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Aperture size adjustment using model based adaptive control strategy to regulate temperature in a solar receiver

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ABSTRACT

One of the main challenges of solar thermal technology is the intermittency of solar radiation which adversely affect temperature stability of the solar receiver. A promising technique to tackle this problem is the use of a variable aperture mechanism to regulate the light entry into solar receiver. Efficiency analysis confirms the advantage of this control technique over shutter adjustment method, which is also based on regulation of solar radiation entry. In order to regulate the temperature in a closed loop circuit based on aperture size adjustment, a model based control strategy was developed. To show the robustness and comprehensiveness of this control strategy, it was applied to a cavity receiver heated by two different radiative heat sources demonstrating the applicability of this control strategy consistently in most commonly practiced solar thermal systems. The first heat source studied is a solar furnace housing a parabolic dish, whereas the second one is a high flux solar simulator. For each radiative heat source, flux entering the receiver was determined using Monte Carlo ray tracing (MCRT) method. MCRT model was then coupled with energy balance equations to derive numerical model describing dynamic temperature variation in solar receiver. Comparison of simulated and experimentally measured temperatures showed appreciable accuracy of the dynamic model. Simulation results of the numerical model were then used to identify a nonlinear adaptive model for use in designing a model predictive controller (MPC). Parameters of the adaptive model were updated continuously to make the controller more robust against model mismatches and external disturbances. Simulation results for both radiative heat sources showed that the proposed controller yields faster response with less overshoot compare to proportional integral derivative (PID) controller. Results showed that this controller exhibits robust performance during sunrise and sunset times as well as passing clouds conditions where significant fluctuations in solar radiation is experienced.

1. Introduction

While solar thermal technology provides clean production of electricity, solar thermochemical processes have the potential to transform solar energy into storable and transportable fuels (Steinfeld, 2005). Solar thermochemical processes typically feature a cavity type receiver capturing concentrated solar energy through a small opening called aperture (Ozalp et al., 2013). Absorbed concentrated energy is being used as high temperature process heat for production of commodities such as ammonia (Michalsky and Steinfeld, 2017), metals (Alonso et al., 2014), fuels (Zeng et al., 2017). One of the main challenges of this technology is the transient nature of solar radiation fluctuating reactor temperature and reducing overall efficiency. Closed loop control of process dynamics can cope with this intermittency problem and can provide more efficient operation of the system (Petrasch et al., 2009; Saade et al., 2014).

There have been several key studies done on closed loop control of solar thermochemical processes which are summarized in Table 1. There are two main control techniques utilized in these studies; (1) adjustment of mass flowrate, and (2) adjustment of solar power entry. The first method is widely practiced in industry. In solar reactor technology, this technique is based on steering feedstock flowrate to compensate adverse effect of fluctuations in incoming solar radiation. Petrasch et al. (2009) implemented such technique to control two different solar reactors for carbothermal ZnO reduction and for thermal gasification of petcoke. Their simulation results confirmed that the controlled reactors exhibited an improved performance in terms of overall efficiency and temperature over uncontrolled ones. Muroyama et al. (2014) used a feedback control system to regulate temperature in a solar steam gasification process. The controller was designed based on linear transfer function models of the process. The results showed that

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Nomenclature

Latin notations

$A(q^{-1})$, $B(q^{-1})$	linear polynomial matrix of Hammerstein model
a_i,b_i,c_i	Hammerstein model parameters
a,b	constants correlating the total lamp power to the input current of HFSS
C	concentration ratio of parabolic dish reflector
C_{max}, σ_g	parameters of Gaussian distribution curve
C_p	specific heat capacity, J/kg K
e	Error
h	convection heat transfer coefficient, W/m^2 K
f	nonlinear function in Hammerstein model
I	Direct Normal Irradiance (DNI), W/m^2
I_c	Input current of HFSS, A
k	conductivity, W/m K
k_p	proportional coefficient of PID controller
k_I	integral coefficient of PID controller
N	number of absorbed rays
$\hat{n}$	normal unit vector of the surface at point of reflection
n_a,n_b,n_c	Hammerstein model polynomial orders
N	total number of rays
N_c	control horizon
N_p	prediction horizon
m	mass, kg
$\dot{m}$	mass flowrate, kg/s
Q	heat rate, W
R	target radius at focal plane of reflector
P	covariance matrix
P_{in}	solar power distribution at focal plane of reflector, W
R_θ, R_1	random number between 0 and 1
t	time, h
$\hat{t}_1$, $\hat{t}_2$	tangential vectors at the point of reflection
T	temperature, K
u	system input
$\hat{u}$	normal direction vector of incoming ray to a surface
$\hat{v}$	normal direction vector of reflected ray from a surface
w	setpoint
X	nonlinear element in Hammerstein model
Y	system output
Z	axial direction

Greek symbols

α	absorptivity
	reflectivity
φ	vector of past observation
ε	emissivity
σ	Stefan-Boltzmann constant, W/m^2 K^4
λ	weighing sequence
χ	fraction of spherical part power to the total power of the lamp
μ	viscosity, Pa·s
ϕ	openness of shutter
η	efficiency of solar power captured inside the cavity receiver
∞	ambient
Δz	length of each control volume, m
ψ	azimuth angle
$\hat{\theta}$	matrix of estimated Hammerstein model parameters
θ_s	polar angle
θ_m	mode of Rayleigh distribution
τ_D	derivative coefficient of PID controller

Subscripts

ab	absorption
ap	aperture
cond	conduction
conv	convection
em	emission
ex	exhaust
g	gas
i, j, k	counter
id	ideal
in	inner
int	intercepted
loss	heat losses through outer surface of the cavity walls
out	outer
rad	radiation heat losses through the aperture
rays	rays
w	cavity wall

Superscripts

pri	primary
sec	secondary

temperature error of this control strategy is less than 3.4 K. In another study, Saade et al. (2014) developed a predictive controller for a solar carbon-steam gasification reactor. Their control system manipulated the gas and steam flowrates as a response to changes in solar irradiation. Computer simulations exhibited superiority of that predictive controller over conventional multi-loop controller. Although these examples show the effectiveness of the temperature control using mass flowrate adjustment technique, it disrupts the flow pattern in solar

Table 1
Some examples of previous studies on closed loop control of solar thermochemical processes.

Process	Manipulated variable	Controller type	Updating method	Reference
Carbothermal reduction of zinc; steam gasification of petcoke	Reactant mass flowrate	LQG/LTR	Non-adaptive	Petrasch et al. (2009)
Hybrid solar/autothermal steam gasification	Oxygen and coal flowrates	PI	Non-adaptive	Muroyama et al. (2014)
Carbon steam gasification	Gas and steam flowrates	MPC	Non-adaptive	Saade et al. (2014)
Thermochemical cycles for water and carbon dioxide splitting	Heliostat field	PI	Non-adaptive	Säck et al. (2015)
Thermochemical cycles for water splitting	Number of heliostats focused	Gain scheduling control	Adaptive	Roca et al. (2013)
Thermochemical cycles for water splitting	Number of heliostats focused	PI and feedforward controller	Non-adaptive	Roca et al. (2016)
Solar furnace	Openness of shutter	MPC	Non-adaptive	Costa et al., 2016
Solar furnace	Openness of shutter	Feedback linearization GPC	Adaptive	Beschi et al., 2013