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Modelling and dynamic simulation of solar heat integration into a manufacturing process in Réunion Island

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Abstract

According to the International Energy Agency, solar thermal energy is rarely used in industrial sector, despite its capacity to generate heat with the existing technologies. Moreover, a large part of the firms of Réunion Island are in the food-processing industry, which is the most heat consuming sector according to these studies. Among them, the Sorélaït-Danone company (yoghurt production) has decided to collaborate so as to analyze the potential impact of solar heat integration into its actual heat generation system. The company has a fuel boiler which generates 7 bar saturated vapor (corresponding to a temperature of 165°C) at a nominal flow rate of 2,5 tons per hour. This boiler is supplied by a tank filled with water. In the latter, condensate coming from the process unit is mixed with the district's cold water, in order to compensate the vapor lost in the process. In this work, possibilities in terms of solar heat integration into the system have been investigated. 4 different cases have been simulated (direct or indirect integration, into the mixing tank or the boiler tank) and the corresponding saved fuel quantities have been estimated. The results of simulation show that in the best case, a fuel saving of 25 % can be expected with a total collector area of 600 m² for this company.

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Keywords: solar heat ; industry ; modelling ; simulation ; manufacturing process ; sustainable development

1. Introduction

By mean of the SHC (Solar Heating and Cooling) program of the International Energy Agency (IEA), a state of the art of the use of solar heat in the industrial sector has been carried out. This early work shows a very limited integration of solar heat in this sector whose temperature needs are nevertheless suitable with the current solar panels

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technologies [1, 2]. Reasons for this include the fact that the industrial actors frequently obtain a preferential rate for the energy purchase, which does not encourage them to invest in solar heat solutions [3]. The second phase (Task 49) of the SHC program focuses on the heat production and its integration into the industrial processes. The conclusions actually demonstrate the substantial potential of the solar heat for industry and suggest guidelines for the growth of the sector [4]. Furthermore, SHC program mainly focuses on the European case [5, 6], while in this work, we have taken an interest in the tropical area, whose solar resources are greater than the sunniest parts of Europe. In Réunion Island, a French overseas department situated in the Indian Ocean close to Mauritius, thermal solar energy has increased steadily for more than 15 years in the final primary energy consumption, in which its part rose from 2,2 % in 2000 to 21,2 % in 2016 [7].

In the light of this situation, a new research project has been launched recently. Initiated by PIMENT Laboratory, jointly with local institutions, it aims to assess the feasibility and relevance of the solar heat use for existing industrial processes. This is how was born a partnership with Sorélaït-Danone, a firm of the food-processing industry (yoghurt production), in order to study the opportunity of solar heat integration into its current heat generation system.

Nomenclature

		<i>Subscripts</i>	
C_p	mass heat capacity, $J \cdot kg^{-1} \cdot K^{-1}$	<i>1 to 5</i>	calculated points of the system
GHI	global horizontal irradiance, $W \cdot m^{-2}$	<i>env</i>	environment (technical room)
h	specific enthalpy, $J \cdot kg^{-1}$	<i>ext</i>	exterior
N	number, -	<i>c</i>	cluster
\dot{Q}	thermal power, W	<i>f</i>	solar field
S	exchange area, m^2	<i>m</i>	mean / average
u	specific internal energy, $J \cdot kg^{-1}$	<i>in</i>	inlet of the solar field
T	temperature, K	<i>out</i>	outlet of the solar field
η	efficiency, -		
δ	state of the boiler (on or off), -		

2. Case of study: Sorélaït-Danone firm

At present time, the heat supplied to the whole process (Fig. 1) is fed by steam provided by a conventional fuel boiler (point 4). The saturated vapor leaves the boiler tank at 7 bar (corresponding to a temperature of 165°C) with a mass flow rate \dot{m}_v . In the process, a major part of the steam is used as a heat vector and comes back to the mixing tank as condensate (point 5) at T_5 with a mass flow rate \dot{m}_{cond} . The other part ($\dot{m}_{v,loss}$) is lost because of specific uses such as washing for instance. In the mixing tank, whose volume is 5 m³ (corresponding to the mass M_{MT}), these losses are compensated by district's cold water at a temperature T_1 with a mass flow rate \dot{m}_{cw} . The temperature of the water in the mixing tank T_2 is supposed to be uniform and the tank is at atmospheric pressure. Hot water flows from this tank to the boiler tank at temperature T_2 with \dot{m}_{hw} flow rate. Thermal losses $\dot{Q}_{loss,MT}$ with the environment are taken into account. The mass and energy balance of the mixing tank are given by:

$$\begin{cases} \frac{dM_{MT}}{dt} = 0 = \dot{m}_{cond} + \dot{m}_{cw} - \dot{m}_{hw} \\ M_{MT} \frac{du_2}{dt} = \dot{m}_{cond} \cdot h_5 + \dot{m}_{cw} \cdot h_1 - \dot{m}_{hw} \cdot h_2 + \dot{Q}_{loss,MT} \end{cases} \quad (1)$$

$$\text{Where } \dot{Q}_{loss,MT} = U_{g_{MT}} \cdot S_{MT} \cdot (T_{env} - T_2) \quad (2)$$

With $U_{g_{MT}}$ the global heat transfer coefficient between the tank and the air in the technical room and S_{MT} the exchange area.

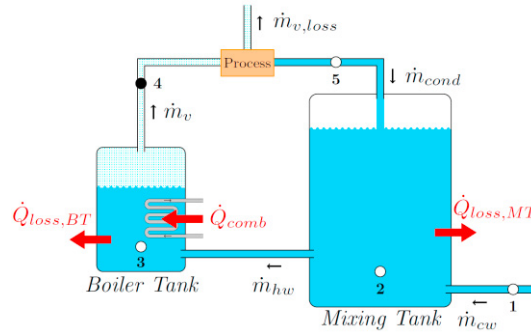


Fig. 1. Current heat supply system of the Sorélaït-Danone firm.

As seen on Fig. 1, the water in the boiler tank [8] is heated by a fuel burner delivering \dot{Q}_{comb} so as to generate saturated vapor at temperature T_4 and flow rate \dot{m}_v . The mass and energy conservation equations are similar to those previously described:

$$\begin{cases} \frac{dM_{BT}}{dt} = 0 = \dot{m}_{hw} - \dot{m}_v \\ M_{BT} \frac{du_3}{dt} = \dot{m}_{hw} \cdot h_2 - \dot{m}_v \cdot h_4 + \dot{Q}_{loss,BT} + \delta_{comb} \cdot \dot{Q}_{comb} \end{cases} \quad (3)$$

$$\text{Where } \begin{cases} \dot{Q}_{comb} = \dot{m}_{fuel} \cdot LHV_{fuel} \cdot \eta_{comb} \\ \dot{Q}_{loss,BT} = Ug_{BT} \cdot S_{BT} \cdot (T_{env} - T_3) \end{cases} \quad (4)$$

With $LHV_{fuel} = 12000$ Wh/kg and η_{comb} the boiler efficiency, which has been considered equal to 0,90. Ug_{BT} is the global heat transfer coefficient between the tank and the air in the technical room and S_{BT} is the exchange area. Lastly, the temperature regulation of the boiler tank has been integrated to the global model. Indeed, the scalar variable δ_{comb} in the equation (3) takes the 0 value when the burner is off and the value 1 when the latter is on.

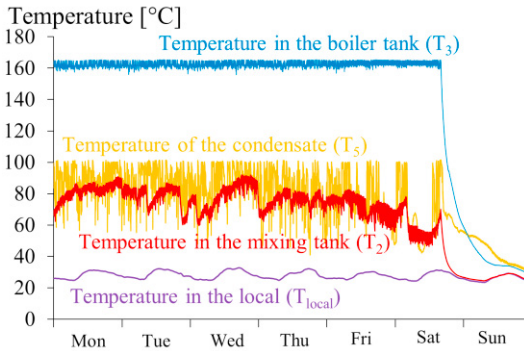


Fig. 2. Measured evolution of the temperatures of outlet boiler tank vapor (T_4), condensate (T_5), water in mixing tank (T_2) and ambient air in the room (T_{local}).

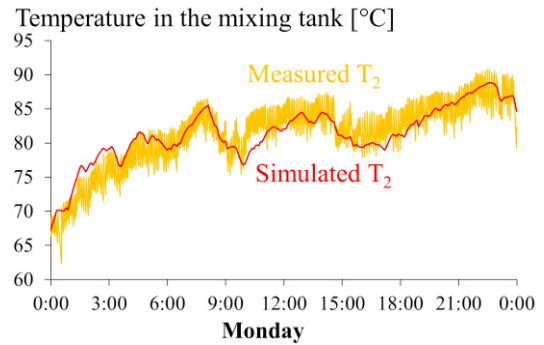


Fig. 3. Comparison between measured and simulated water temperature in the mixing tank (T_2).

In order to test and potentially validate the above model, a three months long set of measurements has been carried out and allowed to obtain the evolution of several temperatures of the system (Fig. 2). Moreover, a weather station has been installed on the roof so as to acquire the climatic condition on the site. Fig. 3 shows the comparison of the measured and simulated water temperature in the mixing tank. One can observe that the calculated values follow relatively well the experimental data all day long. Moreover, our model allows a good estimation of the consumed fuel quantity for a day (difference of 1.9 % between measured and simulated values for a day, 2.5 % for the whole week). At this stage, the simulated and experimental energy balances seem to show satisfactory similarity in order to study the integration of solar heat into the current system.

3. Modelling of the solar heat integration

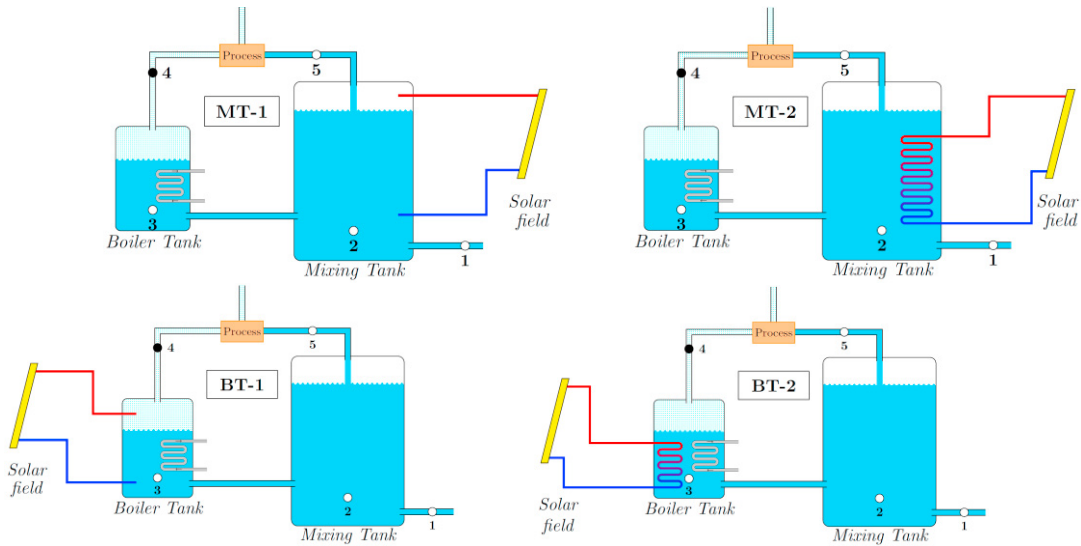


Fig. 4. Studied cases of solar heat integration into the current system – **MT-1**: direct integration into the mixing tank; **MT-2**: indirect integration into the mixing tank through an internal heat exchanger; **BT-1**: direct integration into the boiler tank; **BT-2**: indirect integration into the boiler tank through an internal heat exchanger

Based on the previously tested model, possible integration of solar heat has been investigated and four different cases have been considered (Fig. 4). In the two cases of indirect integration (MT-2 and BT-2), a secondary heat transfer fluid such as thermal oil flows in the solar field, whereas in the two other cases (MT-1 and BT-1) the heat transfer fluid in the solar panel is the water of the tank itself. Vacuum pipes panel technology has been chosen due to its capacity to generate temperature levels between 110 and 200 °C [9]. The solar field is composed of parallel associated clusters of solar panels. Each cluster is made up of five solar panels placed in series. The flow rate in the solar field \dot{m}_f is set by the total area of the solar field. The manufacturer gives indeed the nominal surface flow rate \dot{m}_{panel} of the solar panel [10]. The mass flow rate in the solar field is then calculated as follows:

$$\dot{m}_f = N_c \times (N_{panels/cluster} \cdot S_{panel} \cdot \dot{m}_{panel}) = N_c \times \dot{m}_c \quad (5)$$

N_c is the number of clusters, $N_{panels/cluster} = 5$ the number of panels per cluster, $S_{panel} = 2.99 \text{ m}^2$ the area of one panel and $\dot{m}_{panel} = 25 \text{ L}/(\text{h} \cdot \text{m}^2)$ the nominal surface flow rate for the chosen model (Viessmann's VITOSOL 300-T) [10]. The modelling of the solar field has been carried out thanks to the efficiency definition [11, 12]. The heat absorbed by the heat transfer fluid in the solar field \dot{Q}_{sol} is given by equation (6) which considers a possible phase change of the fluid (liquid to vapor). Eq7 shows the expression of the efficiency of the solar panel η_{panel} , which allows to determine the outlet temperature, when combined with equation (6). Once $T_{f,out}$ and consequently $h_{f,out}$ are determined, \dot{Q}_{sol} can be added into the energy balance of the considered tank (eq1 for mixing tank and eq3 for boiler tank). Solar source GHI comes from the experiments performed on site.

$$\dot{Q}_{sol} = \eta_{panel} \cdot S_f \cdot GHI = \dot{m}_f \cdot (h_{f,out} - h_{f,in}) \quad (6)$$

$$\eta_{panel} = \eta_0 - a_1 \cdot T^* - a_2 \cdot GHI \cdot (T^*)^2 \quad \text{with} \quad T^* = \frac{T_m - T_{ext}}{GHI} \quad \text{and} \quad T_m = \frac{T_{f,in} + T_{f,out}}{2} \quad (7)$$

Where η_0 , a_1 and a_2 are specific parameters of the solar panel for efficiency evaluation. For the two MT-2 and BT-2 cases, a heat exchanger is located in the tank in order to transfer the heat absorbed in the solar field to the water in the tank. Considering that thermal oil enters the heat exchanger at $T_{f,out}$, its temperature $T_{f,in}$ when leaving the tank after transferring its heat to the water, can be determined by using the definition of the heat exchanger efficiency (eff_{HX}):

$$T_{f,in} = T_{f,out} - eff_{HX} \cdot (T_{f,out} - T_{2 \text{ or } 3}) \quad (8)$$

4. Simulation of the solar heat integration

By hypothesis, outlet temperatures in mixing tank and boiler tank can not exceed the saturation temperature of the corresponding pressures ($P_{MT} = P_{atm}$ for the mixing tank and $P_{BT} = 7$ bar for the regulated boiler tank). As seen on Fig. 2, the temperature of the water in the mixing tank is relatively close to 100°C at atmospheric pressure. As the mixing tank is supposed to feed the boiler tank with liquid water only, the best configuration is obtained by increasing the number of clusters until the temperature of water inside the tank remains below the saturation temperature. So, even if we let the water evaporate in the solar panels, only one cluster can be integrated, saving only 49 L of fuel for one week (0,9% of savings). To go further, the mixing tank has been considered as able to reach pressure as high as 7 bar. Under these assumptions, the best results have been obtained with 8 clusters for MT-1 case and 10 clusters for MT-2 case. The corresponding amount of saved fuel are given in Table 1. As an example, Fig. 5.a and 5.b present the temperature evolution over time for the water inside the tank and for input and output of the solar field. Regarding the integration into the boiler tank, the maximum clusters number is higher in this case, due to the fact that water in the boiler tank can possibly be evaporated. It has been calculated that the maximum number of clusters for BT-1 and BT-2 cases are worth respectively 37 and 46. Fig. 5.c and 5.d present also the evolution of the temperatures in this case.

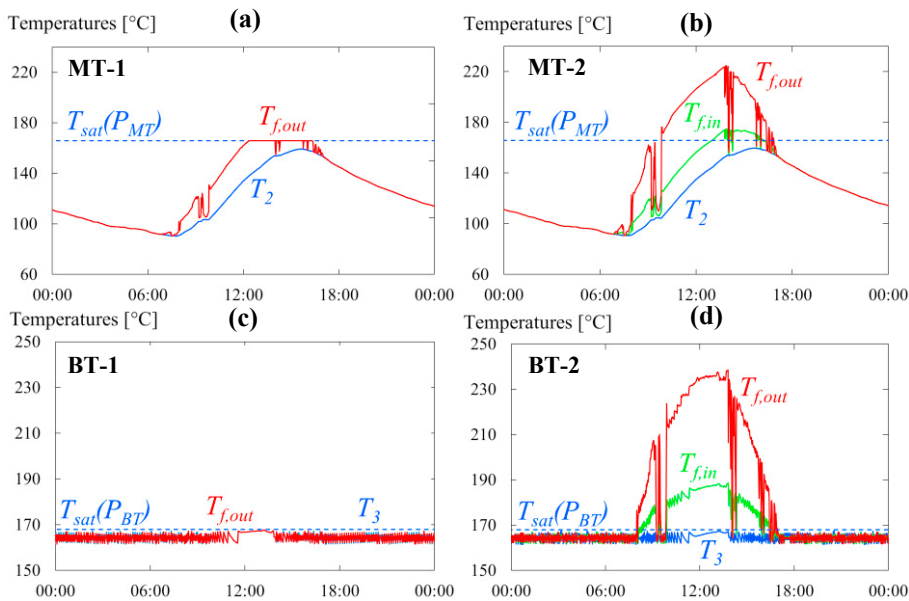


Fig. 5. Simulation results for one typical day – Evolution of the temperatures in the tanks and in the solar field. (a) MT-1 case; (b) MT-2 case; (c) BT-1 case; (d) BT-2 case

Table 1. Simulation results for each of the 4 cases of solar heat integration

Integration mode	MT-1	MT-2	BT-1	BT-2
Solar field area	135 m ²	165 m ²	555 m ²	690 m ²
Saved fuel	6,4 %	6,5 %	24,05 %	24,18 %

In the two indirect integration cases (MT-2 and BT-2), the oil considered in the secondary loop does not undergo any evaporation but reaches higher temperatures than in the case of water.

By mean of these simulations, we also achieved to estimate the saved fuel quantity in each case. The results are given in Table 1. Regardless of the solar field area, integration into the boiler tank allows greater savings than integration into the mixing tank (respectively about 24 % and 6 % of maximum saved fuel). The best integration case seems to be the direct integration into the boiler tank (BT-1), since maximal fuel savings are reached for smaller solar field area than in the indirect integration (BT-2). This difference is explained by the fact that the secondary fluid flowing in the solar field in the 2 indirect cases reaches high temperatures, hence decreasing the solar panels efficiency. Moreover, it is not surprising to note that MT-1 case leads to same savings that MT-2 case (6,5 %), since the number of clusters has been chosen in order to reach the same goal for the two cases (temperature T_2 as high as possible, but without exceeding $T_{sat}(P_{MT})$). The same situation is observed with the boiler tanks (BT-1 and BT-2).

5. Conclusion

In this work, a study of solar heat integration into a manufacturing firm of the tropical area has been carried out and a company: Sorélaït-Danone, which produces yoghurt in the Reunion Island, has been modeled and simulated. Four different cases of solar heat integration into the actual system have been considered. The results showed that the direct integration into the boiler tank seems to be the most relevant choice since it allows a fuel saving of 24 % for one week and for a solar field area of 550 m². Therefore, one can notice that for a solar field area of 700 m², the indirect integration into the boiler tank with an internal heat exchanger reaches to the same amount of fuel saving (24 %) and displays the advantage of avoiding phase change of the thermal fluid (oil) in the solar field.

Moreover, in order to complete this work, exergetic and exergo-economic aspects will be integrated [13, 14] so as the possibility to consider energy storage in the process.

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