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Solar furnace temperature control with active cooling☆

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ABSTRACT

The article describes a control architecture for solar furnaces where active cooling is employed to improve the tracking of a time-varying temperature reference. This capability is important during the decreasing phase of the temperature reference where heat loss must be increased. The results of two different control methodologies, exact linearization and model predictive control with integral action, are shown with active cooling that is done in coordination with the command of the shutter which adjusts the solar incident power.

The controller parameters are computed from the temperature dynamics which is identified off-line from collected process data. This approach is used to avoid online adaptation mechanisms of the controller parameters, that may cause stability problems during the controller startup, and may melt the testing material sample.

The novelty of the present work is to present a control architecture that coordinates the operations of the shutter together with the application of active cooling. This methodology improves temperature reference tracking and increases the usability and the operation of solar furnaces.

1. Introduction

Increased energy costs, past energy crises and energy conflicts, carbon-based energy pollution, and the expected fossil-fuels induced climate changes, have triggered the development of renewable energy technologies such as concentrating solar power systems (CSP). CSP include solar furnaces, photovoltaic (CPV), solar thermal (CST) which have a wide application, such as the "generation" of electrical energy and heat (Camacho et al., 2007a,b), the production of solar fuels, hydrogen and syngas (Agrafiotis et al., 2014), desalinization, and material processing (Oliveira et al., 2015, 2016).

The article addresses the control of solar furnaces for material processing and stress testing, where the temperature of the sample must follow a time-varying reference with precision. The proposed control architecture has a cascade structure where the outer controller is employed to control the temperature of the sample, computes a reference for the incident flux on the sample, and supplies it to the inner controller. The inner controller adjusts the position of the shutter using the information that it receives from the temperature controller and compensates changes present in the solar irradiance. If needed, solar incident flux control experiments can be done using only the inner controller.

Research on control of solar furnaces for material processing and stress testing, developed at the Plataforma Solar de Almeria (Berenguel et al., 1999), have addressed several topics, such as constrained temperature control and disturbance rejection (Beschi et al., 2012, 2013b), linearization with the Generalized Predictive Control (GPC) algorithm (Beschi et al., 2013a) and fractional robust PID control (Beschi et al., 2016).

Motivated by the improvement of operation and automation of small size solar furnaces at PROMES, Odeillo, (France) to obtain repeatable results that do not depend on the human operator that manually controls the experiment, several control strategies have been developed and tested, such as adaptive control (Costa and Lemos, 2009a,b; Costa et al., 2011), predictive adaptive temperature control (Costa and Lemos, 2012), and optimal control (Costa and Lemos, 2016). The work that is presented in this article is based on the previous works (Costa et al., 2016a,b) but has the novelty of considering active cooling to improve temperature reference tracking, in particular when the shutter is closed and the temperature of the sample is above the reference temperature. It is interesting to remark that, by including active cooling to operate when active heating is off and the temperature of the sample is above the temperature reference, a switched temperature dynamics is obtained. The details are described in Section 2.

The article is organized as follows: in Section 2 a description of the

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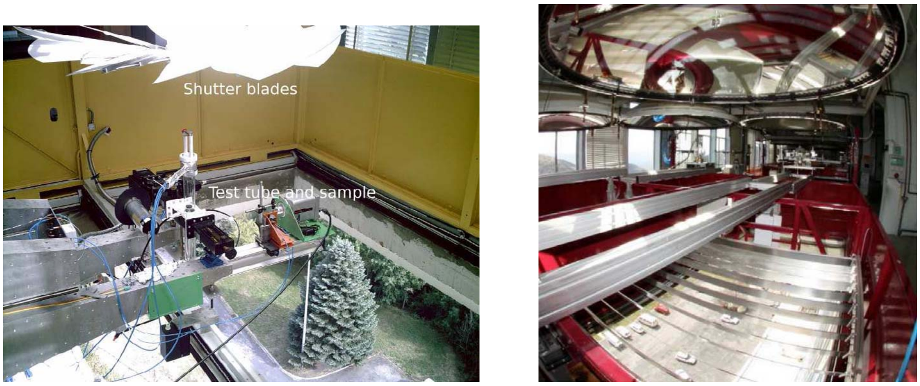

(a) Shutter of the 6kW solar furnace. (b) The 1.5kW solar furnace with a sesame shutter

Fig. 1. Examples of solar furnaces at PROMES with different shutters, located after and before the concentrating flux.

solar furnace and its model are presented; in Section 3 the identification of the process is described and some results are shown; in Section 4 the control system architecture is described and the stability of the switching control is addressed; Sections 5 and 6 show experimental results obtained with several materials and with two control methodologies, *viz.* exact linearization and model predictive control, that includes the application of active cooling to improve the temperature reference tracking; the conclusions are presented in Section 7. Details of the two control methodologies are described in appendix.

2. Solar furnace model

The solar furnace model used in this work comprises three models, namely a temperature model that describes the thermodynamic relation between the temperature of the sample and the amount of heat applied (removed) to (from) the material sample, a model that describes the action of the shutter to heat the sample, and a model that describes the function of the blower/fan employed to remove heat from the sample.

2.1. Shutter model

A shutter, see Fig. 1, is employed to adjust the amount of solar power that is applied to the upper surface of a sample. This objective is achieved by adjusting the position the shutter blades, see Fig. 2, that constrain the amount of irradiance at the focus of the solar furnace. The shutter operates in closed loop and its dynamics is much faster than the thermal dynamics. The controller of the shutter is able to move the blades to the target angle in less than 0.2 s. Thus, in this work, only the static function of the shutter is considered, being

$$s_{fs}(u_s(t)) = 1-\frac{\cos(\theta_0 + u_s(t)(90°-\theta_0)/100)}{\cos(\theta_0)}, \tag{1}$$

where the shutter command is physically constrained to $0 \leqslant u_s(t) \leqslant 100$ and $\theta_0 = 25°$. This assumption must be considered in the design of the controllers since otherwise the control performance may be unacceptable (Costa and Lemos, 2009b).

2.2. Blower/fan model

The bowler/fan is employed to remove heat from the sample. The amount of heat that is removed by forced convection is described by

$$\dot{Q}r_f = h_a A_s [T_s(t)-T_e(t)], \tag{2}$$

where $T_s(\cdot)$ [K] represents the temperature of the sample, T_e [K] represents the temperature of the air that flows on the sample, h_a represents the average convection heat transfer coefficient (that depends on the massic air flow), and A_s is the heat transfer surface area.

The forced convection heat transfer coefficient, h_a, is described by the correlations (Çengel, 2003) involving the Nusselt number ($N_{uL} = h_a L/k$), the Reynolds number ($R_{eL} = VL/\nu$) and the Prandlt number (P_r can be considered constant (0.73) for the temperature interval [20 °C; 2000 °C] of the experiments),

$$h_a = \frac{k}{L}\left(\frac{VL}{\nu}\right)^m P_r^n, \tag{3}$$

where L is the "length" of the material sample, k represents the thermal conductivity of the fluid (air), ν is the kinematic viscosity of the fluid, and V is fluid velocity (air). The constants C,m, and n depend on the type of flow, which can be predicted from the Reynolds number. For $R_{eL} < 5 \times 10^5$ the type of flow is laminar and $C = 0.664$, $m = 1/2$, and $n = 1/3$ but in the case of turbulent flow $5 \times 10^5 < R_{eL} < 10^6$ and $C = 0.036$, $m = 4/5$, and $n = 1/3$. The fluid velocity, V, is a function of the blower characteristic and depends on the electric power, (voltage) applied to the blower. Since the blower used has a large hysteresis and a large dead-zone, it was decided to operate/command the blower using an ON($u_{bf} = 100\%$)-OFF ($u_{bf} = 0\%$) strategy, that imposes V in a very short time (1 s). Thus, in the OFF mode $V = 0$, and for the ON mode $V = V_{max}$.

2.3. Temperature model of the sample

Small size samples are usually used to perform stress tests. Typically, a sample has a circular shape with a diameter of 2 cm and a height of 2 mm, but other sizes and shapes were tested. The temperature model is developed based on an energy balance such as the one made in Berenguel et al. (1999), but in this work active heating (shutter operation), and active cooling (blower/fan operation), are considered to improve temperature reference tracking.

In the case of active heating, the temperature of the sample, $T_s(t)$ [K] is approximately described by

$$\frac{dT_s(t)}{dt} = -\alpha_1[T_s^4(t)-T_b^4(t)]-\alpha_2[T_s(t)-T_e(t)] + \alpha_3 G_s(t)s_{fs}(u_s(t)). \tag{4}$$

Here, T_b [K] represents the temperature of the "environment" that contributes to losses by radiation (Berenguel et al., 1999; Çengel, 2003) and T_e represents the temperature of the surrounding air that contributes to losses by natural convection or air flow disturbances. The factors α_1, α_2 and α_3 represent the process parameters, being defined by

$$\alpha_1 = \frac{\epsilon(T_s)\sigma A_{sr}}{C_p(T_s)m};\ \alpha_2 = \frac{h_{conv}(T_s,T_e)A_{sc}}{C_p(T_s)m};\ \alpha_3 = \frac{\alpha_s A_{si} g_f}{C_p(T_s)m}, \tag{5}$$

where $h_{conv} = 1.32(T_s-T_e)/L_c$[1] for natural laminar flow. The parameters

[1] With $L_c = 4(Area)/(Perimeter)$ of the sample.