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VALIDATION OF A SOLAR THERMAL PILOT PLANT MODEL FOR COPPER MINING PROCESSES

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Abstract

In this work, the behavior of a solar thermal pilot plant installed in a copper mine in the north of Chile is investigated. The pilot plant is directly connected to the water circuit used to heat the electrolyte in the electrowinning processes. For a detailed monitoring of the system, the pilot plant counts with several measuring instruments. Recorded data are compared with results obtained in TRNSYS simulations. In addition to that, because of the high dust deposition on the solar plant, effects of soiling on the system are also investigated. Hence, this paper has the twofold objective of validating the TRNSYS model for future scale up of the solar thermal plant and at the same time to determine the effect of the dust on the collector.

Keywords: *Solar thermal plant, copper mining processes, TRNSYS simulations, soiling*.

1. Introduction

Climatic conditions and energy demand are necessary consideration for solar technology development. In that sense, Northern Chile has a high solar radiation, with an annual global horizontal irradiation of more than 2500 kWh m^{-2} (Escobar et al., 2014) and local industry, which is mainly focused on mining in deserted areas, presents an elevated energy consumption of electricity and heat. The principal activity of Chilean mining industry is extraction and production of copper. The energy demand of Chilean copper mining has reached 44.9 TWh in 2014 (including electricity and heat) and it is 60% higher than 2005 (COCHILCO, 2014).

In copper mining, two kind of process are mainly used to produce metallic cathodes, according to the extracted mineral (copper sulfides or copper oxides). Fossils fuels mostly supply the high thermal consumptions of those processes. The huge fuel consumption generated by the mines produces important quantities of greenhouse gases and it could be reduced significantly by the development of solar thermal plants to supply the heat needed in those processes.

There are two possible applications for solar thermal technology as heat source in the sulfides process: the drying and the smelting of the concentrate. In the latter, it is possible to apply the solar concentrating technologies to separate copper from other materials. Moreover, three applications are also conceivable in the oxides process: heating solutions for leach pads, electrowinning process and anodes washing (see Fig. 1).

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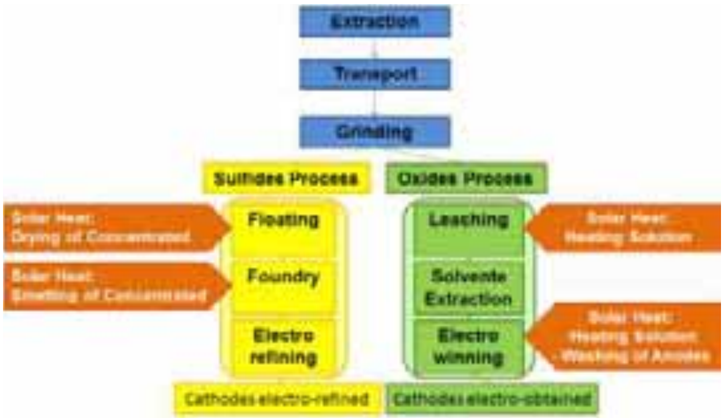


Fig. 1: Solar heat applications in copper mining processes

In Chile, the thermal energy consumption for the process of leaching (LX), solvent extraction (SX) and electrowinning (EW) is 1.5 TWh (COCHILCO, 2014) and it is obtained with fossil fuels, which involves problems for operational costs: price volatility, upward trend and uncertainty of supply. Nevertheless, solar thermal plants can obtain the same amount of heat energy and stabilizing operating costs of mining companies.

The EW process is the last step in the production of copper cathodes. To improve the efficiency of electrodeposition of copper on the plaque it is required that the electrolyte which comes from plant SX, is maintained at temperatures between 45 ° C to 55 ° C (depending on the process). Hot water is also required, at temperatures near to 90 ° C, to wash cathodes and anodes. So far, this task is achieved with a boiler, which also provides heats for the electrolyte using a heat exchanger.

In Chile, the substitution of fossil fuels with solar solutions for the production of thermal energy to the mining process has been implemented only for EW processes. To date, there are only three operating solar plants of this type. (CSP-Today Global Tracker, 2015)

The first solar plant is installed in the copper mine Constanza, and it has been operated since 2012. A surface of 404 m^2 composed of flat plane solar collectors provides energy to heat the electrolyte. The annual generation capacity of this plant is 540 MWh_t. Another solar thermal plant of this type is installed in Gaby mining company and produce 51.800 MWh_t per year, which replace 80% of fossils fuels consumption in the EW process. In this plant, flat plane solar collectors with a surface of 39.300 m^2 are used, too. The third plant has been operated since 2012 in the copper mining El Tesoro and uses parabolic trough technology. The total capacity of this plant is 10 MWt and replace 55% of diesel used in the process. (CSP-Today, 2013).

In the last years, some works have been carried out on this topic. Ushak et al. (2014) studied the behavior and the performance of a thermal solar plant to provide heat for EW process in the copper mine. It was analyzed the global efficiency during four month and the impact on the reduction of CO_2 emission. Another solar application in mining was studied by Gallo et al. (2014). They proposed the integration of thermal collectors with an absorption machine for air-conditioning of containers in mining camps of the Atacama Desert. Currently, at Energy Development Center of Antofagasta several applications for solar energy in mining are being investigated (Portillo et al., 2015).

In this paper is studied the working of a thermal solar pilot plant installed at the end of 2014, by Enermine, in the mine Lomas Bayas, in order to produce thermal energy for the EW process. The pilot plant is currently operating and it is directly connected to the heating circuit of EW system. A TRNSYS (2015) model of the pilot plant has been carried out and simulated results are being compared with operating data during the first months of working. The aim of this paper is the validation of the TRNSYS model in order to design a scaled up solar thermal plant in the near term. Furthermore, because the high rate of soiling on the solar collector can penalizes the performance of the plant (El-Nashar, 2003), simulations help to determine the loss of efficiency due to dust deposition on the collector.

2. Description of the solar thermal pilot plant

Real plant

The pilot solar thermal plant is connected to the water circuit used to heat the electrolyte in the electro-winning processes. One large size solar thermal collector is placed on the roof of a container and it has an active surface of 9.26 m^2 (see Fig. 2a). The rest of the components are protected inside of the container. The storage tank has a volume of 500 liters (see Fig. 2b).

All the elements of the pilot solar plant were installed and tested by the company Enermine. The same enterprise executed the connection between the solar module and the process with standard norms of Lomas Bayas Mining Company. Enermine also provided and disposed the instruments to measure temperatures and flow rates and to calculate the energy captured and dispatched from the solar module to the process.

In order to increase the temperature of electrolyte, the solar module is connected to the output of the main circuit of the heaters. The flow to heat by the pilot plant is obtained directly from the circulation pumps of tempering circuit. This flow is less than what comes out of the heaters (0.2% of the total flow) (Enermine, 2014), so it is possible to observe and measure the temperature rising due to the contribution of the solar module.

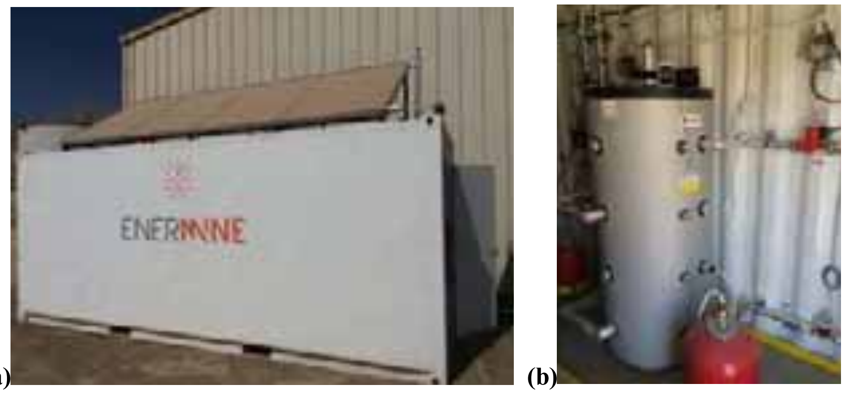
(a)  (b)

Fig. 2: Pictures of the solar thermal collectors (a) and the storage tank (b) of the pilot plant.

Figure 3 shows a schematic flow sheet of the pilot plant and measuring instruments are indicated in it. The system is composed of four hydraulic circuits: solar, storage, dispatch and process. The first circuit collects solar radiation by means of a large flat plate solar collector, disposed with an inclination of 30 degrees and an orientation of 56.6 degrees toward Northeast. The heat transfer fluid is demineralized water and it flows in the collector by the use of a circulation pump (P1) of 380 watt with a nominal mass flow of 350 kg h^{-1}. The heat is transferred by a heat exchanger (HX1) at the second loop where energy is accumulated in the storage tank (ST). In the third circuit, the water is dispatched from the accumulator to another heat exchanger (HX2). Finally, HX2 transmits the energy to the fluid of the process circuit, heating the electrolyte. In the storage circuit and in the dispatch circuit, two identical circulation pumps (P2, P3) of 100 watt move the water in their correspondent loops with two possible mass flows: 350 or 850 kg h^{-1}.

In addition to that, the system is equipped with several measuring instruments of temperature (T) and mass flow (FM). Three calorimeters (CM) calculate the energy exchanged in the circuits. Moreover, a control system (CS) is installed in the plant to activate the circulation pumps. In the solar loop, the pump is activated when the water temperature at the outlet of the collector is 6 °C higher than the temperature at the top of the storage tank. The same controller stops the circulation when the temperature difference is less than 3 °C. In the dispatch circuit, the water flows when the temperature in the tank is above 60 °C.

Because of the location and the presence of a higher building behind the plant, some shadows fall on the solar collector during the afternoon.

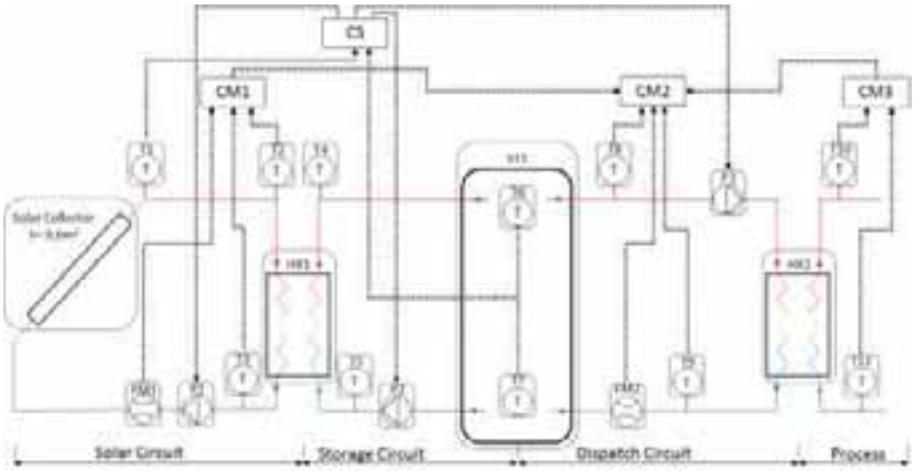


Fig. 3: Pilot plant flow sheet.

TRNSYS model

The same flow sheet of Fig. 3 was modeled in a simulation software to reproduce the pilot plant performances and to validate the model created. In particular, the plant was simulated with a simplified TRNSYS model. The flow scheme consisted in several elements called "Type", which represented the different components of the pilot plant. Table 1 resumes component characteristics. In the model, parameters referring to the size of the components were fixed; other parameters were adjusted to match simulated results with real collected data. Two inputs from collected data were introduced in the model: global radiation on the horizontal that was measured close to the collector and the temperature (T11 in Fig. 3) of the flow entering in HX2 in process circuit.

Tab. 1: summary of elements and parameters values used in simulations for the period from 19 to 31 January.

Component	TRNSYS Type	Main parameter	Value	Unit of measure	Observations
Collector	1b	Absorbing Surface	9.26	m^2 -	
		η_0	0.36	$W\ m^{-2}\ K^{-1}$	Optical efficiency
		K1	2.86	$W\ m^{-2}\ K^{-2}$	Slope efficiency
		K2	0.015		Curvature efficiency
Tank	4a	Volume	500	Liter	
		Thermal losses	2.5	$W\ m^{-2}\ K^{-1}$	Including pipe losses
Pumps	114	Flow P1	205	Kg/hr	
		Flow P2	350	Kg/hr	
		Flow P3	850	Kg/hr	
Heat Exchangers	5b	UA HX1	200	$W\ K^{-1}$	
		UA HX2	150	$W\ K^{-1}$	
Controllers	2b	DTmax	6	°C	Start the flow in solar circuit
		DTmin	3	°C	Stop the flow in solar circuit
	2	Tmax	59.5	°C	Start the flow in Tank load side
		Tmin	56.5	°C	Stop the flow in Tank load side
Solar Pipe	32	Thermal losses	2.36	$W\ m^{-2}\ K^{-1}$	
		Length	1	m	
		Internal diameter	1.905	cm	

Ambient temperature was also necessary to model thermal collector behavior and heat losses in pipes and storage tank. Because no data of ambient temperature in the site were available for the examined period, this parameter was estimated with the following method. Data of daily maximum and minimum ambient temperature in the site were available for the same period for years 2013 and 2014 and from an online database (TuTiempo, 2015) the same data for Calama, the closest city to Lomas Bayas mine (LB), were also available. Hence, an averaged ratio for the period between maximum temperature in LB and in Calama was calculated. The same operation was repeated for minimum temperature. Then, those ratios were used to estimate temperatures for 2015 in LB from Calama temperature values. Following the method of De wit et al. reported in Reicosky et al., (1989) the hourly temperature was calculated from the daily maximum and minimum values. Finally, a lineal interpolation was carried out to determine the values each minute. According to data availability, a 6-minutes time step was used in simulations. Furthermore, since collector mass flow and optical efficiency decreased in February, analyzed period was divided into four sub-periods.

3. Results

Real data

Since the pilot plant have been installed at the beginning of December, no collector cleaning was done. From data corresponding to initial weeks, a daily solar thermal production of 13.28 kWh was measured. This amount represents less than 0.1 % of energy needed to heat the electrolyte in electrowinning process and global efficiency for that period was 52%. According to information provided by Enermine (2014) maximum temperatures measured at collector outlet overcame 80 °C and effects of dust deposition were not appreciable.

For this work, data from 19 January to 20 February were available. In this period, the maximum temperatures at collector outlet were mostly below 70 °C, with the exception for the first days of February, when they reach values close to 74 °C, as it can be observed in Fig. 4a and 5. Then, a gradual decrement was registered until temperature in the tank was always less than 60 °C and no circulation to the load was observed.

Due to the presence of Andes chain at the east, the circulation inside the collector usually started after 10 a.m. and because of the shadow generated by the building behind the plant, the flow usually stopped at 3.30 p.m. Furthermore, the water circulation in the solar loop presented a minor mass flow that decreased along February.

From Fig. 4, 7, 9, 11 low collector efficiencies can be observed, due to the high dust deposition on the panel. Efficiency "Eff" for a period was calculated as the ratio between the harvested energy by the collector and the global irradiance on horizontal "$I_{g,h}$" multiplied by the collector absorbing area "A_{coll}" (see eq.1).

$$Eff = \frac{\sum_i [\dot{m}_i \cdot c_p \cdot (Tout - Tin)_i \cdot \Delta t_i]}{\sum_i (I_{g,h_i} \cdot A_{coll} \cdot \Delta t_i)} \qquad \text{(eq. 1)}$$

Where $\dot{m}$ represented the mass flow in the collector,$\cdot$ c_p was the specific heat, $Tout$ and Tin were the temperatures at the outlet and at the inlet of solar collector and Δt was the period length while the mass flow was considered constant.

Modeled results

Figure 4 shows results for the first period from 19 to 31 of January: the average mass flow relative error in the solar circuit for the period from 19 to 31 January was 4.3% and the average relative error in the circuit between the tank and the load was almost 6.7%. Average daily efficiency in simulations was 17.9% and it was always higher than in collected data. For real data, calculated average daily efficiency was 15%. Harvested energy by the collector in simulations was very sensible to small variation of temperature difference at collector inlet and outlet, and it causes that discrepancy in efficiency values.

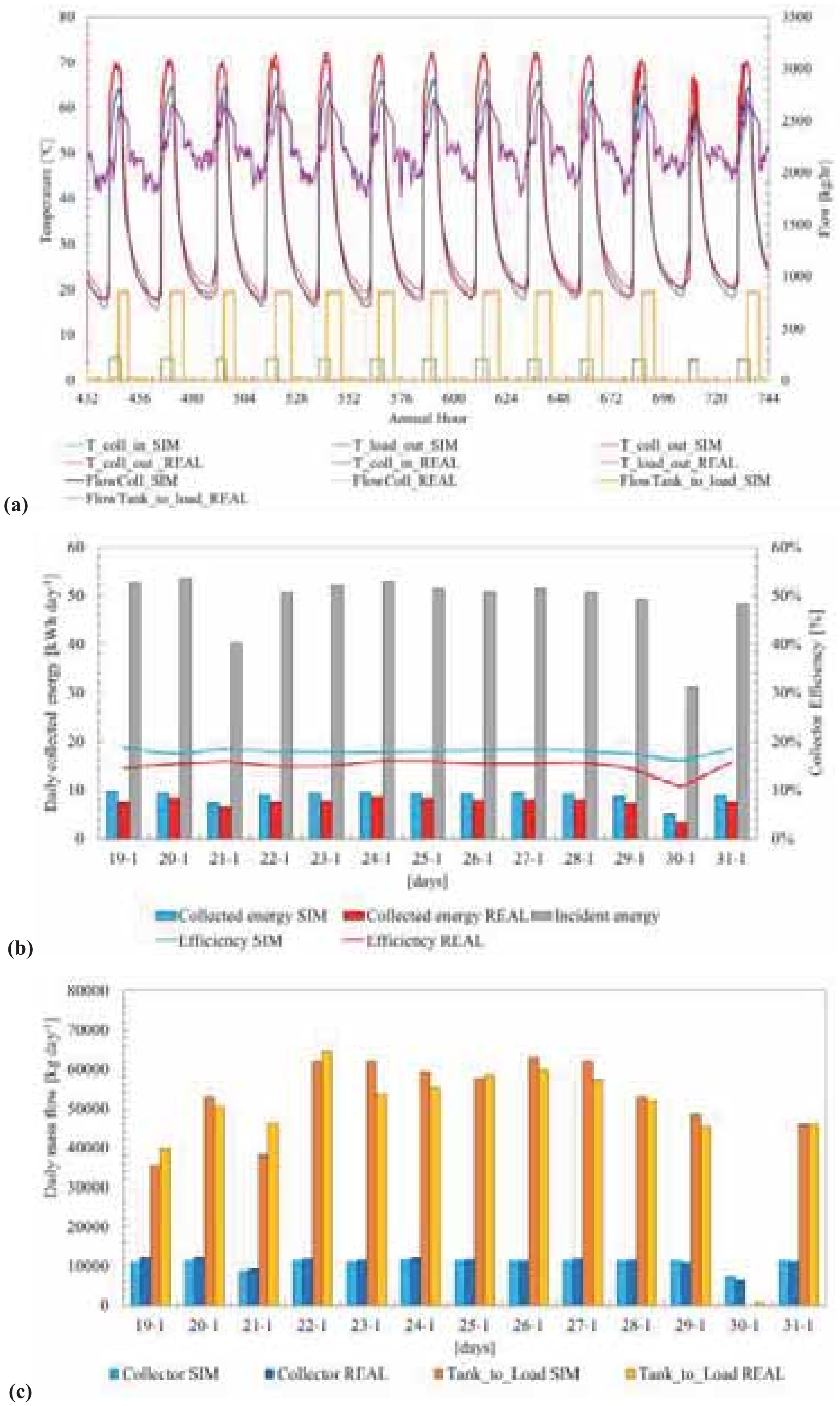
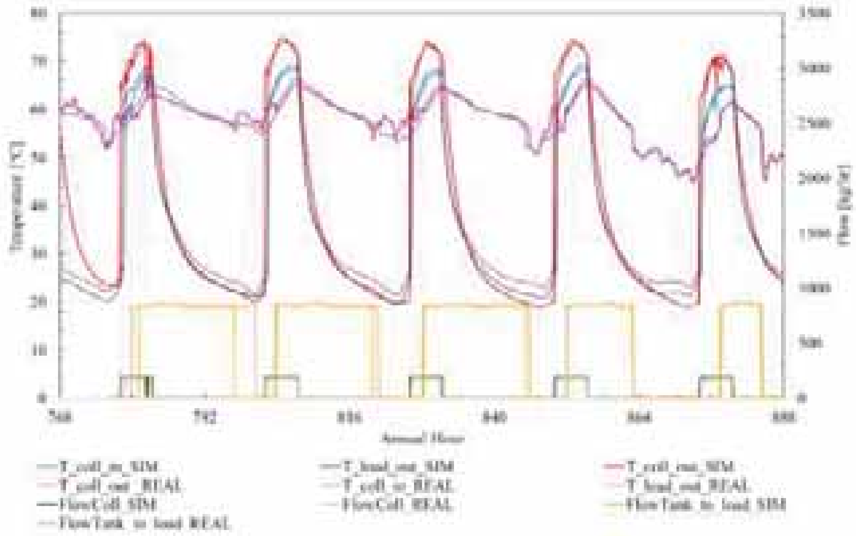
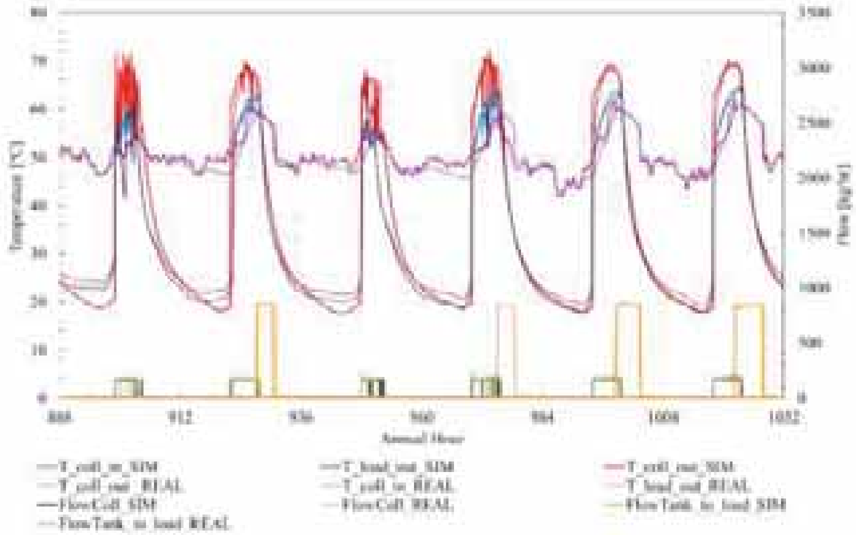


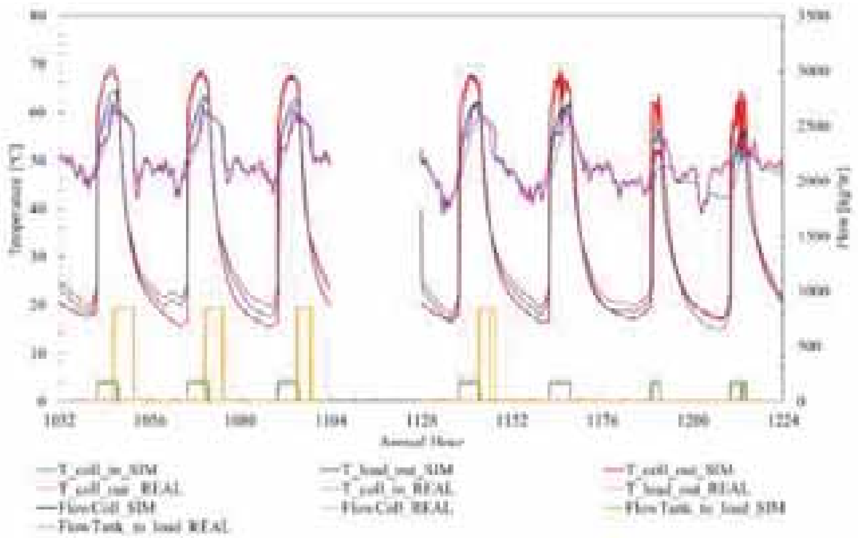
Fig. 4: Simulated and real temperature and mass flow (a), daily collected energy and collector efficiency (b) and comparison of mass flow in the collector and in the circuit tank-to-load (c) from 19 to 31 January.



(a)



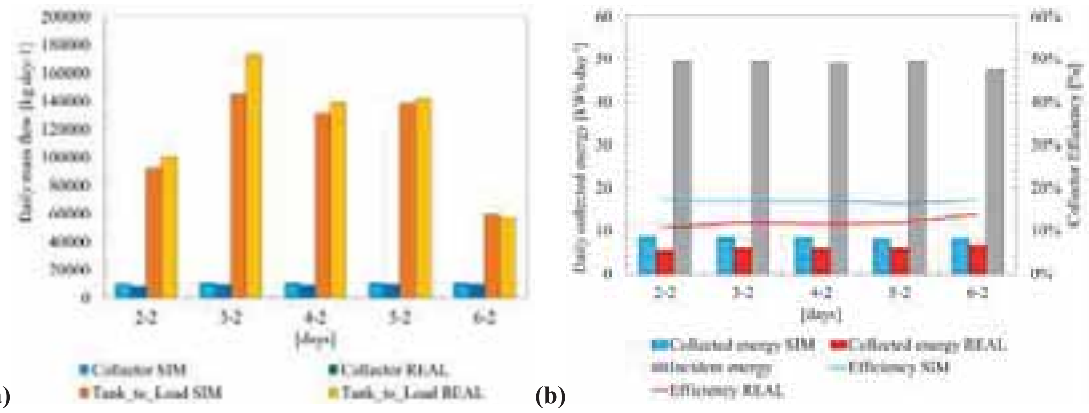
(b)



(c)

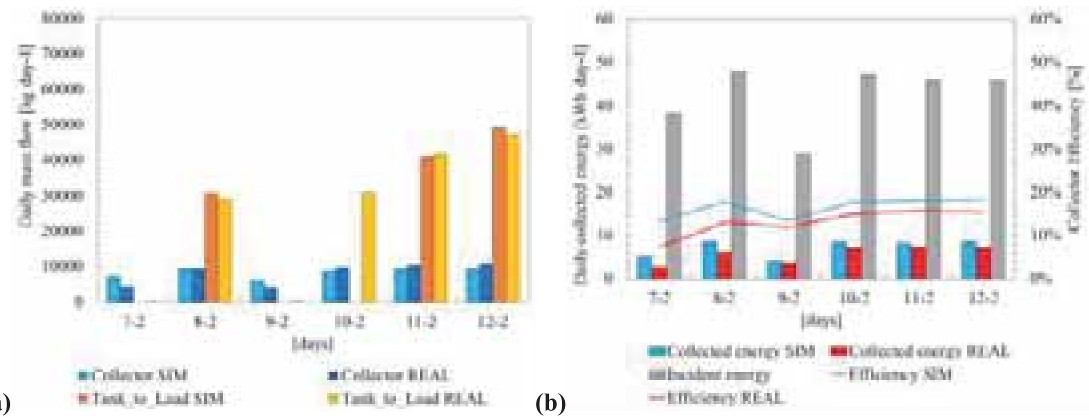
Fig. 5: Simulated and real temperature and mass flow from 2 to 6 (a), from 7 to 12 (b) and from 13 to 20 February (c).

In the second period (see fig 5a, 6) the optical efficiency was decreased to 0.355 and the mass flow was 190 kg h^{-1}. For the third (see Fig. 5b, 7) and fourth period (see Fig. 5c, 8), optical efficiency was 0.35 and 0.325 respectively and the mass flow was 170 kg h^{-1} for both. In February, results show similar trends even if accuracy is lower. This is due to the changes in some parameters and to the difficulties to find a more accurate set for the model. In general, model accuracy is lower every time a normally constant parameter (i.e. mass flow) changes its value and during partial cloudy days because of a quick variation of radiation impinging on the collector. In Fig. 5, 6, 7 and 8, 1st and 16th February are not represented because there was no data availability.



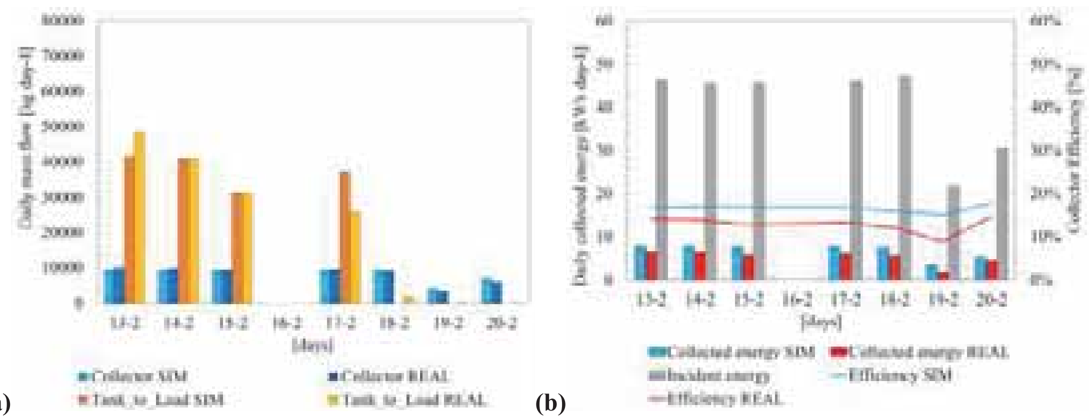
(a) (b)

Fig. 6: Comparison of mass flow in the collector and in the circuit tank-to-load (a) and daily collected energy and collector efficiency (b) from 2 to 6 February.



(a) (b)

Fig. 7: Comparison of mass flow in the collector and in the circuit tank-to-load (a) and daily collected energy and collector efficiency (b) from 7 to 12 February.



(a) (b)

Fig. 8: Comparison of mass flow in the collector and in the circuit tank-to-load (a) and daily collected energy and collector efficiency (b) from 13 to 20 February.

4. Conclusions

In this work, a simplified model of a solar thermal pilot plant was proposed. Simulated results were compared with real data in order to validate the model and at the same time to evaluate the behavior of the plant and the effect of soling on the collector.

Because of data availability, analyzed period started on 19 January and finished 20 February 2015. In that period, daily maximum temperatures at collector outlet were mostly below 70 °C and estimated optical efficiency was 0.36 or less. Hence, outlet temperatures were approximately 10 °C lower then values recorded at the beginning of December by Enermine and optical efficiency was considerable lower than the nominal one, due to the dust deposition on the collector. During the analyzed period was also observed a gradual decrement of daily maximum temperature inside the tank until that value could not achieve 60 °C and no circulation to the load was possible.

The model was realized with TRNSYS and it can estimate the behavior of the solar plant, even if accuracy decreases for partial cloudy days and after a parameter variation (i.e. mass flow or optical efficiency). Average mass flow relative error was 4.3% for solar loop and 6.7% in load-to-tank circuit. However, calculated solar collector efficiency was always higher than the real one because the difficulties to reproduce exactly the temperature difference at collector outlet and inlet during the day.

As future work, a more detailed comparison will be conducted in order to improve achieved results and to determine the optimal frequency for collector cleaning.

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