The design under fouling conditions indicates that it is preferable to design with higher volumetric flow rates per line, since the fouling deposition rate depends inversely on the fluid velocity in the pipes.
4. The total number of collectors per line increases with the volumetric flow rate, but the number of lines required to supply the total flow rate is reduced. This results in a lower total number of solar collectors.
5. When a solar collector network has not been designed taking into consideration the effects of fouling, it is found that the maximum temperature obtained drops by 1.5 °C in a period of six months, while the pressure drop increases approximately four times.
6. The annualized total cost of operation indicates that the design of a solar collector network should be carried out with a volumetric flow per line of 4 l/min, while, if scaling resistance is taken into account, the recommended volumetric flow is 4.8 l/min per line.

Financing

This work has been funded by CONAHCYT [Grant number 2466286]. The present work has been funded by CONAHCYT through the program: Estancia Posdoctoral Académica Inicial 2022 with CVU number 487049.

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