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Nowcasting, predictive control, and feedback control for temperature regulation in a novel hybrid solar-electric reactor for continuous solar-thermal chemical processing

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ABSTRACT

A novel 15 kW reactor for the hybridization of concentrated solar and conventional electric heat was fabricated for renewable and continuous chemical processing at temperatures up to 1700 °C. Solar-electric controllers based on feedback or predictive linear models were used to regulate the device at 925 °C for the production of syngas via the gasification of carbon. The system was challenged with cloud transients programmed on a 45 kW high-flux solar simulator that approximated weather observed in the San Luis Valley (Colorado, USA). In experiment it was found that model predictive control with a 1 min ahead nowcast of incipient clouding best regulated solar-electric reactor temperatures, potentially averting thermal fatigue. Upon clouding, model predictive control with a nowcast yielded temperature disturbances of ± 10 °C, whereas feedback control alone featured ± 25 °C excursions. Overall, the performance of model predictive control with a nowcast was 75% better than feedback as indicated by the integral squared error of temperature excursion residuals. The importance of nowcast accuracy was explored, and although the model-based controller was robust to forecast amplitude inaccuracy, temporal forecast inaccuracy wholly negated the benefits of predictive control.

1. Introduction

Concentrated solar power harnesses energy with mirrored heliostats, dishes, or troughs – optics that heat a boiler, receiver, or reactor with focused sunlight (Behar et al., 2013; Roeb et al., 2011; Romero and Steinfeld, 2012). Commercially this approach is used to warm a working fluid to high temperature, where the fluid then directly or indirectly drives electrical turbines (González-Roubaud et al., 2017). Currently, state-of-art concentrated solar power plants operate at 565 °C with hot fluid storage for continued energy dispatch during inclement weather (Dunn et al., 2012). These facilities avert weather-induced thermal fatigue largely by manipulating receiver fluid flows, either by slowing flows, by redistributing flows, or by recycling hot fluid during clouding (Camacho et al., 2014; Kesselring and Selvage, 2013; Powell and Edgar, 2011). However, despite the availability of an energy reservoir to mitigate cloud transients thermal shock remains an important consideration in the design (Augsburger and Favrat, 2013; Du et al., 2016; Rodríguez-Sánchez et al., 2014; Terdalkar et al., 2015; Zheng et al., 2017), operation (Ashley et al., 2017; Papaelias et al., 2016; Relloso and García, 2015; Schellinger et al., 1993), and even economic simulation of concentrated solar plants (Feldhoff and Hirsch, 2017). At the higher operating temperatures proposed for new concentrated solar applications (> 750 °C) weather transients likely pose a heightened challenge to solar receiver lifespan and plant feasibility (Besarati and Goswami, 2016; Murray et al., 1995; Roeb et al., 2011; Romero and Steinfeld, 2012).

Commodities and fuels production feature the highest planned solar-thermal temperatures and likely represent the most extreme solar controls challenge. Specifically, direct sunlight has been proposed and tested for hydrogen fuels production at 1400+ °C (Furler et al., 2012; Roeb et al., 2011), biomass gasification for liquid fuels at 750+ °C (Lichty et al., 2010; Romero and Steinfeld, 2012), and metallurgical

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Nomenclature

English symbols

A	state transition matrix
B	process transition matrix
B_d	disturbance transition matrix
c	process horizon, 24 sample intervals (12 min)
C	output transition matrix
C_p	heat capacity, J/(mol K)
d_n	disturbance deviation from the nominal disturbance at time index n (solar %)
e_n	setpoint minus process variable at time index n, (Celsius)
E	absolute electrical power, W
f	forecast horizon, varied
F	view factor, unitless
L	Luenberger gain
k	thermal conductivity, W/(K m)
K	transfer function process gain
K_d	solar disturbance gain, °C/%
K_p	electric process gain, °C/%
H	process Teoplitz matrix
n	time index, integer
N	local flux, W/m^2
N_{conv}	convective contribution to local flux (cavity only), W/m^2
N_{exchg}	radiative contribution to local flux (cavity only), W/m^2
N_r	local flux coincident with radial direction, W/m^2
N_z	local flux coincident with axial direction, W/m^2
N_θ	local flux coincident with angular direction, W/m^2
N_{elc}	electric contribution to local flux (cavity only), W/m^2
N_{rad}	radiative contribution to local flux (cavity only), W/m^2
p	prediction horizon, 120 sample intervals (60 min)
P	absolute high-flux solar simulator power, W
P	forecast Teoplitz matrix
r	radial coordinate
R	move suppression matrix (coefficient)
t	time
T	temperature, K
$T_{ambient}$	mean air temperature, 293 K
T_c	mean water coolant temperature, 288 K
u_n	manipulated variable deviation from nominal input at time index n (electric %)
U	heat transfer resistance, W/(K m^2)
$\vec{x}_n$	state vector at time index n, 2 × 1
y_n	process variable deviation from setpoint at time index n (Celsius)
Y	vector of model predicted process setpoint departures $Y^T = [y_n \ \ y_{n+1} \ \cdots \ y_{n+p}]^T$,
z	axial coordinate

Greek symbols

Δd_n	velocity formulation of the disturbance variable, $d_n - d_{n-1}$
ΔD	velocity mode disturbance forecast used in control,$\Delta D^T = [\Delta d_n \ \ \Delta d_{n+1} \ \cdots \ \Delta d_{n+f}]^T$
ΔH^o	heat of reaction, kJ/mol
Δu_n	velocity formulation of the manipulated variable, $u_n - u_{n-1}$, aka control move
ΔU	input control actions, $\Delta U^T = [\Delta u_n \ \ \Delta u_{n+1} \ \cdots \ \Delta u_{n+c}]^T$, control moves
Δt	control sampling interval, 25 sec for feedback, 30 sec for model predictive control
$\Delta \vec{x}_n$	velocity formulation of the state,$\vec{x}_n - \vec{x}_{n-1}$
ε	effective grey body emissivity, unitless
ρ	density, mol/m^3
θ	angular coordinate
ϑ	observability matrix
τ	dominant reactor temperature time constant, minutes
τ_1	process time constant for distributed control system transfer functions, seconds
τ_2	process time constant for 2nd order distributed control system transfer functions, seconds
τ_D	derivative time constant, zero throughout
τ_I	integral time constant, minutes or seconds
τ_p	total process time constant of distributed feedback controllers, minutes or seconds
ξ	fractional solar into a given cavity finite volume element, unitless
ζ	fractional electric into a given cavity finite volume element, unitless

extraction at 1000 + °C (Murray et al., 1995; Wieckert et al., 2007). Previously, pilot solar facilities running at these elevated temperatures have served as platforms for the study of thermal shock (Douale et al., 1999; Glaser, 1958; Riskiev and Suleimanov, 1991), whereas sustained plant operation relies on rejecting thermal transients.

Different strategies have been explored to regulate higher temperature solar operation despite weather, studies that are summarized in Table 1. Several techniques involve oversizing the solar field and manipulating heliostats and/or blocking light to modulate cloud disturbances (Beschi et al., 2013; Najafabadi and Ozalp, 2018; Roca et al., 2013, 2016). This direct use of solar collection equipment may rapidly reject temperature transients. However, the solar field is already 40% of facility cost (Bhargav et al., 2014), can be only 66% efficient (Bradshaw et al., 2002; Vogel and Kalb, 2010), and parasitically consumes 3.8% of

Table 1

prior studies on the control of solar heat in commodities and fuels production processes. (PI = proportional integral control, GPC = generalized predictive control, LQG = linear quadratic Gaussian, LQR = linear quadratic regulator, MPC = model predictive control, NMPC = nonlinear model predictive control, FSF = full state feedback).

Process	Control simulations	Control experiments	Manipulated variable	Feed forward	Forecast	Disturbances (approximate)	Controller	Reference
Gasification	✓	✓	Electricity	✓	✓	100%	PI, MPC	This study
Gasification	✓		Flowrate(s)	✓		100%	LQG/LQR	Petrasch et al.
Gasification	✓		Flowrate(s)	✓		100%	PI	Muroyama et al.
Gasification	✓		Flowrate(s)			20%	PI, MPC	Saade et al.
H_2 looping	✓	✓	Heliostats	✓		25%	PI	Roca et al., 2013
H_2 looping	✓	✓	Heliostats	✓		100%	PI	Roca et al., 2016
Sintering	✓	✓	Shutters	✓		20%	GPC, PI	Beschi et al.
Superheating	✓		Shutters			100%	NMPC, PI	Najafabadi et al.
Superheating	✓	✓	Flowrate(s)	✓		100%	FSF	Zapata.