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On the representativeness of simulation models for control studies of solar thermal fields

Summary

Concentrating Solar Thermal (CST) technologies can contribute substantially to the decarbonization of industrial heat, through the supply of renewable heat at industrially relevant temperature levels. Their low-level control strategy aims to maintain steady outlet temperature despite the inherent variability of solar radiation, through the regulation of the solar pump flow rate. Simulation models usually assume idealized behavior for this low-level control. The present study is concerned with the modeling aspects that enhance the representativeness of such computational tools to realistically study, design and improve control strategies. Additionally to a semi-physical model with one-dimensionally spatial discretization, the proposed model incorporates a series of non-idealities for the solar pump, such as discrete control timestep, quantization of the potential flow rate range, actuator ramp constraint and first-order inertia for its dynamic response.

Keywords: solar thermal energy, computational modeling, control
Field of application for the findings: Concentrating Solar Heat, Industrial Heat, Computational Modeling
Addressed audience: Researchers, Engineers

1. Introduction

Solar thermal fields are expected to contribute to the reduction of fossil fuels combustion. Particularly, Concentrating Solar Thermal (CST) technology is a promising renewable energy source (RES), for providing sustainable heat to the industry, an increasingly crucial field, since industrial heat represents 25% of the global energy consumption while being satisfied mostly by fossil fuels. Additionally to other common RES challenges, such as upfront finance and space requirements, these systems compete with fuel-burning boilers, a highly mature, dispatchable and controllable technology, able to provide steady temperature to the heat load. While able to provide heat in industrially relevant temperatures, CST fields have a variable energy input - the solar radiation - therefore, their outlet temperature is unsteady and must be regulated. In the case of linear concentrating solar technologies like Parabolic Trough Collectors (PTC) and Linear Fresnel Reflectors, this objective is additionally hindered, since the heat transfer fluid (HTF) circulates through long distributed collector fields, having high residence time and being exposed more to the variable solar irradiance. As a result, the performance of their control strategy has a determining impact on the successfulness of these technologies. In the literature, various simulation tools are reported for these technologies, however, they are mostly focused on their thermal performance and their high-level supervisory control. In those cases, low-level control is usually considered idealized or there is lack of documentation. This exploratory study aims to elaborate the representativeness of simulation tools and their capability to realistically simulate low-level control strategies within their dynamic constraints, in order to study, challenge and improve them.

2. Case study context and computational model

The case study under consideration pertains to the control of a solar field comprised of 24 PTC collectors* in series, aiming to provide heat to industrial processes. The inlet temperature is 160 °C and the target outlet temperature is 185 °C. The mass flow rate of the solar pump is regulated by the control system, in order to adjust the outlet temperature to the desired setpoint.

A transient simulation tool has been developed using the Modelica language, within the OpenModelica environment. The semi-physical model for the PTC collectors is based on their Solar Keymark certificate (ISO 9806). It provides the same results regarding the efficiency as reported in the certificate, while incorporating elements to improve its behavior in other operating conditions (e.g. distinct temperature in tube and HTF, flow-dependent convection coefficient between them, physical-based thermal inertia etc.).

*Information omitted for the blind review

Since the focus of the study is to improve the model capacity to capture transient effects that are exhibited in low-level control regimes, the temporal and spatial discretization is higher than what is commonly used in studies focusing on the performance and supervisory control. The temporal discretization of the simulation is $\Delta t_{\text{sim}} = 0.1$ s. This timescale is essential since the physics must be simulated at a lower timestep than the control timestep Δt_{con}. Moreover, it should be lower than the HTF residence time inside the solar field (in this case 1-5 min). The solar field is spatially discretized one-dimensionally in the axial direction (200 control volumes), in order to capture the HTF residence time, as well as hot and cold plugs that are trapped inside the field. The adequacy of the temporal and spatial discretization was determined by independence studies.

This work focuses on the modeling characteristics of the control of the solar pump, the actuator of CST fields. These characteristics determine the representativeness of the model, which could be employed for the formulation and the design of the controller. In supervisory control studies idealized behavior of the control of the solar pump is sufficient. However, idealized behavior is not adequate when the objective is to utilize the model for studying, challenging and improving the low-level control strategies (i.e. regulation of outlet temperature). A series of non-idealities are incorporated in the model. The control of the mass flow rate of the solar pump is dictated by the following: (a) minimum and maximum bounds (eq. 1), (b) the control timestep (interval at which sensors are read and actuators are manipulated) is discrete and higher than the simulation Δt_{sim} (eq.2), (c) quantization, namely the mass flow rate proposed by the controller cannot take continuous values, it can only be adjusted to $N_q + 1$ discrete values from $\dot{m}_{\text{min}}$ to $\dot{m}_{\text{max}}$ (eq. 3), (d) actuator ramp constraint, namely the change rate imposed to the pump is finite, either for self-protection of the pump or as plant management strategy (e.g. regulate the influence on downstream valves and pumps); the definition of the maximum $d\dot{m}/dt$ is based on the minimum allowable time t_{ramp} for a change equal to $(\dot{m}_{\text{max}} - \dot{m}_{\text{min}})$ (eq.4), and (e) the imposed $\dot{m}$ by the controller is not instantaneously attained, its dynamic response is simulated with a first-order inertia model, using the actuator time constant τ (eq. 5).

$$\dot{m}_{\text{min}} \leq \dot{m} \leq \dot{m}_{\text{max}} \tag{1}$$

$$\Delta t_{\text{con}} > \Delta t_{\text{sim}} \tag{2}$$

$$\dot{m}_{\text{quant,i}} = \dot{m}_{\text{min}} + i\,\Delta m, \quad \text{where } i = 0, ..., N_q \text{ and } \Delta m = \frac{\dot{m}_{\text{max}} - \dot{m}_{\text{min}}}{N_q} \tag{3}$$

$$\left.\frac{d\dot{m}}{dt}\right|_{\text{max}} = \frac{\dot{m}_{\text{max}} - \dot{m}_{\text{min}}}{t_{\text{ramp}}} \tag{4}$$

$$\tau \frac{d\dot{m}}{dt} = \dot{m}_{\text{control}} - \dot{m} \tag{5}$$

3. Framework of the study

This study aims to investigate the influence of the four parameters that introduce non-idealities in the control of the mass flow rate of the solar pump, as defined in the previous section. The four parameters and their studied values are summarized in the following table.

Tab. 1: Parameters and respective values under consideration

Parameter		Values
Controller timestep	Δt_{con}	1, 10, 30, 60 90 s
Quantization intervals	N_q	100, 50, 20, 10
Ramp constraint	t_{ramp}	1, 30, 60, 120, 240 s
Actuator time constant	τ	1, 30, 60, 120, 240 s

The system is simulated for one day using the aforementioned model. The DNI input of the model are measurements every 2 seconds, to preserve the dynamics and mimic the input of the controller . The Modelica model is encapsulated using the Functional Mock-Up Interface (FMI) standard and run through Python using the FMPy package. Various performance metrics are calculated, the most important being the average error ΔT_{ave} in °C (integral of the error normalized by the evaluation period t_{eval}), the maximum error throughout said period ΔT_{max}, time with error over 2 °C and over 5 °C, as well as the average mass flow rate variation $\overline{\left|\frac{d\dot{m}}{dt}\right|} = \frac{1}{t_{\text{eval}}} \int^{t_{\text{eval}}} \left|\frac{d\dot{m}}{dt}\right| dt$. The latter is an indicator of the oscillatory behavior, aggressiveness of the controller, and pump fatigue, while the rest indicators concern the performance.

The focus of the study is to evaluate the representativeness of the model per se. To isolate its effect and exclude the influence of the low-level and the supervisory controller, the evaluation period of the metrics is set between 10:00 and 16:00 (white background in Figure 1 graphs). In this way, the metrics are not affected by the controllers' effectiveness on the transition from the start-up pre-heating to the operational mode. A criterion of the employed controller was to be timestep-independent. A simple model-based feedforward controller with a corrective integral term is used. It is emphasized that the controller is not the objective of the study.

$$\dot{m}_{\text{control}} = \frac{\eta \, \dot{Q}_{\text{DNI}}}{c_p (T_{\text{setpoint}} - T_{\text{inlet}})} + k_{\text{int}} \int (T_{\text{outlet}} - T_{\text{setpoint}}) dt \tag{6}$$

4. Results discussion and conclusions

The simulations were conducted for the 500 combinations of the parameters summarized in Table 1. Within the studied range, the ΔT_{ave} varies between 0.05 – 0.85 °C, while ΔT_{max} between 0.14 – 3.24 °C. It should be emphasized that the derived results (i) pertain to one day with fairly smooth DNI profile without challenging disturbances, (ii) assume accurate reading from pyrheliometer as input to the controller, (iii) exclude transitional periods (gray background in Figure 1 graphs), (iv) consider steady inlet temperature (v) involve a specific solar field in terms of size and collectors, and (vi) are based on a specific controller (equation 6). In this sense, these results might not be extrapolatable if any of the aforementioned factors differs.

The base case ($\Delta t_{\text{con}} = 1$ s, $N_q = 100$, $t_{\text{ramp}} = 1$ s, $\tau = 1$ s) approximates an idealized behavior, as the controller acts frequently, quantization is high so the discrete flow rate values have smaller steps, the actuator ramp constraint is not strict and the pump dynamics are fast. Consequently, it exhibits a quasi-idealized behavior with $\Delta T_{\text{ave}} = 0.05$ °C and $\Delta T_{\text{max}} = 0.15$ °C. In all combinations with ($\Delta t_{\text{con}} = 1$ s, $N_q = 100$), the ΔT_{ave} and ΔT_{max} range between 0.05 – 0.09 °C and 0.14 – 0.48 °C, respectively. When quantization decreases to $N_q = 10$, ΔT_{ave} ranges between 0.34 – 0.51 °C, while ΔT_{max} ranges between 0.97 – 1.53 °C. This reveals the important influence of the quantization. Indicatively, in this case $N_q = 10$ means that the pump can be regulated with a precision step of 0.06 kg/s. The worst performance in terms of ΔT_{ave} (values higher than 0.6 °C) is manifested in the cases of ($\Delta t_{\text{con}} = \{60, 90\,\text{s}\}$, $N_q = 10$, $t_{\text{ramp}} = \{1, 30, 60, 120, 240\,\text{s}\}$, $\tau = \{1, 30, 60\,\text{s}\}$). The same cases with $\tau = \{120, 240\,\text{s}\}$ perform better, suggesting that Δt_{con} can increase when the system dynamics are slower.

Within the studied range, the quantization level and the control timestep have the strongest effect on ΔT_{ave}, which monotonically increases with decreasing N_q and increasing Δt_{con}. The actuator ramp constraint t_{ramp} does not have a significant impact within the studied range, with its impact being eliminated at $\Delta t_{\text{con}} \geq 60$ s. The effect of the actuator ramp constant τ is not straight-forward as it interacts with the effect of other parameters. Taking the example of $\Delta t_{\text{con}} = 60$ s and $t_{\text{ramp}} = 30$ s, ΔT_{ave} increases with τ for $N_q = 100$, whereas ΔT_{ave} decreases with τ for $N_q = 10$. Figure 1 illustrates the temporal profile of the solar field outlet temperature and the solar pump mass flow rate for the aforementioned example. This study illustrates that modeling accuracy has a significant impact on the controller performance, moving from simulation to real applications. Conclusively, it aims to motivate a more systematic study of simulation tools used for the design of low-level controllers.

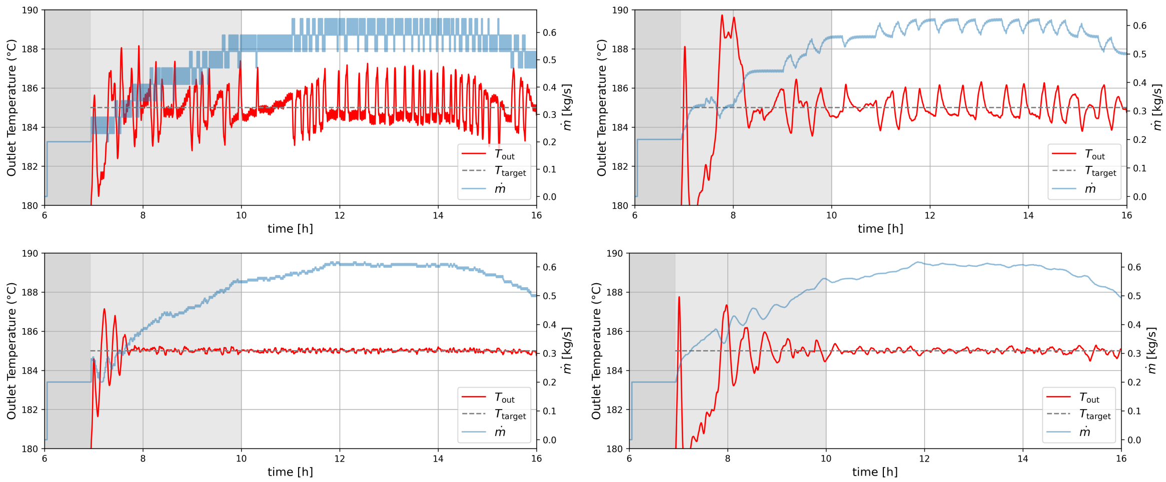

Fig. 1: Solar field outlet temperature and solar pump mass flow rate profiles for $\Delta t_{\text{con}} = 60$ s and $t_{\text{ramp}} = 30$ s. Upper row: $N_q = 10$ (left: $\tau = 1$ s , right: $\tau = 240$ s). Bottom row: $N_q = 100$ (left: $\tau = 1$ s , right: $\tau = 240$ s)