The 4th International Symposium - Supercritical CO2 Power Cycles
September 9-10, 2014, Pittsburgh, Pennsylvania

IMPROVING PERFORMANCE OF EXTREMUM-SEEKING CONTROL APPLIED TO A SUPERCRITICAL-CO2 CLOSED BRAYTON CYCLE IN A SOLAR THERMAL POWER PLANT

RAJINESH SINGH
Postdoctoral Research Fellow
School of Mechanical & Mining Engineering,
The University of Queensland, St. Lucia,
Queensland, 4072, Australia
r.singh5@uq.edu.au

MICHAEL P. KEARNEY
Lecturer
School of Mechanical & Mining Engineering,
The University of Queensland, St. Lucia,
Queensland, 4072, Australia
m.kearney@uq.edu.au

CHRIS MANZIE
Associate Professor
Department of Mechanical Engineering
The University of Melbourne, Parkville,
Victoria, 3010, Australia
manziec@unimelb.edu.au

Rajinesh Singh graduated with a BE(Hons I) degree in mechanical engineering from the University of Auckland in 2007. He subsequently completed a PhD in mechanical engineering at The University of Queensland in 2013. Dr. Singh is currently a postdoctoral research fellow at The University of Queensland. His main research focus is on dynamics and control of advanced power generation systems including the supercritical CO2 closed Brayton cycle and direct-steam generation in solar thermal power plants.

Michael Kearney graduated with a BE(Hons I) in mechatronic engineering and a BSc from the University of Queensland in 2005. He completed a PhD from the University of Queensland in 2010 and worked as a postdoctoral research fellow at the University of Melbourne from 2010-2012. Since 2012, he has been a Lecturer in the School of Mechanical and Mining Engineering at The University of Queensland. His research interests are in model predictive control (MPC), and the application of MPC and other optimization-based control methods to problems in mining automation and renewable energy generation and storage.

Chris Manzie is an Associate Professor in the Department of Mechanical Engineering at The University of Melbourne and an Australian Research Council Future Fellow. He leads a research group working in model-based and model-free control and optimisation, with applications in a range of areas including systems related to energy and mechatronics. He is an Assistant Dean (Research Training) and the Mechatronics Discipline coordinator in the Melbourne School of Engineering. He was a Visiting Scholar with the University of California, San Diego in 2007 and a Scientific Visitor at IFP Energies Nouvelles, Rueil Malmaison in 2012.

ABSTRACT

The supercritical-CO2 (sCO2) closed Brayton cycle (CBC) power block offers the opportunity to reduce costs of the electricity generated in concentrating solar thermal (CST) power plants through delivering higher power cycle efficiencies and compact plant, amongst several other benefits. However, the highly variable nature of CO2 fluid properties in the vicinity of its critical point make the power block susceptible to performance instabilities as a result of fluctuating solar heat input and cooling air conditions. Previous investigations using dynamic simulations have shown that manipulation of CO2 inventory in the CBC can overcome these instabilities and improve the power output from the block. To maximize the performance of the CBC power block an optimal inventory controller that can maximise the power output from the sCO2 CBC whilst maintaining operation within permissible temperature and pressure ranges is required. Model-based optimal control approaches are unsuitable for this controller as the development of simple low-order models of the CBC required for controller development is difficult due to the highly- variable fluid properties of supercritical CO2. These requirements suggest the use of a model-free optimal control method, such as Extremum-Seeking (ES) control. ES control has previously been demonstrated in simulation to improve the performance of a supercritical CO2 Brayton cycle, compared to ad-hoc methods, while satisfying the operational constraints of the sCO2 CBC. Inclusion of constraints within the ES control scheme leads to a cost function that is asymmetric. This paper investigates the use of a gain-scheduled ES controller, with different gains for positive and negative gradients to improve the performance of the sCO2 CBC.

The performance of the gain-scheduled ES controller is evaluated using a simulation study based on typical summer and winter day environmental conditions in the Western Queensland town of Longreach in Australia. Power block performance comparisons are made in the presence of the gain-scheduled ES controller manipulating CO2 inventory against non-scheduled ES controller and a fixed-inventory approach. Results of this study indicate that improved ESC tuning for the manipulation of CO2 inventory in the CBC using the gain-scheduled ES rule increases overall power generation performance during the winter day. This performance improvement results due to the controller raising and maintaining turbine inlet temperature close to maximum permissible values during periods of low solar heat input throughout the winter day. Improved summer performance over the fixed inventory approach is also maintained on the representative summer day and the plant is kept within turbine inlet temperature and pressure limits.

INTRODUCTION

Small to medium scale (<10 MW) concentrating solar thermal (CST) power plants offer significant potential for electricity generation using Australia’s extensive solar resource. Such small to medium scale CST power plants can be utilised for supplementing expensive and polluting diesel-generator based electricity in remote communities and mining towns (Beath 2012). Such an opportunity however is currently unrealised due to the high capital investment involved and the lack of available power block options for small plants operating with relatively high turbine inlet temperatures (>350°C), amongst other factors. A reduction in power block capital costs and higher power block efficiency therefore offer avenues for increasing deployment of small to medium scale power CST plants. The supercritical-CO2 (sCO2) closed Brayton cycle (CBC) power block offers:

- the opportunity for delivering high thermal efficiencies of up to 50% (Wright, Vernon et al. 2006) at relatively low turbine inlet temperatures (Dostal 2004; U.S Department of Energy 2012)
- the opportunity to use a working-fluid that is cheap, non-toxic, non-flammable, stable at very high temperatures, and has a relatively low critical pressure (7.38 MPa) and critical temperature (31.1°C)
- power block compactness, simplicity, and scalability arising from very compact turbomachinery in the cycle (Delussu 2012)
- the ability to use sCO2 both as a single-phase heat-transfer fluid and power-cycle working fluid in a single-loop consequently avoiding two-phase flow complications, and eliminating heat-transfer losses in intermediate heat-exchangers

The sCO2 CBC power block therefore offers promise therefore in contributing to lowering the costs of electricity generated by CST power plants (U.S Department of Energy 2012) through offering reduced plant, operational, and maintenance costs.

Operation of the sCO2 CBC power block in a CST power plant in the absence of control with fluctuating solar heat input and ambient air temperatures can result in significant performance deviations (Singh, Miller et al. 2013). Such deviations can result due to the interaction of these fluctuations in boundary conditions with the highly variable nature of CO2 fluid properties in the vicinity of its critical point. Extremum seeking control (ESC) has been applied to mitigate these deviations in (Singh, Kearney, Manzie, 2013) while improving the power output of the CBC and simultaneously remaining within operational constraints.

Extremum-seeking control is a non-model based optimal control approach which has received increased interest in recent years and has been applied in a range of applications including automotive (Matraji, Ahmed et al. 2012), thermal management (Li, Li et al. 2013), and renewable power generation (Bizon 2013). The extremum-seeker (ES) tunes plant inputs using continuous measurements of a plant performance function for optimising plant performance. Continuous measurements made by the ES are used as inputs to appropriate filters which estimate the gradient of the plant performance function with respect to the steady state plant input. This information is then used by the ES with an appropriate optimisation routine to tune the plant input and provide convergence towards optimal plant operation. Extremum-seeking implementations commonly involve a 'black-box' approach which requires minimal prior knowledge of plant optimal conditions and eliminates the requirement for a model of the system for controller development. In this manner, complications due to model mismatch that model-based controllers face are avoided. The incorporation of prior knowledge of the plant into the ES framework is also possible in a more advanced 'grey box' approach (Nesic, Mohammadi et al. 2012). The ES approach can also readily be extended to multidimensional input plants.

Application of ESC to the sCO2 CBC presents a unique case as it involves an asymmetric extremum-seeker. This is due to the presence of power cycle operational constraints, namely turbine inlet pressure and temperature limits. The ESC concept applied to the sCO2 CBC in a CST power plant was demonstrated in (Singh, Kearney et al. 2013), previously, and showed promising results. The study however also indicated that ESC performance could be improved especially in winter and during solar heat input dips due to events such as cloud passing.

This paper presents an extension of the study in (Singh, Kearney et al. 2013) and contributes to a proof-of-concept investigation into the application of ESC for sCO2 CBC inventory control in the CST power plant. A 'black-box' extremum-seeking (ES) approach is employed, similar to that utilised in (Singh, Kearney et al. 2013) for tuning multiple parameters in the sCO2 CBC despite fluctuating solar and ambient air temperature conditions. Specifically, the improvement of ESC performance when applied to the sCO2 CBC is investigated through implementing a gain-scheduled ES rule. Such a requirement is heralded by the sCO2 CBC power block in the air-cooled solar thermal power plant as a result of the several non-uniformities in the steady-state plant performance functions which the ESC utilises for achieving optimal plant performance within constraints. The very high gradients on one side of the optima mean that a fixed controller gain needs to be very small in order to guarantee closed loop stability. A very small fixed controller gain however also means that the convergence rate of the controller is very slow when the gradients are not as steep on the other side of the optima.

The performance of the gain-scheduled ES tuning approach is compared against a non-scheduled ESC controller and a fixed-inventory scheme. The extremum-seeking controller makes use of existing hardware in the plant, so there is minimal or no additional hardware cost.

SUPERCRITICAL-CO2 CLOSED BRAYTON CYCLE CONTROL IN A CST POWER PLANT

The benefits and high-performance of the sCO2 CBC are a consequence of operating the power cycle entirely above the critical point (termed 'supercritical' or 'non-condensing'). The nature of CO2 fluid properties in the vicinity of its critical point including its very low compressibility, significantly reduces compressor work. Although beneficial from a steady-state perspective, CO2 fluid properties in the vicinity of its critical point exhibit large and abrupt changes, such as rises in specific-heats and density which can affect power cycle performance during transient events. Furthermore, these fluid property variations coupled with the dynamic nature of CST power plants including fluctuating solar heat input and ambient air temperatures in air-cooled plants make the sCO2 CBC susceptible to performance deviations (Singh, Miller et al. 2013). These possibilities necessitate the investigation of both, control strategies and suitable controllers, for the sCO2 CBC in applications with fluctuating operating conditions such as CST power plants.

Previous investigations into dynamic characteristics of the sCO2 CBC in solar thermal applications were conducted in (Singh, Miller et al. 2013; Singh, Rowlands et al. 2013). These studies were conducted to demonstrate the impact of variations in solar heat and ambient air temperatures on power cycle performance in a CST power plant based at Longreach in Queensland, Australia. These studies involved a simple plant configuration in which the sCO2 CBC was employed as the power block connected to parabolic troughs in a direct-heated configuration (CO2 both flows through the solar collectors and through the power block, in a single-loop). The results from these previous investigations highlighted the excessive rises in turbine inlet temperatures in the sCO2 CBC as a consequence of fluctuations in solar heat input and ambient air temperature during representative summer and winter days. Importantly, the ability to utilise CO2 inventory manipulation for improving sCO2 CBC performance in the CST power plant was also highlighted. The extent to which performance deviations occur was shown to be influenced by the relative volume on the hot and cold sides of the sCO2 CBC in (Singh, Rowlands et al. 2013). The relative hot-to-cold side volume ratio was also shown to influence the time response of the power block to fluctuations in solar heat input and ambient air temperatures.

Inventory control in addition to turbine-bypass control has also previously been proposed as primary control strategies for part-load operation of the sCO2 CBC in nuclear power generation applications using proportional-integral (PI) controllers (Dostal 2004; Carstens 2007).

The main control objective for a sCO2 CBC power block in a CST power plant is maximising power output while maintaining critical performance parameters including turbine inlet pressure and temperature within design constraints. Furthermore, ambient air temperatures at potential CST power plant site across Australia can experience large swings within the day and across seasons. These ambient air temperature variations in combination with fluctuating solar heat input necessitate an optimal controller for the execution of plant control strategies with the ability to deliver maximum power output from the plant at any of the several possible combinations of ambient air temperature (above the critical temperature) and solar heat inputs. Unlike conventional ideal-gas power cycles, modelling of the sCO2 CBC at low orders required for controller development is difficult. The difficulty is associated with the fine spatial resolution of the heat-exchanger volumes required in modelling, to capture the highly nonlinear behaviour of supercritical-CO2. Reduction and linearisation of such a highly non-linear plant model with several operating points, required for conventional model-based control approaches, is tedious and difficult. A suitable non-model based controller approach is therefore required.

The occurrence of the design point power output from the sCO2 CBC at the maximum permissible turbine inlet temperature of 350°C for the 1 MWe plant under consideration is shown in Figure 1. This figure demonstrates that although power generated by the CBC increases with turbine inlet temperature across the operating region, the desired operating point is at the upper boundary of the operating region at approximately 350°C. Frequent or extended excursions beyond this temperature can lead to a reduction in power cycle life or component failure due to structural issues such as fatigue and material limitations. For similar reasons, the pressure in the CBC must be kept below 25 MPa. A thorough discussion of optimal temperature, pressure, and mass-flow operation points for the sCO2 CBC is presented in (Singh, Miller et al. 2013).

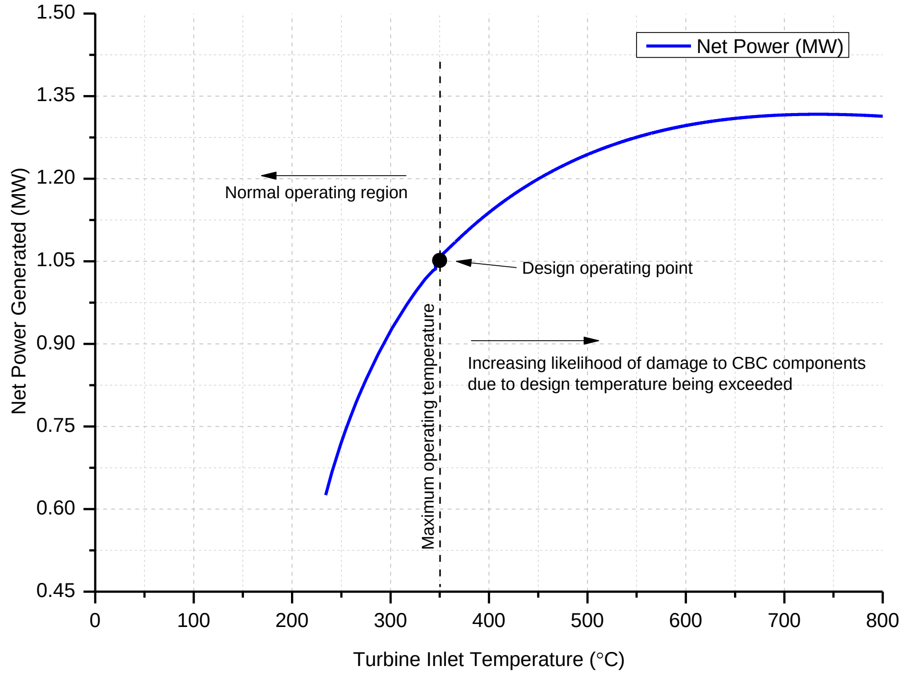

Figure 1 Influence of turbine inlet temperature on net power generated by the sCO2 CBC with 4.73 MW of solar heat, an ambient air temperature of 26°C, and air flow rate is 365 kg/s.

PLANT DESCRIPTION AND MODELLING APPROACH

The utilisation of a direct-heated configuration in which the working-fluid of the power cycle (CO2) is also used as the heat-collection medium, allows the elimination of thermal losses associated with an intermediate heat-exchanger otherwise required in CST power plants with secondary thermal-oil or molten-salt circuits. This contributes to an increase in the overall solar-to-electric conversion efficiency.

Figure 1 illustrates the typical layout of a simple recuperated sCO2 CBC in a direct-heated and air-cooled CST power plant. The main elements of the sCO2 CBC in Figure 1 include a compressor which raises CO2 pressure, a heater which represents the solar collector receiver, a recuperator for recovery of available/unused energy after the turbine, and a cooler for the rejection of heat energy from the cycle. In addition, a turbine produces mechanical work by expansion of CO2 at high pressure and temperature and subsequently drives the generator for electricity production.

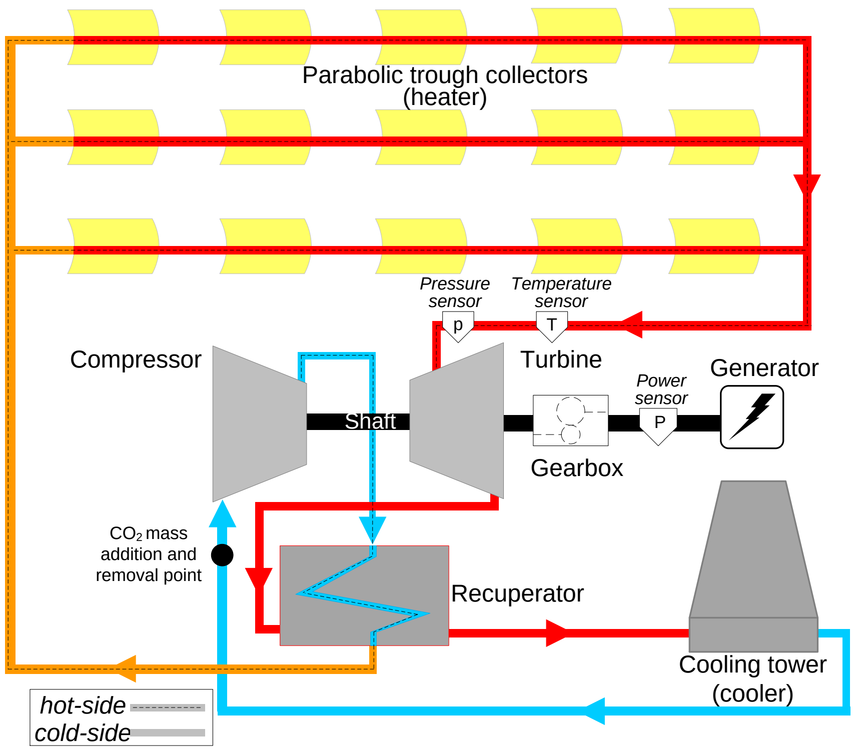

Figure 2 Schematic of the sCO2 CBC power block showing major components, sensor locations, and the point of CO2 inventory addition and removal.

Supercritical-CO2 Closed Brayton Cycle Modelling

Modelling of the sCO2 CBC was conducted using the *Modelica Standard* and *Air-Conditioning* libraries in Dymola®. The modelled turbomachinery comprises a single-stage radial compressor and radial turbine mounted on a common-shaft, rotating at a constant synchronous speed of 60,000 RPM through a gearbox. The gearbox reduces generator speed down to the grid frequency of 50 Hz. The compressor performance model is based on actual test data from a sCO2 compressor (Wright, Conboy et al. 2011) and applied in the model using similitude (Dyreby, Klein et al. 2011). Due the lack of actual sCO2 turbine performance data, the radial turbine is modelled as a nozzle.

Three heat-exchangers are modelled in the system. These include a heater representative of the absorber-tube in the solar collector receiver, a recuperator for heat-recovery, and a cooler which is representative of the sCO2 cooling element of the cooling-tower for sCO2-to-air heat-exchange. Further details on modelling of the sCO2 CBC and assumptions utilised can be referred to in (Singh, Miller et al. 2013).

The design point parameters of the sCO2 CBC were selected based on the analysis conducted previously in (Singh, Miller et al. 2013) for determining optimum operating conditions. These steady-state design parameters of the power cycle are summarised in Table A.1 of Appendix A.

Heat input into the sCO2 CBC is assumed to be through direct-heating (no intermediate heat-exchanger). This heat input was determined based on modelling conducted for a parabolic-trough solar field with an oil-circuit. The main parameters used in determining the thermal energy output of the solar field for typical winter (21-Jun) and summer day (21-Dec) conditions at Longreach in Queensland, Australia are listed in Table A.2. A detailed description of the solar field including parasitic electric energy usage and piping heat-loss assumptions is presented in Ref. (Singh 2013).

EXTREMUM-SEEKING CONTROLLER IMPLEMENTATION AND STEADY-STATE PLANT PERFORMANCE FUNCTION CHARACTERISTICS

Carbon-dioxide inventory in the sCO2 CBC is varied with time by the ESC. Inventory addition is conducted at the compressor inlet to minimise parasitic power losses associated with pumping CO2 into the cycle, as it is also the point of minimal pressure and temperature in the sCO2 CBC. Gas is generally bled at the compressor outlet and recycled to its inlet in control of conventional Brayton cycles. However this investigation involves CO2 removal conducted at the compressor inlet instead. This is considering practicality for introducing perturbations into the system required by the ESC. Carbon-dioxide removed from the power block and added to it by the ESC will be transferred into and out of a separate inventory control tank system maintained at conditions close to critical. Furthermore, CO2 bled from the compressor inlet is cooler at conditions close to critical and will therefore potentially eliminate the requirement for cooling or pressure regulation of the gas fed into the inventory control tanks. The handling of CO2 in a high-density or critical state is also more economical in terms any associated pumping power and storage tank size due to its low compressibility. The inventory storage and delivery system involves mainly pressure dynamics with significantly smaller time constants than the dominant dynamics of the power block and is hence treated as a lumped system in modelling.

The plant input is varied by the ESC to drive the system towards the optimal operational point defined by the cost function, *J*. The cost function describes the optimal plant operational point as a function of the steady-state plant input and incorporates net power along with maximum turbine inlet temperature and pressure operational constraints.

The cost function is given by

$$J = P_{net} - \alpha \Gamma\left(T_{t,in}, T_{\text{maximum}}\right) - \beta \Gamma\left(p_{t,in}, p_{\text{maximum}}\right), \quad (1)$$

where the first term is the net power produced, which is to be maximized, and the next two terms describe penalties for constraint violations. These penalties are positive only when a one-side constraint is violated, and are implemented using the following operator,

$$\Gamma(x,y) = \begin{cases} 0 & if \quad x < y \\ x - y & if \quad x > y \end{cases} \quad (2)$$

Steady-state plant performance (or cost) functions determined using open loop tests for different solar heat input and ambient air temperature combinations are shown in Figure 3. The curves exemplify the cost function using five combinations of ambient air temperatures between 26°C and 32°C, and solar-heat input of 4.33 MW to 5.05 MW. The cost curves demonstrate that peak power block performance varies with operating conditions. Each case also presents a unique maximum with continuous gradients. The sCO2 CBC in the CST power plant therefore presents as an application for ESC to a constrained optimal control case.

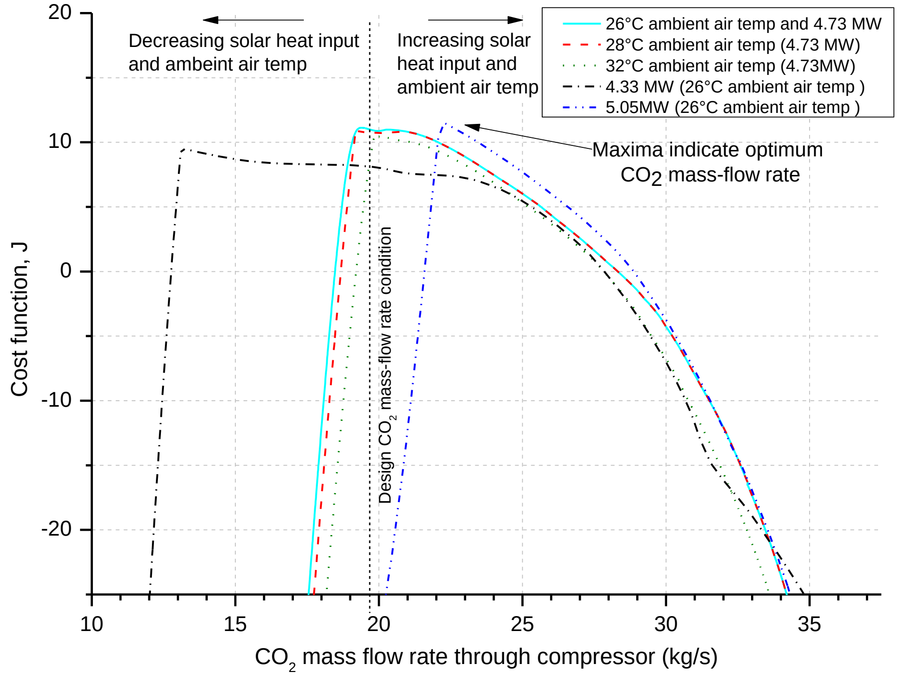

Figure 3 Cost function plots defining optimal CO2 mass-flow rates for different heat input and ambient air temperature conditions.

In addition to being individually asymmetrical, the cost curves in Figure 3 also exhibit characteristic differences with variations in operating conditions. Specifically, the negative gradients of the cost functions for below-design solar heat input values exhibit flatter profiles in the vicinity of the optimal performance point. The large positive gradients of the cost curves are due to the soft-constraints implemented into the cost function for increasing propensity of the power block against achieving turbine inlet temperature and pressure above 350°C and 25 MPa, respectively.

A gain-scheduled ES rule is therefore applied to address such irregularities in the cost functions for different operating conditions and is presented in Figure 4. This approach is a modified form of the basic ES scheme reported in (Cochran and Krstic 2009). In the ES scheme, a sinusoidal dither is applied to the plant input to provide persistency of excitation in the gradient estimates at the output of the high pass filter. The plant input for the ESC is considered to be the inventory rate of change in the sCO2 CBC, designated as $\dot{\theta}$.

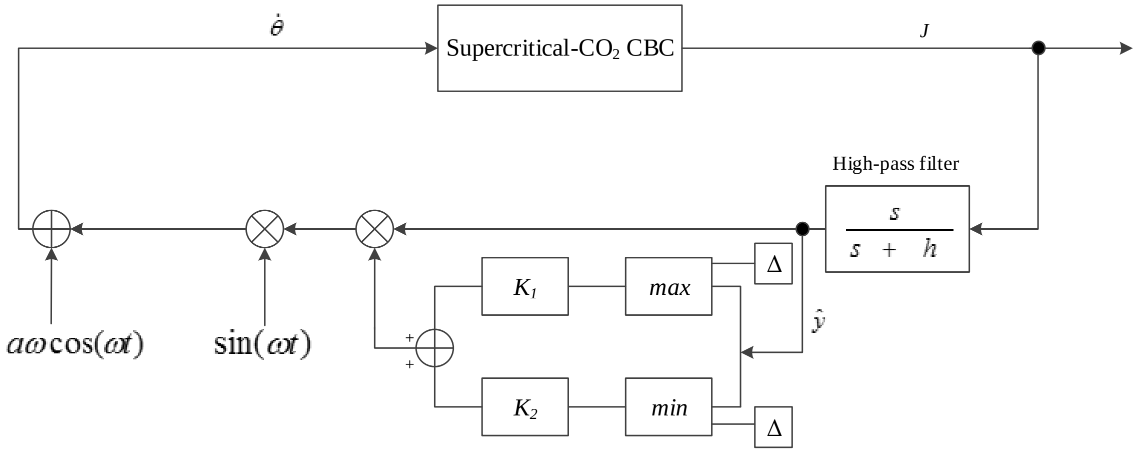

Figure 4 Gain-scheduled ESC schematic when applied to the sCO2 CBC.

The scheduled gains K_1 and K_2, are introduced into the ES scheme subject to the gradient estimate as

$$K(\hat{y}) = \begin{cases} K_1 & if \quad \hat{y} > \Delta \\ K_2 & if \quad \hat{y} < \Delta \end{cases} \tag{3}$$

where, Δ, represents the estimation error.

A basic non-scheduled version of this ES approach was previously implemented in the proof-of-concept ESC study applied to the sCO2 CBC in a CST plant (Singh, Kearney et al. 2013). The non-scheduled ES controller implemented in the previous study can be reproduced using the current gain-scheduled approach by setting the fixed gains, $K_1=K_2=K$, and $\Delta=0$..

RESULTS

The gain-scheduled ESC is now applied in the simulations of the sCO2 CBC in the context of power generation in a solar thermal power plant with air-cooling. The analysis is conducted on the simulated model of a 1-MWe direct-heated (no secondary thermal-oil loop) and air-cooled parabolic-trough solar thermal power plant supplementing diesel generators in a remote community. The design parameters of the power block and solar field are described in Appendix A.

Performance of the gain-scheduled ES controller when applied to the sCO2 CBC is evaluated during fluctuations in solar heat energy and ambient air temperatures on summer and winter solstice days. Heat input on the summer day is capped at 4.73 MW assuming solar field defocusing handled by a secondary controller. It is acknowledged that solar insolation can fluctuate significantly and at high frequencies (Kang and Tam 2013) compared to those in the simulations. However, the actual fluctuations in heat-flux experienced by supercritical-CO2 flowing in the solar collector tubes will also be somewhat dampened due to the thermal inertia associated with the thick-walls of the tubes in the solar collectors. Dampened solar heat input characteristics have been demonstrated for studies involving similar gas cycles such as for solarised gas turbine applications (Heller, Pfänder et al. 2006). The impact of solar insolation fluctuations will also be significantly dampened if thermal storage is later integrated into the CST power plant. However, simulations are conducted in the absence of thermal storage in this work to gain an understanding of the ability of the gain-scheduled ES scheme in the sCO2 CBC to maximise cycle power output within operational constraints prior to implementation of any thermal buffer. Operational constraints of the power plant include turbine inlet temperature and pressure which have the values of 350°C and 25 MPa, respectively.

Gain-scheduled ES performance is also compared against results for a non-scheduled ES approach and a fixed inventory (ad-hoc) approach. The amount of CO2 inventory in the fixed inventory approach was determined previously through manual tuning to achieve sufficient performance for the plant design conditions listed in Table A.1 of Appendix A. A specific charge of 300 kg/m^3 was selected for winter operation. A higher specific charge of 382 kg/m^3 was selected for summer operation to alleviate the occurrence of excessive turbine inlet temperatures highlighted in (Singh, Miller et al. 2013) which would otherwise occur with a lower specific charge.

Temperatures of ambient air used for cooling at the potential CST power plant site can drop 20°C below the design ambient temperature of 26°C, especially in winter. A cooling-medium (air) controller is therefore assumed to be present that maintains ambient temperature at a point where supercritical conditions always exist at the compressor inlet. The dynamics of this secondary controller are assumed to be much faster than the more dominant mass movement dynamics in the power cycle and are therefore neglected in modelling.

Comparison of Controller Performance

Table 1 Parameters of the gain-scheduled extremum-seeking controller applied for both summer and winter simulations.

Dither frequency, ω (rad/s)	0.0017
Gain, K_1	3
Gain, K_2	2
High pass filter cut-off frequency, h (rad/s)	0.001
Dither amplitude, a	10
Slack variable weights, α,β	0.5
Estimation error, Δ	0.15

The impact of the ad-hoc (fixed inventory) approach, and ES controller with and without gain-scheduling is now compared for both summer and winter operation. Parameters of the gain-scheduled and non-scheduled ES controller obtained by manual tuning are listed in Table 1. These fixed controller parameters are listed for both the summer and winter operating conditions. Additionally, the non-scheduled controller utilised a fixed gain, K, equal to 2 and $\Delta=0$ for both summer and winter.

Both non-scheduled and gain-scheduled ES tuning approaches utilise fixed controller parameters which remain unchanged on a day-to-day and seasonal basis unlike the baseline fixed-inventory approach that has dedicated feedforward control for each condition.

The simulation results are presented in Figure 5 and Figure 6, for summer and winter, respectively, and include:

- the trajectories of the plant outputs of interest and states subject to constraints (turbine inlet temperature, net power generated, turbine inlet pressure); and the plant input (CO2 specific charge) in a) to d)
- the solar heat input and ambient air temperature, which act like disturbances on the system in e) and f)

Summer Operation

Improved tuning of the ESC through the proposed implementation of a gain-scheduled ES rule has been able to help maintain improved performance over a fixed-inventory approach during summer without any degradation in performance. Both ES approaches are able to improve power generation over the fixed-CO2 strategy throughout the summer day whilst avoiding excessive turbine inlet temperature rises during the day. Turbine inlet pressure is also maintained within limits. In contrast, the fixed-inventory approach achieves lower overall net power generation throughout the day mainly as a result of the comparative lower turbine inlet temperatures delivered. However as observed during the large drop in turbine inlet temperature at 16;30, an improvement in performance of both ES schemes is required during large dips in solar heat input. The degradation in performance here can be attributed to the large plateau in the gradient of the cost functions for low solar heat input cases as observed in Figure 3.

An average electrical energy generation of 8.6 MWh was achieved over the 10-hour normal solar insolation period (between 08:00 and 18:00) with the gain-scheduled ESC manipulating CO2 inventory. This average generation was slightly lower than the 8.7 MWh delivered using the non-scheduled approach mainly due to the gain-scheduled approach maintaining turbine inlet temperature closer to the target value of 350°C.

In comparison, an average of 7.9 MWh was generated using the fixed inventory approach. The improved power output using the gain-scheduled and non-scheduled ESC approaches is also due to the plant attaining the design net power output of 1 MW much earlier at the start of the day.

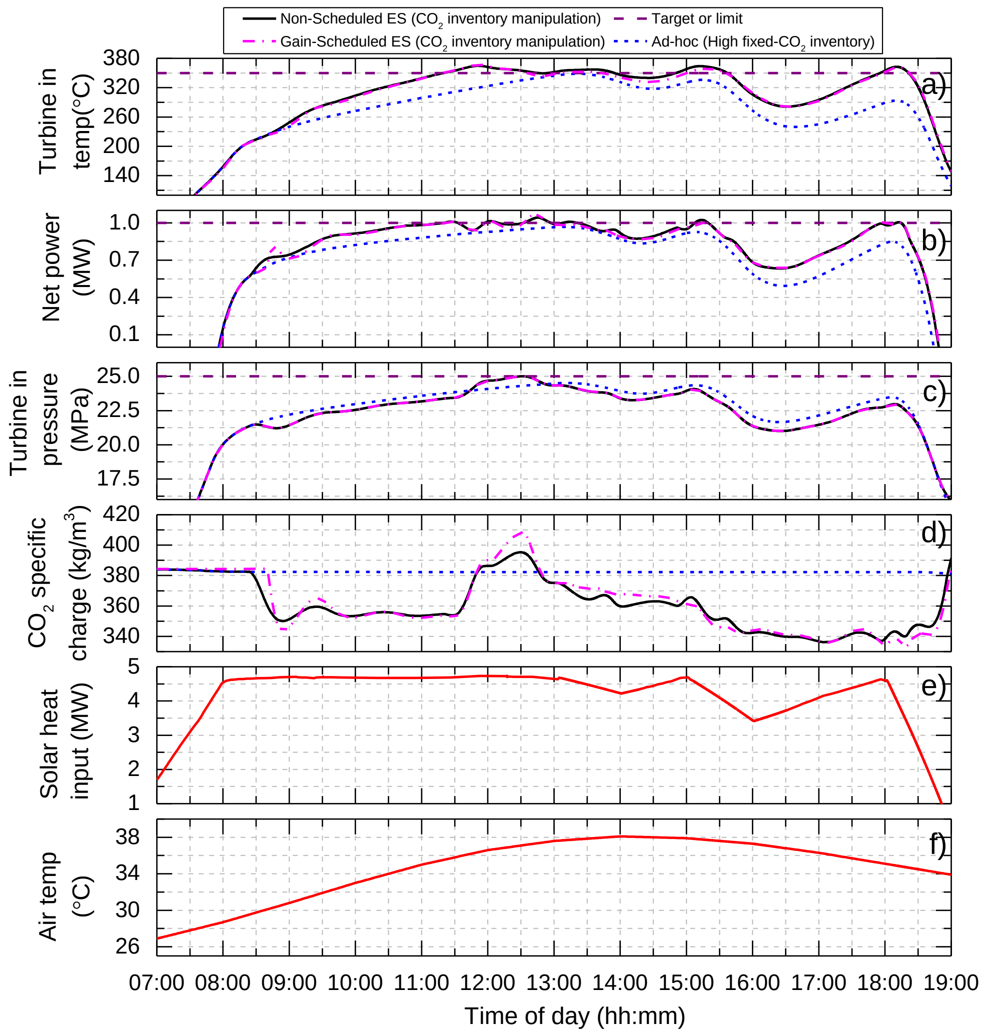

Figure 5 Comparison of sCO_2 CBC plant dynamic response with gain-scheduled extremum-seeking control on a representative summer day.

Winter Operation

It is clear that tuning the ES controller with a gain-scheduled ES rule improves sCO2 CBC performance in winter, over the fixed inventory approach and non-scheduled ESC. The gain-scheduled ES rule when applied to the sCO_2 CBC exhibits an overall improvement in net power generation whilst maintaining turbine inlet temperature and pressure at or below permissible limits for the entire solar insolation period. To this effect, an improvement in turbine inlet temperatures towards the limit of 350°C is achieved using the gain-scheduled ES approach over both the non-scheduled ES approach and the fixed-inventory approach. The gain-scheduled ES controller also improves power generation early and late into the today when compared to the non-scheduled controller. However, some performance degradation is observed through slightly lower turbine inlet temperatures between 12:00 and 14:00 in Figure 6 when solar heat input falls. As highlighted earlier, this can be attributed to the large plateau in the cost functions for low heat inputs.

Higher overall net power generation is delivered using the gain-scheduled ES approach over the non-scheduled ES approach especially due to the extra power generated early and late into the day. Overall net power generation delivered for the whole day by the gain-scheduled ES scheme is 6.3 MWh compared to only 6.0 MWh delivered by the non-scheduled scheme.

The fixed inventory approach in contrast delivers 6.4 MWh. This slightly higher average power output is however because of turbine inlet temperatures violating the limit of 350°C late into the day which results in the power block producing slightly more power. The fixed rates of CO2 inventory used in the fixed-inventory strategy have been carefully tuned for improved power generation performance in winter. The strategy therefore expectedly performs well however lacks the robustness and adaptability to inter-day changes in solar heat and ambient air conditions.

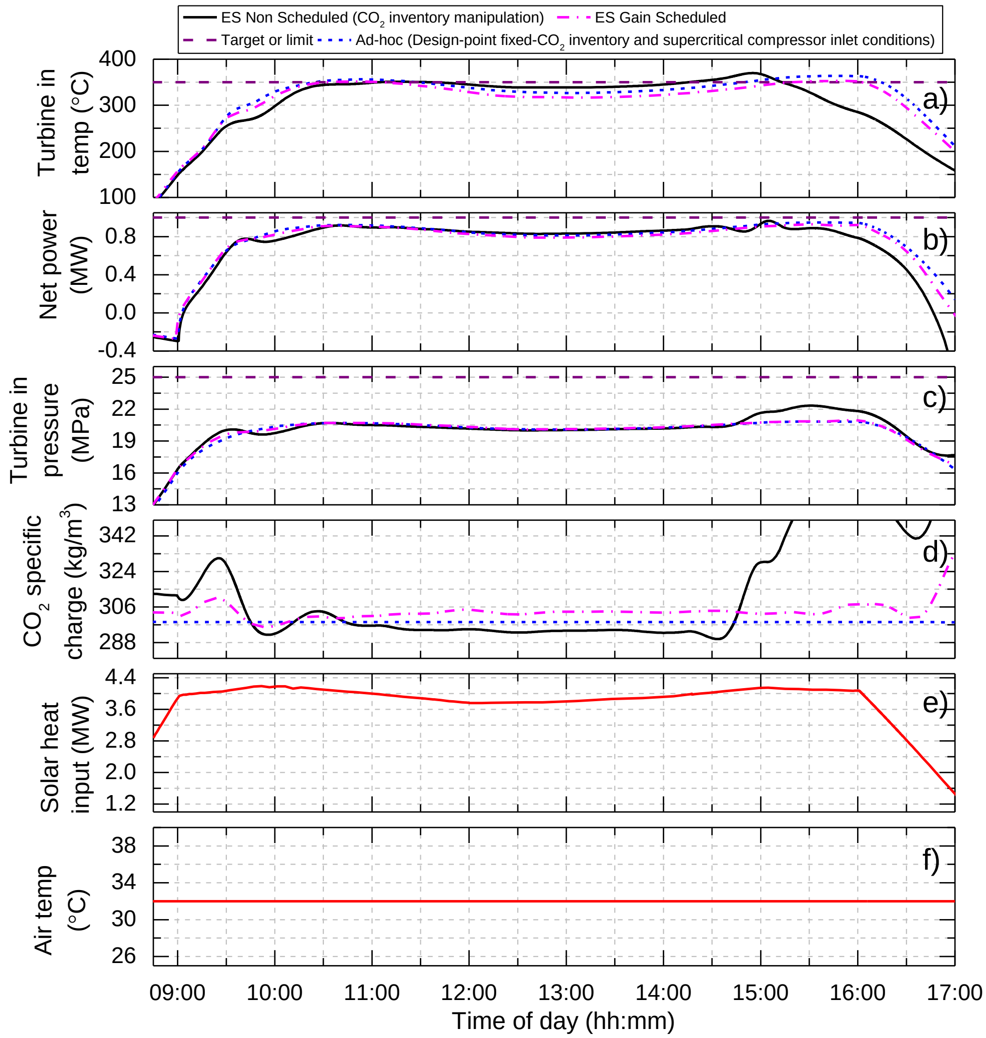

Figure 6 Impact of gain-scheduled extremum-seeking control on sCO_2 CBC plant dynamic response for representative winter day conditions.

CONCLUSIONS

Improved tuning of the ES controller for CO2 inventory manipulation using the gain-scheduled ES rule has been found to improve controller performance. In doing so, tuning the ESC using the gain-scheduled ES rule has demonstrated increased overall net power output from the sCO2 CBC in the CST power plant during winter while maintaining improved performance over the fixed-inventory approach during summer. Tuning using the gain-scheduled ES rule has shown to increase and mostly maintain turbine inlet temperatures close to maximum permissible limits throughout the representative winter day with low solar heat input to the plant. Both the gain-scheduled and non-scheduled ES schemes are also able to prevent excessive turbine inlet temperatures in summer with high solar heat input and ambient air temperatures. Extremum-seeking controller performance in general can however be improved especially during dips in solar heat input for both summer and winter cases. The lack of performance during low solar heat input can be attributed to the large plateau in the negative gradients of the cost functions and will be addressed in future work. However the controller performs well when required to prevent turbine inlet temperatures and pressures rising beyond allowable limits due the sharper gradients in the positive slopes of the cost function curves.

Although the benefits of utilising ESC for manipulating inventory in the sCO2 CBC have been highlighted, experimental tests are nevertheless required for fully ascertaining benefits and drawbacks. Future work will involve conducting experimental validation, and investigating gain-scheduled ESC performance when applied to the sCO2 CBC with high frequency variations in solar heat input. The design and dynamics of the inventory control system will also be investigated.

APPENDIX A: DESIGN PARAMETERS OF THE SCO2 CBC POWER BLOCK AND SOLAR FIELD

Table A.1 Steady-state design point parameters of the sCO2 CBC (adapted from (Singh, Kearney et al. 2013)).

Turbine inlet temperature	350°C
Turbine inlet pressure	20 MPa
Compressor inlet temperature	32°C
Compressor inlet pressure	7.8 MPa
Generator/ Turbine/ Compressor efficiency	1/ 0.83/ 0.69
CO2 mass-flow rate	19.6 kg/s
Cooling air mass-flow rate	365 kg/s
Thermal efficiency with recuperation	23.4%
Design net heat input/ ambient air temperature	4.73 MW/ 26°C
Net-power generation	1 MWe
Compressor/ Turbine rotational speed	60,000 rpm
Compressor/ Turbine wheel diameter	65.8 mm/ 92 mm
Non-condensing cooler heat exchange area/ approach temperature	1510 m^2/ 6°C
Recuperator heat exchange area/ approach temperature	121 m^2/ 10°C
Solar heater heat exchange area	1360 m^2
System specific charge at design condition	300 kg/m^3
CBC Hot side: Cold side volume-ratio	1

Table A.2 Parameters used to determine the solar field thermal energy output used in simulations.

Trough aperture width	5 m
Collector reflectance	0.935
Solar field temperature (°C)	391
Trough aperture area	10,158 m²
Thermal storage (h)	0
Evacuated tube receiver	Schott PTR70
Solar field availability	99%
Heat transfer fluid	VP-1
Solar multiple	1.2
Reference direct normal insolation	950 W/m²
Reference wind speed	5 m/s
Reference ambient air temperature	25°C
Collector	SolarGenix single-axis with 5m aperture
Heat transfer fluid inlet/ outlet temperature	293°C / 391°C

REFERENCES

Beath, A. C. 2012. "Industrial energy usage in Australia and the potential for implementation of solar thermal heat and power." Energy **43**(1): 261-272.

Bizon, N. 2013. "Energy harvesting from the PV Hybrid Power Source." Energy **104**: 326-336.

Carstens, N. A. 2007. Control strategies for supercritical carbon dioxide power conversion systems. Doctor of Science in Nuclear Engineering Doctoral Thesis, Massachusetts Institute of Technology.

Cochran, J. and Krstic, M. 2009. "Nonholonomic source seeking with tuning of angular velocity." Automatic Control, IEEE Transactions on **54**(4): 717-731.

Delussu, G. 2012. "A qualitative thermo-fluid-dynamic analysis of a CO_2 solar pipe receiver." Solar Energy **86**(3): 926-934.

Dostal, V. 2004. A supercritical carbon dioxide cycle for next generation nuclear reactors. Doctor of Science in Nuclear Engineering Doctoral Thesis, Massachusetts Institute of Technology.

Dyreby, J. J., Klein, S. A., et al. 2011. Modeling off-design operation of a supercritical carbon dioxide Brayton cycle (11SM1-3). Supercritical CO_2 Power Cycle Symposium Boulder, Colorado, USA, May 24-25.

Heller, P., Pfänder, M., et al. 2006. "Test and evaluation of a solar powered gas turbine system." Solar Energy **80**(10): 1225-1230.

Kang, B. O. and Tam, K.-S. 2013. "A new characterization and classification method for daily sky conditions based on ground-based solar irradiance measurement data." Solar Energy **94**: 102-118.

Li, X., Li, Y., et al. 2013. "Dynamic modeling and self-optimizing operation of chilled water systems using extremum seeking control." Energy and Buildings **58**: 172-182.

Matraji, I., Ahmed, F. S., et al. 2012. Extremum seeking control for net power output maximization of a PEM fuel cell using second order sliding mode. Variable Structure Systems (VSS), 2012 12th International Workshop on. Mumbai, India, January 12-14**:** 331-336.

Nesic, D., Mohammadi, A., et al. 2012. "A framework for extremum seeking control of systems with parameter uncertainties." Automatic Control, IEEE Transactions on **PP**(99): 1-14.

Singh, R. 2013. Dynamics and control of a closed carbon-dioxide Brayton cycle. Doctor of Philosophy in Mechanical Engineering Doctoral Thesis, The University of Queensland.

Singh, R., Kearney, M. P., et al. 2013. "Extremum-seeking control of a supercritical carbon-dioxide closed Brayton cycle in a direct-heated solar thermal power plant." Energy **60**: 380-387.

Singh, R., Miller, S. A., et al. 2013. "Dynamic characteristics of a direct-heated supercritical carbon-dioxide Brayton cycle in a solar-thermal power plant." Energy **50**: 194-204.

Singh, R., Rowlands, A. S., et al. 2013. "Effects of relative volume-ratios on dynamic performance of a direct-heated supercritical carbon-dioxide closed Brayton cycle in a solar-thermal power plant." Energy **55**: 1025-1032.

U.S Department of Energy 2012. Chapter 5: Concentrating solar power: technologies, cost, and performance in SunShot vision study.

Wright, S. A., Conboy, T. M., et al. 2011. Break-even power transients for two simple recuperated S-CO_2 Brayton cycle test configurations (11TE1-3). Supercritical CO_2 Power Cycle Symposium. Boulder, Colorado, USA, May 24-25.

Wright, S. A., Vernon, M. E., et al. 2006. Small scale closed Brayton cycle dynamic response experiment results, Sandia National Laboratories, Alberqueque, California, USA.

ACKNOWLEDGEMENTS

This research was performed as part of the Australian Solar Thermal Research Initiative (ASTRI), a project supported by the Australian Government, through the Australian Renewable Energy Agency (ARENA).