CHEMICAL ENGINEERING TRANSACTIONS

VOL. 76, 2019

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976161

Multi-Objective Optimisation of Flat Plate Solar Collector-Networks

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The use of solar heat for industrial applications is of growing interest in the academic and governmental areas. The development of thermal integration techniques, design approaches for minimum cost of solar collector fields and its operation are fundamental to motivate the interest of the process industries. About the design of a solar field, the investment and pay-back period are fundamental for decision making, therefore, cost minimisation is of paramount importance. The present work deals with the minimisation of the total cost of a network of solar collectors using a multi-objective optimisation approach. The optimisation approach uses a new cost equation for flat plate solar collectors and a validated thermal model. The optimisation model is solved in a Mat-Lab GAMS platform. It is found that tube diameter, the tube length and collector width, are the variables that most impact the total cost, and in the case of solar networks, the number of collectors in series to achieve a fixed temperature. With respect to commercial geometries, the cost of the optimised designs is 41 % cheaper.

1. Introduction

The transition to the large-scale use of solar energy into processing plants is still an outstanding issue to attend. Among the challenges to overcome are the costs associated with the integration of the thermo-solar plants into the productive processes and the payback period. Karagiorgias et al. (2001) reported that the cost of the network of solar collectors represents 54 % of the total installation costs. The system consisted of the network of solar collectors, a heat storage system, heat exchangers and the piping. Atkins et al. (2010) stated that one of the major challenges in the integration of solar energy in industrial processes are related to the intermittent nature of the solar radiation and the high capital cost associated. In a low temperature solar collector network, the total number of collectors are determined by the number of collectors in series and number of collectors in parallel. The network structure depends on the heat load, the delivery temperature, the pressure drop, and the operating and environmental conditions. Picón-Núñez et al. (2016) found that the structure of a solar field is a combination of series-parallel arrays, where the number of lines in parallel are determined as a function of the mass flow rate to meet the required heat load and proposed a methodology to size the collector surface area and determined that inlet temperature is a design variable that largely impacts the outlet temperature. To date, only a few publications focus on the minimisation of the number of collectors in a network. In their work, Martínez-Rodríguez et al. (2018) quantified how the change on the operating conditions can reduce the size of the network. According to the International Renewable Energy Agency (IRENA), the payback time of a thermo-solar installation must be lower than 3 years for the investment to be reasonable.

Walmsley et al. (2018) carried out an analysis of various energy indices that measure the profitability and sustainability of renewable energy electricity plants. Out of the five indices studied, the most relevant are the Energy Return on Investment (EROI) and the Energy Payback Time (EPT). The major contribution of this paper is the introduction of the time-worth for the calculation of energy. An analogy is established with the time-worth of money and provides the means to understand the temporary characteristic of the investment on and the generation of energy.

Even though the installation of thermo-solar plants has increased in the world, its number is still not significant. In this regard, the quest for the reduction of the solar-collector-network size is a subject that still needs to be

Paper Received: 18/03/2019; Revised: 05/05/2019; Accepted: 07/05/2019
Please cite this article as: Lizarraga-Morazan J.R., Martinez-Rodriguez G., Fuentes-Silva A.L., Picon-Nunez M., 2019, Multi-Objective Optimisation of Flat Plate Solar Collector-Networks, Chemical Engineering Transactions, 76, 961-966 DOI:10.3303/CET1976161

further developed. IRENA reported that in 2014, the number of industrial thermo-solar plants in the world came up to 140. Most thermo-solar plants in Europe are installed to supply district heating and Denmark takes the lead in this regard (Bava et al., 2015). In a solar plant located in Taars, Denmark, Tian et al. (2018) designed and simulated the performance of a network with 5,960 m^2 of flat plate collectors and 4,039 m^2 of parabolic concentrators. They concluded that the cost of district heating can be reduced from 5 % to 9 % using renewable energy.

The reported works in the open literature on the optimisation of the variables associated to solar collector networks is scarce. In this regard, Hajabdollahi and Hajabdollahi (2017) developed a thermo-economic model of a flat-plate collector which was later optimised. This optimisation searched for the maximum thermal efficiency and the minimum annual cost. The main limitation of a thermo-economic optimisation is however, that they do not consider the actual size of the components of the system.

The present work introduces a multi-objective NLP optimisation methodology to determine the size of a network of flat plate solar collectors (FPSCN) arranged in series. The approach uses a new cost equation to minimise the total cost and the maximisation of the thermal efficiency based on temperature increment, which is the difference between the fluid inlet and outlet temperatures. The total cost equation involves the surface area, the pumping systems and the operating costs. The system was solved using GAMS (General Algebraic Modeling System) and the solver CONOPT (Continuous Nonlinear Optimisation). This work focuses on the design and optimisation of the collector field and does not consider the storage system for the operation of the plant at this stage.

2. Sizing solar collector networks

The methodology for the design of a network of solar collectors is taken from Martínez-Rodríguez et al. (2019). The approach determines the network with the minimum area that meets the heat load and the target temperature throughout the year. The application of the methodology to two case studies are reproduced in Table 1. In case study 1 (dairy products), is possible to supply the total process heat duty at a temperature of 95 °C (Quijera et al., 2011); while in case study 2, the solar network supplies a small fraction of the total load (0.067) at 99 °C (Oseguera-Villaseñor, 2016).

Table 1: Solar network design and operating data for two case studies (Martínez-Rodríguez et al., 2019).

	Case study 1	Case study 2
Production process	Dairy products: yogurt, cheese and milk drinks	Bioetanol: fuel
Plant feed	20. 6 t/day	22.66 t/day
Plant throughput	20.5 t/day	4.96 t/day
Boiler heat load	4,401.01 kWh	97,914.4 kWh
Boiler operating time	(360 day/year) 5 h/day	(350 day/year) 24 h/day
Process hot temperature ºC	95 °C	204 °C
Heat load from solar network	4,401.01 kWh	5,662.00 kWh
Solar fraction, f	1	0.067
Solar target temperature	95 °C	99 °C
Solar network structure (series-parallel)	28x34	29x74

3. Optimisation model

The thermal model reported in Martínez-Rodríguez et al. (2019) was implemented in the Mat-Lab platform, and then exported to the GAMS environment. The optimisation of the flat plate solar collector (FPSC) is based on the minimisation of the total cost as a function of the minimum temperature increment between the inlet and outlet collector temperatures. The temperature increment of a commercial collector whose total costs are known is taken as a reference. Figure 1 shows the optimised designs for different values of temperature increment fixing the inlet temperature to 60 °C. For a temperature rise of 1.2 °C, the total costs are 936 USD for the commercial collector and 632 USD for the optimized design. This indicates a cost reduction of 32.48 %.

The multi-objective optimisation methodology based on restrictions was used to solve the model. A sensitivity analysis was performed to identify the design variables that have a largest impact upon the size of the network. From the results, these variables are: the tube length, tube diameter, collector width, number of collectors in series and the specified network target temperature. These variables define the network of solar collectors that minimises the total cost for a fixed target temperature.

The Mat-Lab model provides the thermal data for a specific network geometry and the GAMS model optimises the geometry required to meet the heat load. The Mat-Lab and GAMS models can operate independently. Therefore, for a specific case, the GAMS model optimises a single collector or a network of collectors by means of a multi-objective function.

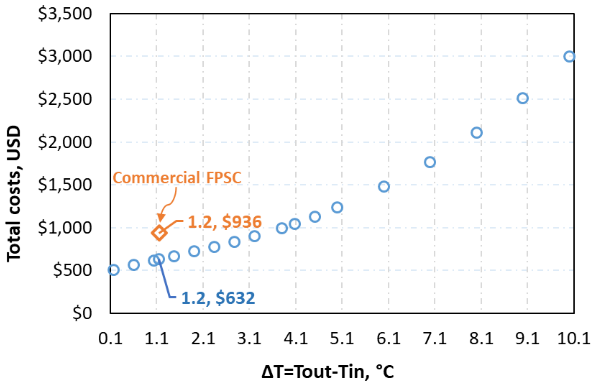


Figure 1: Pareto front of optimal configurations of a FPSC as a function of temperature increment (ΔT).

To carry out the multi-objective optimisation, a new cost model for plat plate collectors was developed. The model was validated by comparing it against the models published by Herrera-Alcázar and Andrade-Vallejo (2010) and Bava et al. (2015). These models differ in the way they are structured, however the results they produce are very similar between each other. The proposed multi-objective optimisation model is as follows:

$$min\, Z = [Total\ costs,\ Network\ area] \text{ s.t. } h(\overline{x}) = 0; \quad g(\overline{x}) \leq 0 \tag{1}$$

Where $h(\bar{x})$ is given by the mathematical expressions that make up the model, and $g(\bar{x})$ represents the group of restrictions of the system:

$$T_0 \leq T_{pm}; \quad T_{cover} \leq T_{pm} \tag{2}$$

The expression for the total cost is:

$$Total\ Cost = \gamma_0 + \frac{A_C N_C}{\pi}\left(\gamma_1 d + \gamma_2 + \frac{\gamma_3}{d}\right) + WL\gamma_4 + \gamma_5\left(\frac{\dot{m}H_b}{eff}\right) + \gamma_{10}\frac{\dot{m}L\mu}{\pi\rho d^4} \tag{3}$$

Where γ_i are adjustment parameters, Nc is the number of collectors in series, $\dot{m}$ is the mass flow rate, H_b is the pump head, d and L are the diameter and length of the tubes, w is the collector width, eff is the efficiency of the pump, ρ and μ are the density and viscosity of water. Eq(3) includes the costs of manufacture, installation and accessories as well as the operating costs (due to pumping).
The expression to determine the network surface area is represented by:

$$Network\ area = LwN_C \tag{4}$$

The nonlinear optimisation problem was solved using the GAMS platform; Eq(1) was discretised using a fifth order Runge-Kutta method and the CONOPT solver. Table 2 shows the geometry of a commercial flat plate collector and the range within which some variables are to be optimised.

Table 2: Commercial FPSC geometry.

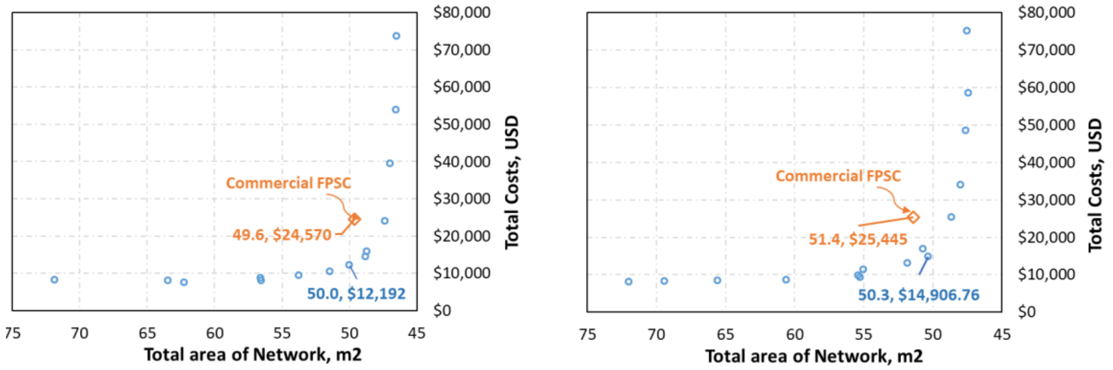
Features	Geometry	Optimisation range
No. Tubes	8	8
Length, m	1.97	0.5≥ *L* ≤ 3
Width, m	0.9	0.5≥ *w* ≤ 3
Diameter, m	0.051	0.008≥ *di* ≤ 0.051

4. Results

The operating conditions of the network of solar collectors for the two case studies are shown in Table 3. Figure 2 shows the variation of total cost against the surface area for the optimised designs. The design to achieve the target temperature using commercial collectors for each case study is also shown for the purposes of comparison.

Table 3: Operating data.

Operating conditions	Case study 1	Case study 2
Mass flow rate per collector line, kg/s	4.5	4.5
Inlet temperature, °C	60	60
Target temperature (outlet temperature), °C	95	99
Irradiance, W/m^2	725.32	761.13
Ambient temperature, °C	19.73	20.14
Wind velocity, m/s	1.6	1.0



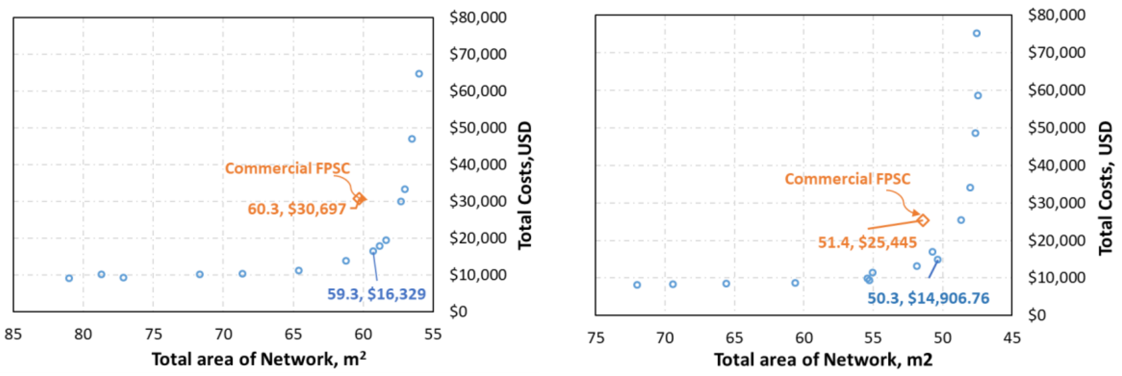
(a) (b)

Figure 2: Pareto front of optimal configurations of FPSC Networks. Comparison between optimised networks and networks designed using commercial geometries for: (a) Case study 1, and (b) Case study 2.

From Figure 2 it can be observed that the total cost grows rapidly as the surface area reaches the minimum value that can thermodynamically achieve the specified target temperature. As the surface area is reduced, the number of collectors in series required is increased thus affecting the total cost. For instance, for case 1, the minimum surface area that reaches 95 °C is 46.5 m^2. This design condition requires 186 collectors (0.5 m long and 0.5 m wide) in series. The results for the optimised solution indicate that the target temperature can be achieved with a surface area of 50 m^2 that requires only 8 collectors in series (3 m long and 3 m wide). Comparatively, if commercial collectors are used, 49.6 m^2 are needed. The cost of the design using commercial units is 24,570 USD while cost of the optimised design is 12,192 USD (Figure 2a). For case study 2 (Figure 2b), the minimum possible thermodynamic design requires a surface area of 47.5 m^2 with a total of 190 collectors (0.5 m long and 0.5 m wide) in series. The optimised design achieves the target temperature with 50.3 m^2 and a total cost of 14,96.76 USD while the design using commercial collectors requires a surface area of 51.4 m^2 with a total cost of 25,445 USD.

Figure 2 provides more information to aid the designer in making the right decision based on the objective. For instance, if the objective is to go for the minimum cost, there are other options that with an increment in surface area will meet the objective. The different optimal point in the Pareto front, indicates different collector geometries and different number of collectors in series. In the case land for the installation of the solar plant is limited, then the choice must go in the direction of reduced surface area.

The designer may also be interested in evaluating the effect upon surface area of the inlet temperature to the network. Further analysis is shown in Figure 3 using the information of case study 2. Figure 3a shows the Pareto front for an inlet temperature of 45 °C and Figure 3b for 60 °C. The network design using the commercial collectors is included in both diagrams for comparison. Taking as a reference the surface area from commercial collectors, it can be observed that reduction of the inlet temperature from 60 °C to 45 °C results in an increment of approximately 9 m^2 of surface area in the case of the optimised designs. This represents a cost increment of almost 20 %.



(a) (b)

Figure 3: Effect of inlet temperature upon the network surface area for case study 2: (a) Inlet temperature 45 °C, (b) inlet temperature 60 °C.

For a feed temperature of 60 °C, Table 4 shows the detailed results of the optimisation for each of the case studies and the geometries of the commercial and optimised designs. It can be observed that for the same surface area between the optimised network and the commercial one, the optimised network fulfils the target temperature with a 50 % reduced cost for case 1, and a cost reduction of 41 % for case 2. The substantial reduction in the total costs justifies the optimisation and more importantly, the determination of the optimal geometry of the collectors.

Table 4: Comparison between commercial and optimised network designs.

	Case 1		Case 2	
FPSC Network Features	Commercial	Optimised	Commercial	Optimised
Length, m	1.97	2.80	1.97	2.61
Width, m	0.90	0.81	0.90	0.67
Tube diameter, m	0.051	0.01	0.051	0.008
Number of collectors in series, N_c	28	22	29	29
Surface area of series arrangement, m^2	49.6	50.0	51.4	50.3
Installed costs, USD	24,357.73	12,008.38	25,227.65	14,609.97
Operating costs, USD	60.58	108.82	60.58	205.01
Total costs, USD	24,418.31	12,117.20	25,288.25	14,814.98
Savings	50 %		41 %	

Payback time is another important parameter to consider in any thermo-solar installation. The analysis in this work did not include maintenance costs. Table 5 shows the payback time for the different case studies. What is important to highlight is that the main reason that hinders the widespread use of solar energy in industrial processes apart from the intermittent nature of the solar resource is the high cost associated. The former can be dealt with by means of proper design and energy storage (Walmsley et al., 2015) while the second, as it is shown in this work, can be reduced substantially by optimising the collector geometry. Since it is estimated that the solar filed takes almost 54 % (Karagiorgias et al., 2001) of all the associated costs, and since it is demonstrated that the costs can be reduced up to 50 %, then the total cost of the installation, can in principle, be reduce approximately 25 %. This cost reduction can make solar plants more competitive.

Table 5: Optimised costs and payback time.

	Case study 1		Case study 2	
	Commercial	Optimised	Commercial	Optimised
Network arrangement, series-parallel	28x34	22x34	29x74	29x74
Total number of collectors	952	748	2,146	2,146
Total surface area, m^2	1,687.89	1,696.46	3,804.85	3,752.71
Total cost of network, USD	830,223	411,985	1,871,329	1,096,309
Operating days/year	350	350	350	350
Payback time, years	1.5	0.75	2.63	1.54

5. Conclusions

This work introduces an optimisation approach for flat plate solar collector plants. It uses a new cost equation and focuses only on the solar field. The main conclusions of this work are:

- The geometrical variables that most affect the cost of a solar collector are: length, inner tube diameter and collector width.
- In the case of solar collector networks, the variable to optimise is the number of collectors in series for a fixed target temperature.
- For a single solar collector, the cost reduces as the surface area decreases. However, for a network of collectors in series, cost does not necessarily reduce as surface area reduces. The reason for this being that for smaller surface areas, smaller collectors are needed but in increased number which increases the cost.
- The multi-objective optimisation approach using Mat-Lab GAMS is an effective tool for solar collector networks.
- The payback time keeps a relation to the solar fraction (fraction of the process heat load that is substituted by solar energy). Case study 1 exhibits a solar fraction of 1 and a payback period of 9 months, and case study 2, with a solar fraction of 0.067, has a payback time of 19 and a half months. In all cases, the payback time is below the recommended by the International Renewable Energy Agency.
- Further analysis to consider the storage system into the overall optimisation approach is underway.

References

Atkins M.J., Walmsley M.R.W., Morrison A.S., 2010, Integration of Solar Thermal for Improved Energy Efficiency in Low-Temperature-Pinch Industrial Processes, Energy, 35, 1867-73.

Bava F., Furbo S., Bengt P., 2015, Simulation of a Solar Collector Array consisting of two types of solar collectors, with and Without Convection Barrier, Energy Procedia, 70, 4–12.

Hajabdollahi Z., Hajabdollahi H., 2017, Thermo-economic modeling and multi-objective optimisation of solar water heater using flat plate collectors, Solar Energy, 155, 191–202.

Herrera-Alcázar C., Andrade-Vallejo M.A., 2010, Estudio técnico-económico de colectores solares planos para zonas rurales del estado de Oaxaca, Investigación y Ciencia [online], 18, 55-68.

IRENA, 2015, Solar Heat for Industrial Processes Technology Brief <irena.org/publications/2015/Jan/Solar-Heat-for-Industrial-Processes> accesed 21.07.2018.

Karagiorgias M., Botzios A., Tsoutsos T., 2001, Industrial Solar Thermal Applications in Greece Economic Evaluation, Quality Requirements and Case Studies, Renewable and Sustainable Energy, 5, 157-73.

Martínez-Rodríguez G., Fuentes-Silva A.L., Picón-Núñez M., 2018, Solar thermal networks operating with evacuated-tube collectors, Energy, 146, 26-33.

Martínez-Rodríguez G., Fuentes-Silva A.L., Lizárraga-Morazán J.R., Picón-Núñez M., 2019, Incorporating the Concept of Flexible Operation in the Design of Solar Collector Fields for Industrial Applications, Energies, 12, 570.

Oseguera-Villaseñor I., 2016, Reducción en el consumo de combustible fósil para generar el calor requerido en la sección de deshidratación y purificación en la obtención de bioetanol anhidro mediante el uso de energía solar, Master Thesis, Universidad de Guanajuato, Guanajuato, MEXICO.

Picón-Núñez M., Martínez-Rodríguez G., Fuentes-Silva A. L., 2014, Design of Solar Collector Networks for Industrial Applications, Applied Thermal Engineering, 70, 1238-45.

Picón-Núñez M., Martínez-Rodríguez G., Fuentes-Silva A.L., 2016, Targeting and Design of Evacuated-Tube Solar Collector Networks, Chemical Engineering Transactions, 52, 859-64.

Quijera J.A., González-Alriols M., Labidi J., 2011, Integration of a solar thermal system in a dairy process, Renewable Energy, 36, 1843-1853.

Tian Z., Perers B., Furbo S., Fan J., 2018, Thermo-economic optimisation of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series, Energy Conversion and Management, 165, 92–101.

Walmsley T. G., Walmsley M. R. W., Varbanov P., Klemeš J., 2018, Energy Ratio analysis and accounting for renewable and non-renewable electricity generation: A review, Renewable and Sustainable Energy Reviews, 98, 328–345.

Walmsley T. G., Walmsley M. R.W., Tarighaleslami A. H., Atkins M. J., Neale J. R., 2015, Integration options for solar thermal with low temperature industrial heat recovery loops, Energy, 90, 113-121.