Solar Heat Integration in Rotational Molding Process: Case Study

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Abstract

Rotational molding process (RMP) is conventionally used to manufacture plastic products. This process is based on the use of considerable amounts of heat in order to reach the required operating temperature (300°C) for plastics melting. As fossil fuels are the primary source of the required heat in industrial processes, RMP suffers from their drawbacks (e.g. CO_2 emissions, and instable cost of the used fossil fuels). One promising way to reduce these negative impacts is the use of solar thermal technologies as source of energy. Thus, the main objective of this paper is to study the potentiality of the integration of solar heat into Rotational Molding process, as well as its environmental and economic benefits. For this purpose, a real case study of a plant located in Casablanca city in Morocco was simulated in EBSILON® Professional software. The obtained numerical simulation results show that up to 26% of cost-effective solar share could be achieved with a reasonable payback time (around 6 years).

Keywords: Solar Heat for Industrial Process, Rotational Molding Process, EBSILON Professional, Annual Life Cycle Savings, Payback time.

1. Introduction

Among several applications of solar energy, solar heat for industrial process (SHIP) is a promising field. In fact, industrial sector accounts for approximatively 32% of total final energy consumption worldwide, and it's projected to grow by 56% in 2040 (Philibert, 2017). In most of industries, three quarters of the energy demand are for process heat supplying, which is important to attain materials transformation required in the manufacture of industrial products such as heating, drying, cooking, etc. Generally, the conventional combustion of fossil fuels (oil, coal and natural gas) is the primary source providing the required heat for industries. Greenhouse gas emissions from fossil fuel combustion in industrial processes contribute undoubtedly to global warming (Schnitzer et al., 2007). Thus, reducing the consumption of fossil fuels in the industry sector is one of the big challenges of the energy transition worldwide. Therefore, integrating renewable energy sources and particularly solar heat into industrial processes is a clean and suitable alternative to fossil fuels, which can fulfill a considerable amount of heat demand in the sector.

In Morocco, the energy system is very dependent on imported fuels to meet the energy demand of the Kingdom, and primary energy sources are: Petroleum (67,6%), coal (16,1%) and natural gas (5,7%) (Energy Policies Beyond IEA Countries - Morocco 2014,). Fortunately, the country has an important solar potential, which creates favorable conditions for exploitation of solar into the reduction of its energy bill. In this context, the industrial sector has a considerable energetic consumption, which represents around 26% of the national energy consumption. This value is going to grow up, as this sector has known recently a strong development. Thus, the importance of SHIP for improving the local energetic situation. However, to convince the local stakeholders to go into this promising vison, many real case studies should be performed. In this scope, the aim of this work is to study the feasibility of SHIP in rotational molding process, which is used conventionally to manufacture different plastic products in the desired forms. To fulfill this study, real data related to this process were obtained from a plant located in the region of Casablanca city, Morocco. Currently, the needed heat demand is provided by a gas burner in order to achieve the required process temperature of 300 °C. Linear Fresnel Collector (LFR) technology was selected as suitable to attain this temperature levels, and a

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solar thermal plant was optimally designed to supply the process with maximum feasible solar thermal energy to reduce the manufactory gas consumption. All the simulations related to this study were performed in EBSILON Professional software in order to select the best configuration based on two economical indicators, namely Annual Life Cycle Savings (ALCS) and the Payback time.

2. Overview of solar heat in industrial processes

Integration of solar heat in industrial process has a promising outlook as demonstrated by several feasibility studies. The concept of SHIP consists at providing the required heat in the process through a solar thermal plant. The solar field is usually coupled with a thermal energy storage system and installed parallel to a conventional boiler system to ensure a continuous thermal energy supply. The design of SHIP systems consists at defining the most technically and economically suitable solar technology and the most suitable integration point in the process (Baniassadi et al., 2018). Selection of these parameters is totally depending on the process key parameters (fluid medium process, heat supply and distribution networks, working temperature, heat demand, industry location etc.). Generally, different integration concepts are possible and the chosen one for this present study is the most used by previous SHIP investigations (see Fig.1). This concept uses a solar heat exchanger between the solar field and the supply line of the process medium (e.g. hot water, steam, air) in order to integrate efficiently the solar heat into the process.

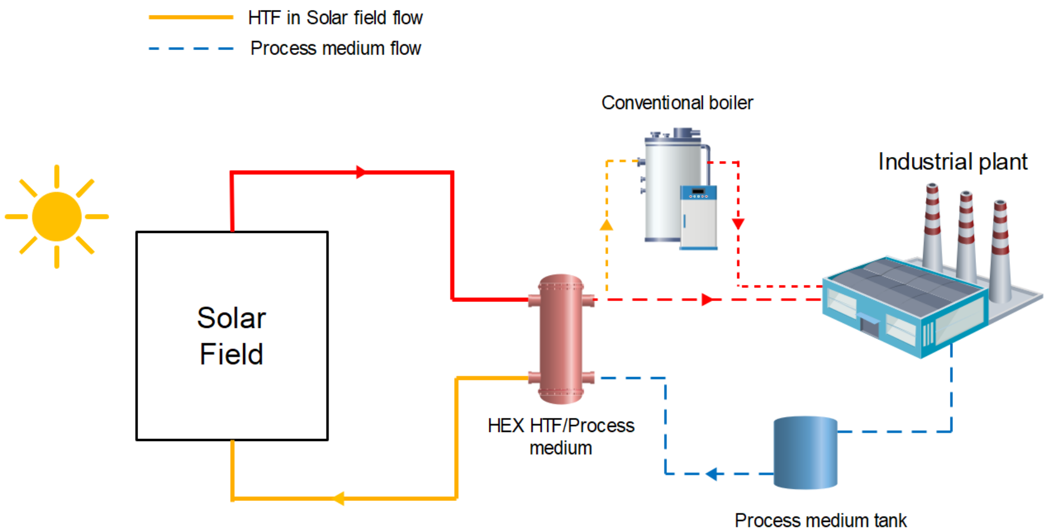

Fig. 1: Integration of solar heat in an existing industrial plant

3. Rotational molding process

Several industrial sectors have been identified with favorable conditions for the integration of solar heat into their processes. In the present work, the study is related to the rotational molding process. The latter is used to manufacture hollow plastic products such as plastic tanks, separators and vessels. Essentially, the process consists of four main operations (see Fig. 2). Firstly, a quantity of plastic powder is introduced into a mold (a: charging). Then, the mold is heated and rotated continuously until the plastic material forms a layer on the mold surface (b: heating). Thirdly, the mold rotation continues during the cooling phase (c: cooling). Finally, when the plastic is sufficiently rigid, the plastic product is demolded to get the final product (d: demolding) (Crawford et al., 2001).

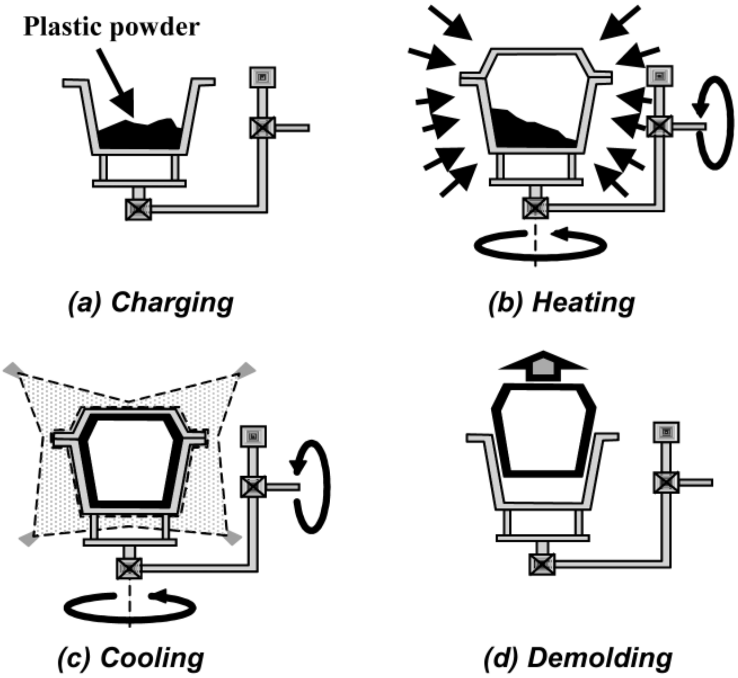

Fig. 2: Steps of rotational molding process (Crawford et al., 2002)

Currently, the majority of local RMP industries use polyethylene as plastic raw material in its several forms. It accounts for approximatively 85% to 90% of all polymers used in the process (Crawford et al., 2001). The real processing program of the studied case of study is presented in Fig. 3, where the second (heating) and third (cooling) steps of the RMP are illustrated. The duration of one cycle of heating/cooling inside the furnace takes approximately about 35 min. in the same figure are presented also the temperature variations of the mold and the plastic as function of time. With respect to this real heat demand curve, the solar heat plant would be designed.

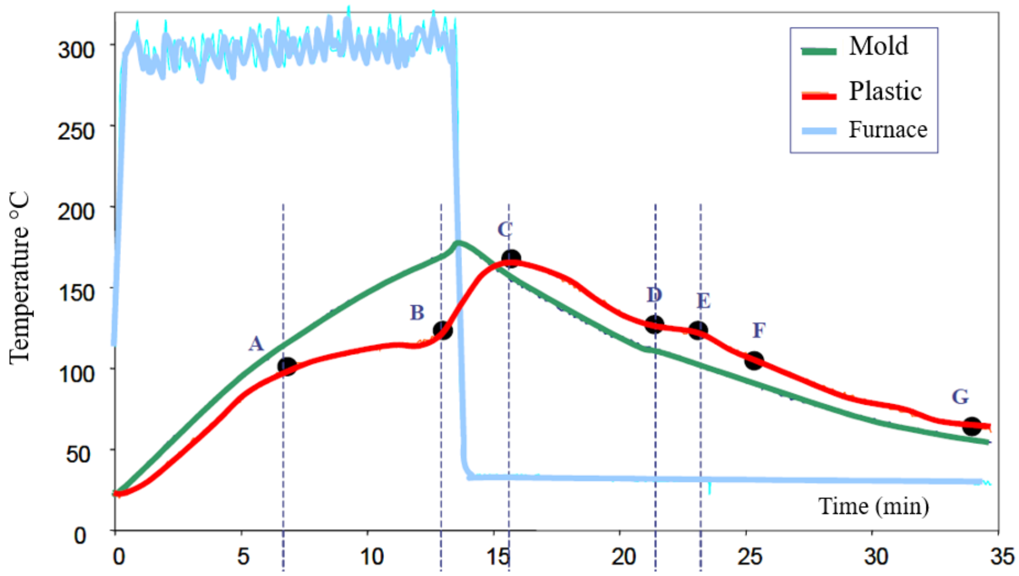

Fig. 3: Temperature variation during a rotational molding cycle *(Pérot, 2006)*

4. Modeling and simulation

4.1. Proposed integration system

The proposed scheme of the integration is illustrated in Fig. 4. The solar field was designed to supply the required heat during the curing period of the process through a heat exchanger between the heat transfer fluid (HTF) circulating in the solar plant and the air used as a process medium. During the operation of the plant, he air takes the maximum heat from the solar field. In the case where the air temperature is below 300 °C, which is the working temperature of the process, the gas burner, installed in serie with the solar field, is activated in order to heat up the air to attain the targeted temperature inside the process mold.

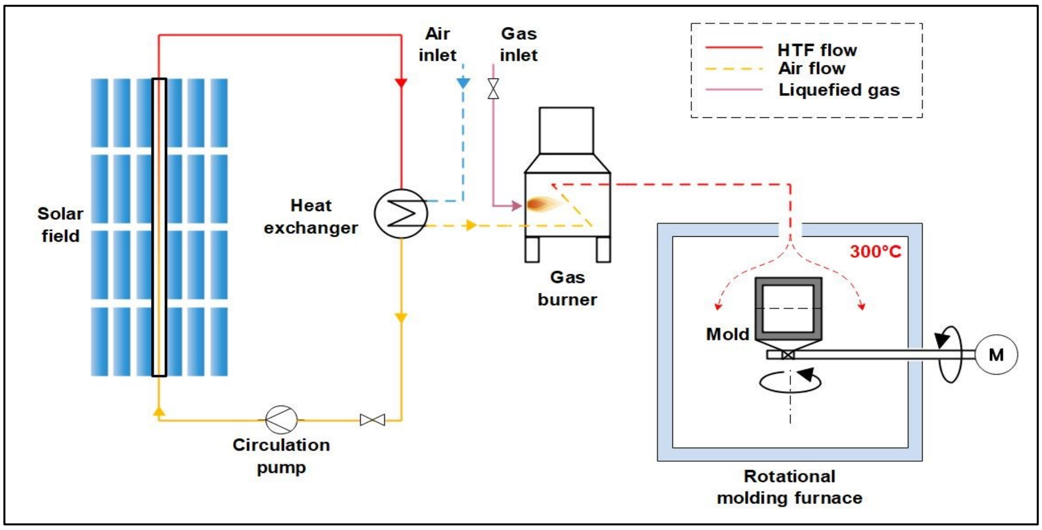

Fig. 4: scheme of the proposed solar heat integration in RMP

In the case of the unavailibility of the solar radiation, the existing gas burner is supplying the additional or the total heat demand in the process. The implementation of a thermal energy storage system was not taken into consideration during this study.

4.2. Process load profile

In the present real case investigation, the solar plant was designed to supply heat for two RM machines. As indicated previously, the duration of each cycle accounts for approximatively 40 min. Since the thermal energy is needed only during the curing phase of each cycle, which takes about 20min, and in order to simplify the conducted numerical study, the two machines have been supposed to work alternately. In other words, the curing phase of one is corresponding to the cooling phase of the other machine. In this case, the supplying of hot air will be continuously. The heat power required in the process can be computed by using the following equation:

$$\dot{Q}_{process} = \dot{m}_{air} c_p (T_{out} - T_{in}) \qquad \text{(eq. 1)}$$

Where $\dot{m}_{air}$ is the mass flow of the hot air, c_p is the specific heat of the air, T_{out} and T_{in} indicate respectively the outlet and inlet temperature of the air in the process.

Fig. 5 depicts the heat demand profile considered during 24 hours. Furthermore, the hot air mass flow required by the process is also presented in the same figure. The demand in the factory is supposed constant during all the days of the year.

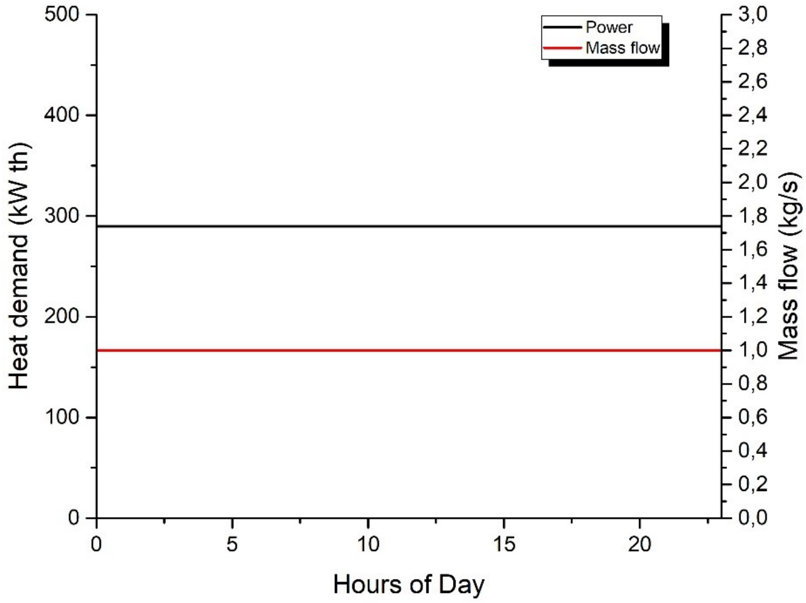

Fig. 5: Heat demand profile of the process

4.3. Solar collectors

According to published studies (Kalogirou, 2003; Pulido-Iparraguirre et al., 2019), line focusing systems, i.e., parabolic-trough collectors (PTCs) and linear Fresnel reflectors (LFRs), are typically the suitable concentrated solar technologies for SHIP in medium temperature applications (up to 300°C). For the purpose of this work, LFR collectors are selected since the technology presents some economic advantages compared with PTC in this range of temperature (Sait et al., 2015). Therefore, Soltigua's Linear Fresnel collectors re exploited in the present simulation work. Technical characteristics of collectors used in the study are listed in Table. 1 ("Soltigua - PV trackers, Solar Tracker Manufacturers, parabolic trough and linear Fresnel collectors,").

Tab 1. Technical characteristics of solar collectors

Collector type	**Net collecting surface (m^2)**	**Reference thermal capacity (kWt)**	**Working temperature (°C)**	**Heat transfer fluid**
FLT10v-48	297,0	166	T_{outlet}=300, T_{inlet}=180	DelcoTerm Solar E 15
FLT10v-60	371,3	207		
FLT10v-72	445,5	249		

4.4. Plant location

The studied RMP plant is located in Casablanca city in Morocco. The city is considered as the commercial capital of the country and the hub of its industry. As the majority of the industrial cities worldwide, and according to statistics published by the World Health Organization ("WHO | World Health Organization,"). The city suffers from air pollution due to the greenhouse gas emissions caused by the industrial activities. With regard to the weather conditions, Casablanca has a hot and humid Mediterranean climate. The main meteorological characteristics related to the city are presented in Table 2 (Ouammi et al., 2012).

Tab. 2: Characteristics of Casablanca city

City	Coordinates	Altitude (m)	Annual Solar Irradiation ($Wh/m^2/day$)
Casablanca	33°35'N 7°36'W	22	5832

4.5. Model in EBSILON Software

To simulate the performances of the proposed system, a numerical study was conducted using EBSILON Professional Software. This commercial program is widely used in modeling, simulation and evaluation of thermodynamic cycle processes. Fig. 5 presents the studied model using available components in the software component libraries.

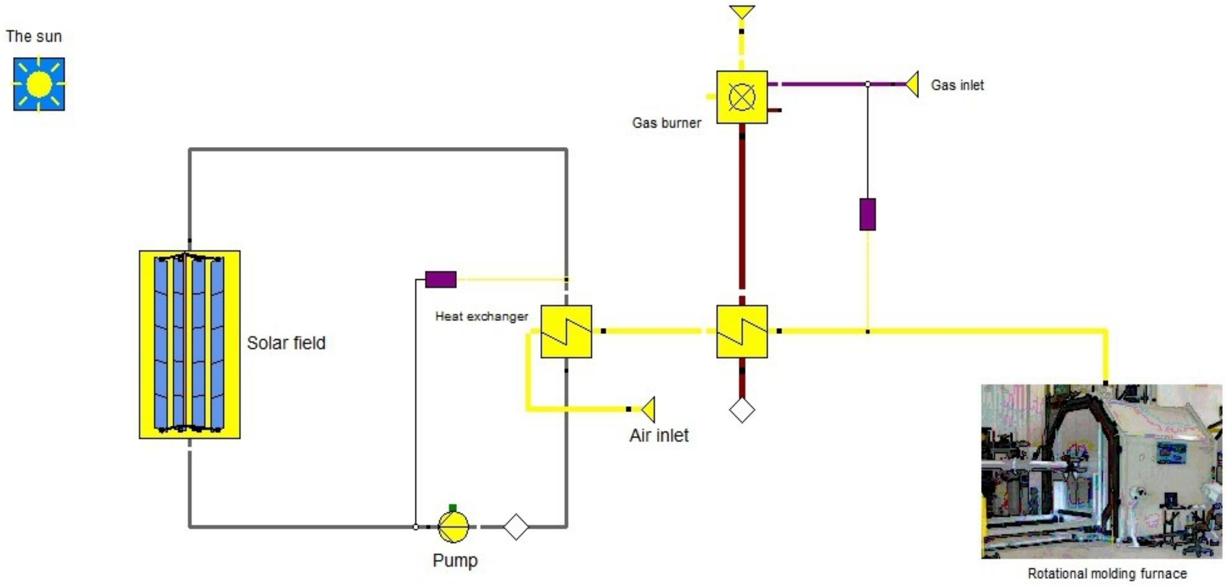

Fig. 6: Layout of the proposed model in EBSILON

As it's indicated previously, the solar field based on LFR collectors was implemented to heat up the process medium (air) through a heat exchanger. The process heat demand was modeled by the determination of the hot air flow rate in the output of the heat exchanger. Depending on the temperature of the extracted air, the gas flow in the inlet of the gas burner varies in order to provide the required heat to meet the recommended temperature of the process. In the considered model, the component "Sun" serve to calculate the parameters related to the solar incident radiation using meteorological data of the plant location. The "Solar field" component simulates the performances of the used LFR collector taking into account the variation of the meteorological data provided by the component "Sun". The absorbed heat by the collector is calculated by the following expression:

$$Q_{solar} = DNI \times A_{SF} \times \eta_{opt,0} \times IAM \times f \times Cl \times \eta_{endloss} \times \eta_{shading} \quad \text{(eq. 2)}$$

Where DNI is the direct normal irradiation, A_{SF} is the net aperture area, $\eta_{opt,0}$ is the optical efficiency for perpendicular sun on collector, IAM is the incidence angle modifier, f is the focus state of the collector, Cl is the cleanliness factor, $\eta_{endloss}$ and $\eta_{shading}$ are the end loss effects factor and shading losses factor respectively. In the present work, the cleanliness factor is not considered in the performed simulations.

The useful thermal output of the collector is given by:

$$Q_{eff} = Q_{solar} - Q_{loss} \quad \text{(eq. 3)}$$

Where Q_{loss} presents the thermal losses in the tube receiver. Heat losses are varying as function of the outlet temperature according to the manufacturer instructions datasheet.

For each collector, the HTF flow rate is varying as function of the DNI to maintain 300°C outlet temperature of the thermal oil using the component "Internal controller" in EBSILON. In the case where the solar radiation are insufficient to attain the nominal operating conditions in the solar field, the "Gas burner" component is implemented in serie to supply the additional heat needed to meet the process conditions. As function of the solar thermal power obtained, the component calculates the additional heat to supply by varying the gas flow rate using the "internal controller" component based on the following expression:

$$\dot{Q_{g.u}} = \dot{m}_{air} \times (h_{process} - h_{solar}) \qquad \text{(eq. 4)}$$

Where $\dot{Q_{g.u}}$ is the useful heat produced by the gas burner, $h_{process}$ being the enthalpy of the air needed in the process, h_{solar} being the enthalpy of hot air obtained through the solar field heat exchanger.

5. Results and discussion

5.1. Solar field sizing

For the sizing of the solar system, the method followed is based on the optimization of solar field surface. Six configurations were chosen accordingly to the Solar Multiple coefficient (SM) expressed by the following equation:

$$SM = \frac{Q_{demand}}{Q_{SF}} \qquad \text{(eq. 5)}$$

Where Q_{demand} being the required thermal power in the process and Q_{SF} is the reference thermal capacity of the solar field.

The technical characteristics of each selected configuration are resumed in Table 3.

Table 3. Technical characteristics of selected configurations

Configuration	Q_{sf} (Reference thermal capacity (kWt))	Number of collectors	Solar multiple
1	166	FLT10v-48 × 1	0,57
2	207	FLT10v-60 × 1	0,72
3	249	FLT10v-72 × 1	0,86
4	332	FLT10v-48 × 2	1,15
5	414	FLT10v-60 × 2	1,44
6	498	FLT10v-72 × 2	1,73

5.2. Selection of the optimal solar field size

The optimal solar field size can be determined based on an economical analysis. For this purpose, a financial evaluation of the six investigated configurations is carried out based on two economical indicators, Annual Life Cycle Savings (ALCS) and Payback time (PB). These parameters are decisive to evaluate the economics of solar systems. The aim of this methodology is to obtain the optimal design corresponding to the maximum life cycle net energy savings and the minimum payback time. The ALCS can be expressed by the following equations (Duffie and Beckman, 2013; Kalogirou, 2013):

$$ALCS = ALCC_{gas} - ALCC_{sol} \qquad \text{(eq. 6)}$$

Where $ALCC_{gas}$ and $ALCC_{sol}$ are the annual life cycle cost related to the conventional system (gas burner) and solar one respectively. The latter one is taking into account the cost of the fuel used when the solar system is not available. The $ALCC_{gas}$ is given by:

$$ALCC_{gas} = C_{gas} \times Q_{load} \times PWF \qquad \text{(eq. 7)}$$

Where C_{gas} is the natural gas cost, Q_{load} is the total thermal energy required by the process and PWF is the present worth factor, which is expressed by:

$$PWF = \frac{1}{d-i}\left[1-\left(\frac{1+i}{1+d}\right)^n\right] \qquad \text{(eq. 8)}$$

Where d is the market discount rate, I is the inflation rate and n the number of years.

The annual life cycle cost related to the solar system is approximated by:

$$ALCC_{sol} = IC + (MC + C_{gas} \times Q_{g.u}) \times PWF \quad \text{(eq. 9)}$$

Where IC represents the initial investments covering the cost of solar collectors and installation, MC refers to the maintenance costs and $Q_{g.u}$ is the total thermal energy used by the conventional burner during the unavailability of the solar system.

The payback time is a widely used financial indicator to evaluate projects. It corresponds to the number of necessary years for the undiscounted accumulated fuel saving to commensurate the initial solar plant investments. It is given by the following formula:

$$Payback\ time = \frac{ln(\frac{IC \times i}{f \times \frac{Q_{load}}{\eta_b} \times C} + 1)}{ln(1+i)} \qquad \text{(eq. 10)}$$

All the terms in the above expression are already given previously, with the exception of the term f which refers to the annual solar fraction related to the proposed solar system and η_b which represents the efficiency of the gas burner. Estimation of all the previous parameters are listed below based on Moroccan market considerations (Allouhi et al., 2017; Otanicar et al., 2012) and the results of the conducted simulations in EBSILON software:

- Natural gas cost is considered as 0.1 €/kwh.
- Total annual thermal load of the process is $Q_{load} = 2528110\ kwh$.
- Natural gas cost inflation rate is considered 2.5% per year.
- Annual market discount rate in Morocco is 5%.
- Specific cost of solar field is estimated as 300 €/m^2.
- Installation cost and maintenance cost are taken as 1% and 2% of IC respectively.

Table. 4 indicates the obtained simulation results related to further parameters for each solar size combination. Furthermore, Fig. 6 presents the calculation results obtained for the six configurations. It can be seen that as the solar multiple is increased the ALCS indicator increases as well to reach a maximum value for the fifth configuration (SM=1.44). Then, after this point, the increasing of SM is unnecessary, as the investment, cost is more important than the extracted solar heat. On the other hand, the PB increases with respect to SM due to the subsequent increase in the investment cost. The best-achieved annual solar fraction was obtained for configuration No. 6 as it involve the biggest solar field. However, the optimal configuration is the fifth one as it has the maximum ALCS and reasonable PB, while it achieve an important SF. This configuration was used to perform the annual simulations in the upcoming sections.

Table 4.Simulation results of the selected configurations

Configuration	ALCC$_{sol}$ (k€)	Annual solar fraction
1	3305	6%
2	3286	7.4%
3	3267	9%
4	3228	11.7%
5	3216	14%
6	3228	15.6%

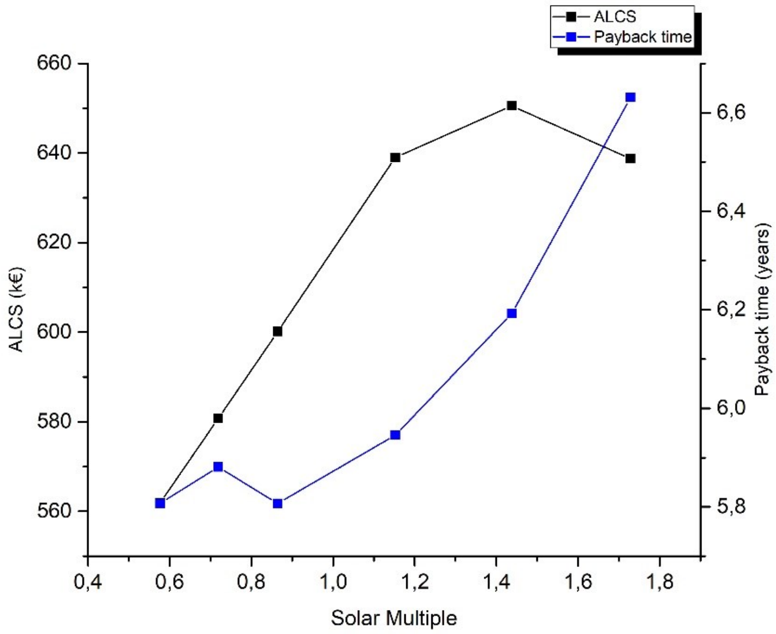

Fig. 7: ALCS and payback time with respect to SM

5.3. Annual results of the optimal configuration

As it has been shown in the previous section, the optimal design corresponds to the maximal annual life cycle saving with a payback time of 6,2 years. To investigate the performances of this configuration, annual simulation considering an hourly time step were conducted. As shown in Fig. 8, the solar field output varies between 7,67 (December) and 55,85 MWh (August), while the gas burner output varies between 154,37 (August) and 210,13 MWh (December). Consequently, high solar fraction values are obtained during summer period. In fact, the highest solar fraction value obtained is 26% (August), and it was reached during August month. It can be explained by the high solar irradiation available in this month. Furthermore, the monthly variation of solar fraction is following the trend the DNI variation. Finally, these obtained results indicate the potential of SHIP for the RMP. Further, work including thermal energy storage component needs to be done in order to increase the potentiality of SHIP and reach higher cost-effective solar share while reducing the energy bill and the CO2 footprint of the RMP.

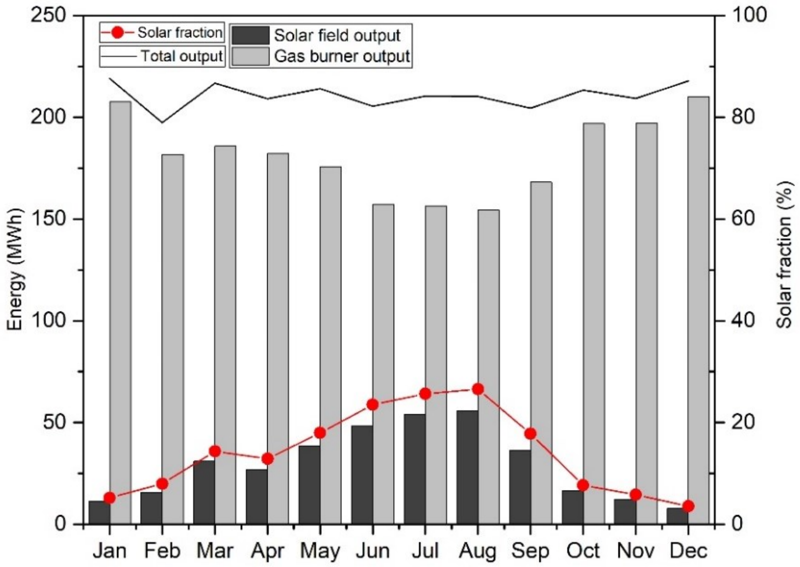

Fig. 8: Monthly solar fraction for the optimal configuration

6. Conclusions

In this effort, a real case of study of solar heat integration (SHIP) into the rotational molding process (RMP) was investigated in order to demonstrate its feasibility and help in increasing the awareness of the local industrial stakeholder for the importance of SHIP for the nowadays-energetic situation of Morocco. Six configurations of solar thermal field based on Linear Fresnel collectors were studied in order to select the most optimal one. To fulfill this, two critical indicators were used and they are namely ALCS and Payback time. The obtained result suggested that the configuration No. 5 performs the best as it achieves the highest ALCS (650 k€) with a reasonable payback time (6.2 years) and an important annual solar share. Moreover, this optimal configuration were used to perform the annual simulation and the obtained results have shown a great potential of SHIP for RMP. Actually, it reached up to 26% of solar fraction during August month. This value could be increased more if a thermal energy storage system is implemented in the integration scheme.

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