Recompression Closed Brayton Cycle Control Options

Nuclear Science and Engineering Division

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ABSTRACT

The attractive performance of the S-CO₂ recompression cycle arises from the thermo-physical properties of carbon dioxide near the critical point. However, to ensure efficient operation of the cycle near the critical point, precise control of the heat removal rate by the pre-cooler upstream of the main compressor is required. With respect to the S-CO₂ recompression cycle at SNL, presently an operator is tasked with manually adjusting the opening of the valve that governs the water flow rate through the pre-cooler.

This report describes a procedure to design an automatic controller that uses the water flow rate as a controlling variable to regulate the S-CO₂ temperature at the pre-cooler outlet. The work relies on the GPASS control-oriented model of the pre-cooler developed last year. A model-based approach is used to design a PI (Proportional-Integral) controller. Then a transfer function describing the influence of the water flow rate on the S-CO₂ outlet temperature is derived from the pre-cooler model. Suitable values for the controller gains are then derived and finally the gains are tested on the initial time-discrete non-linear model.

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1 Introduction

The S-CO₂ Recompression Closed Brayton Cycle's advantageous performance is greatly enhanced by using high efficiency, yet compact, heat exchangers in the form of Printed Circuit Heat Exchangers (PCHEs) [1]. In particular, the efficiency gains calculated for the S-CO₂ cycle are significant if advantage can be taken of the changes in the carbon dioxide thermo-physical properties near the critical point. An increase in efficiency is achieved when the main cycle compressor operates just above the critical point where the sharp increase in density with pressure minimizes compression work. From this standpoint, the S-CO₂ cooling system plays a fundamental role since its task is to regulate precisely the minimum temperature in the cycle, i.e. the S-CO₂ temperature at the main compressor at its first stage inlet at different operating conditions. In Figure 1, the layout of the S-CO₂ recompression cycle at SNL is represented.

Figure 1. Layout of the S-CO₂ recompression cycle (courtesy of B. Lance (SNL)).

As stressed in previous work [2], the effective monitoring and control of the compressor inlet temperature is fundamental to ensure a safe and efficient operation of the energy conversion cycle. Accomplishing this task is not trivial because of the large variations in fluid properties with respect to temperature and pressure conditions. Currently, an operator instantaneously adjusts the opening of the valve that governs the water flow rate through the pre-cooler. In this work, the procedure to design an automatic controller which allows adjusting the water flow rate starting from the measured values of the S-CO₂ temperature at the pre-cooler outlet is presented. The final goal is proposing a robust feedback controller that can effectively accomplish this task by dealing at the same time with uncertainties affecting the system parameters and the sensor measurements. To this aim, the first step consists in adopting a robust control algorithm. In current industrial applications, the PI (Proportional-Integral) controllers represents the most reliable and proven solution. As for the tuning of the corresponding gains, the traditional approach consists in testing

initial estimated values by means of a dedicated simulator. It is an iterative procedure where the solution is progressively refined. At the beginning, a series of controlled transients is foreseen. Then, the initial estimates are tested and refined by simulating the system response during the listed transients, i.e., if the process variable responses are acceptable, then these controller gain values will be adopted in the real plant.

This approach is to a degree approximate as it relies on the accuracy of the model responses. The model invariably contains a number of assumptions and approximations, such as model parameter uncertainties and un-modeled time delays. In addition, the number of simulations that can be performed to assess the validity of the gain values is limited as it is not possible to test all the possible transient scenarios that might occur.

In this work steps were taken to overcome some of the potential shortcomings of this *model-based* approach. The key ingredient of the proposed design procedure is the adoption of a reliable model of the system to identify the governing dynamics and the ruling time constants. This provides controller gains that guarantee stable system response by ensuring reasonable phase margin that to a degree protects against uncertain parameter values. The successive stages of the approach taken are defined below:

1. *Development of a control-oriented model to characterize Pre-cooler Dynamics*

Since the S-CO₂ recompression cycle is expected to be operated over a wide range of conditions, the pre-cooler heat disposal capabilities will need to be promptly adjusted according to the instantaneous inlet conditions of the working fluid. Therefore, as a first step, it is necessary to develop a control-oriented model of the dynamic system sufficiently accurate for our purposes. It does not need to be as accurate as a high-fidelity simulation model. It needs to represent the main control inputs influences on the system dynamics and to provide for some outputs of major interest for real-time control. To this aim, last year we preliminarily developed a model based on first-principle equations, i.e. energy, mass and momentum conservation equations [2]. A one-dimensional control-oriented model of the PCHE was developed by adopting the General Plant Analyzer and System Simulator (GPASS) code [3]. Originally developed to study and compare the dynamic behavior of different configurations of helium closed-loop Brayton cycles, GPASS is a transient simulation control design and cycle scoping code whose modeling capabilities and the solution scheme were upgraded to support analysis of power conversion cycles based on the S-CO₂ Brayton cycle.

2. *Validation of developed control-oriented model against experimental data*

This step phase is crucial. First there must be satisfactory agreement between the simulation outcomes and the experimental data at steady-state conditions to calibrate the geometrical parameters. Then, to verify that the time constants governing the system dynamic behavior are correctly represented, an appropriate benchmark for assessing dynamic transient

behavior is needed. To this end, a set of control system design-oriented operational transients was scheduled to be performed this fiscal year. In particular, SNL suggested that a set of transients triggered by ramp-like perturbations affecting the water flow rate be performed. This provides a means to confirm the modeling of the system dynamics and the correct estimate of the system time constants. Unfortunately, the scheduled tests were delayed, and in the end the tests were not conducted. These tests are expected to be performed in FY19. At the moment, without a solid experimental benchmark validating the system model, the outcomes of our analysis cannot be definitive.

3. *Derivation of the feedback loop transfer function and PI controller tuning*

Once the validity of the developed model is confirmed and the accuracy of the model predictions are verified by experimental data, we can proceed with the derivation of the transfer function describing the influence of the control variable (i.e. water flow rate) on the controlled process variable (i.e. S-CO₂ temperature at the pre-cooler outlet). The PI controllers can be tuned by relying on classic linear control theory to ensure the feedback loop has suitable values for the phase margin and the cut-off frequency. This procedure will provide the desired dynamic performance while providing at the same time the needed robustness with respect to modeling uncertainties and time delays. Thanks to the Bode theorem, the robust asymptotic stability of the designed feedback loop can be assessed by satisfying the corresponding hypotheses.

4. *Verification of the performance of the designed controller*

The controller gains derived from the state-space model are finally tested on the original non-linear model to evaluate their performance in the presence non-linear dynamic behavior. In particular, the performance of the regulator will be evaluated in terms of the settling time and the amplitude of the overshoots during the dynamic transients. Eventually, the regulator capabilities will be assessed at perturbed operating conditions as well, i.e. the controller is expected to ensure the acceptable performance at different power levels.

2 Steady-state conditions

In Figure 2, a schematic representation of the experimental layout of the S-CO₂ recompression cycle is displayed. The main sensors providing the measurements that will be used to assess the dynamic model of the PCHE are outlined. In particular, the profiles of flow rate, pressure and temperature evolution at the PCHE inlet are imposed as time-dependent boundary conditions. The variables representing the pressure and temperature evolution at the PCHE outlet are used to assess the simulation outcomes. In Figure 2, the boundary condition variables are outlined in blue, while the variables to be compared with the experimental data are outlined in red.

Figure 2. Experimental layout. The adopted temperature (T), pressure (p) and flow rate (F) sensors are outlined.

The GPASS model of the pre-cooler developed in [2] has not been modified, i.e. the geometrical parameters were not adjusted. Conversely, with respect to last year, the operating conditions of the S-CO₂ recompression cycle have changed [4]. The new temperature, pressure and flow rate values are reported in Table 1.

Table 1. Nominal pre-cooler operating conditions.

Variable	Steady state value
S-CO ₂ inlet temperature	90.85 °C
S-CO ₂ outlet temperature	32.96 °C
Water inlet temperature	26.85 °C
Water outlet temperature	41.0 °C
S-CO ₂ inlet pressure	7.80 MPa
S-CO ₂ outlet pressure	7.80 MPa
S-CO ₂ mass flow rate	1.0 kg/s
Water mass flow rate	3.27 kg/s
S-CO ₂ inlet enthalpy	508.9 kJ/kgK
S-CO ₂ outlet enthalpy	313.6 kJ/kgK

It was verified that these operating conditions correspond to a quasi-static equilibrium point by comparing the thermal power exchanged between the two fluids (Eqs.(1)-(2)) as shown below.

$$Q_{water} = \dot{m}_{water} \cdot cp_{water} \cdot (T_{water}^{out} - T_{water}^{in}) = 194.75 \text{ kW} \quad (1)$$

$$Q_{S-CO_2} = \dot{m}_{S-CO_2} \cdot (h_{S-CO_2}^{in} - h_{S-CO_2}^{out}) = 195.30 \text{ kW} \quad (2)$$

3 Transfer function derivation

The transfer function representing the influence of the water flow rate on the S-CO₂ temperature at the pre-cooler outlet will be evaluated in correspondence of the nominal conditions. This procedure represents an approximation of the original nonlinear system. In particular, since the transfer function properly represents the system dynamic behavior only near the nominal conditions, the performance of the designed PI controller will rapidly get worse as the system departs from nominal conditions. Notwithstanding, this approach is extremely useful to deal with specific problems, since the powerful methods of analysis and synthesis of linear systems can be adopted.

With this in mind, we can proceed with the derivation of a state-space Linear Time Invariant (LTI) representation of the system by adopting an identification method. To perform LTI state-space model estimation, *subspace methods* are usually employed. The key step in all these methods is the extraction of a signal subspace from a matrix constructed from measured data. From this signal subspace, a state-space model is constructed by utilizing the geometrical properties of the signal subspace. The subspace methods use robust numerical algebra methods, namely the Singular Value Decomposition (SVD) and QR factorization. The identified state-space model is derived without any iteration except in the SVD calculation. The lack of iterations and the numerical robustness of the calculations as well as the representation have opened up the possibilities to identify high order systems with lightly damped modes. Additional information about this approach can be found in [6][6].

To implement this identification procedure, the MATLAB System Identification Toolbox [7] is used. A non-iterative subspace method represented by the following MATLAB commands was used.

```
mydata=iddata(yref,uref,Ts);  
opt = n4sidOptions('Focus','stability');  
model = n4sid(mydata, 5, opt);
```

(3)

In addition to obtaining a fair approximation of the system governing dynamics, the necessary stability condition (Eq. (4)) for discrete-time LTI system poles (λ_i) needs to be met.

$$|\lambda_i| < 1 \quad i = 1, \dots, n \quad (4)$$

System identification of the physical system (the pre-cooler) was performed by perturbing the water mass flow rate according to the ramp shown in Figure 3. In Figure 4, the blue line represents the evolution of the S-CO₂ temperature at the pre-cooler outlet simulated by means of

the GPASS code, whereas the red dash line represents the system response predicted by the identified LTI system. In virtue of the good agreement between the original system response and the identified model, we can proceed with the derivation of the transfer function which is expressed by Eq. (5). The corresponding Bode plot is shown in Figure 5.

$$G(s) = \frac{-0.01675 \cdot s^4 - 0.01648 \cdot s^3 + 1.404 \cdot s^3 - 51.04 \cdot s + 0.07835}{s^5 + 11.89 \cdot s^4 + 435.5 \cdot s^3 + 497 \cdot s^2 + 111.6 \cdot s + 0.06625} \quad (5)$$

Figure 3. Induced water flow rate perturbation.

Figure 4. Comparison of GPASS non-linear model dynamic response (red curve) and the linearized model response (blue curve) obtained through identification method.

Figure 5. Bode plot corresponding to the transfer function between the water flow rate and the S-CO₂ temperature at the pre-cooler outlet.

4 Controller gain tuning and test with GPASS non-linear model

PI controllers are linear controllers. The corresponding graphical representation is displayed in Figure 6. The corresponding control action ($u(t)$) is expressed in Eq. (6).

$$u(t) = K_p \cdot \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right] = K_p \cdot e(t) + K_I \cdot \int_0^t e(\tau) d\tau \quad (6)$$

$$e(t) = y(t) - y^{SP}(t) \quad (7)$$

where K_p is the coefficient of the proportional control action, K_I is the coefficient of the integral control action, T_i is the integral time, $y(t)$ is the controlled variable, $y^{SP}(t)$ is the set-point (i.e., the desired value of the controlled variable), $e(t)$ is the error between the set-point and the instantaneous value of the controlled variable (Eq. (7)), s is the Laplace variable.

Figure 6. Graphical representation of a PI controller.

By adopting the derived transfer function (Eq. (5)), the gains of the PI controller can be tuned to ensure the feedback regulator the asymptotic stability and the robustness against time delays and parameter uncertainties, according to the Bode theorem. Generally, it is necessary to trace the Nyquist diagram to verify the asymptotic stability of the feedback system. Under certain assumptions, though, the condition expressed by the Nyquist criterion can be verified by taking advantage of the analysis of the Bode plots. By adopting the concepts of phase margin and gain margin, it is possible to formulate asymptotic stability criteria which are more straightforward,

though valid for particular systems. If $G(s)$ represents the transfer function of the process to be controlled and the $R(s)$ is the transfer function of the PI controller, if the loop function $L(s) = G(s) \cdot R(s)$ has no positive real part poles (1), and the Bode magnitude plot of $L(j\omega)$ crosses just once the axis at 0 dB (2), then necessary and sufficient conditions to have the system asymptotically stable are that the gain (μ) and the phase margin (φ_m) of the loop function are positive [8]. Being the feedback loop properties evaluated from a transfer function derived from a LTI model, the control actions are optimized for the nominal conditions. The controller performance might degrade when the system operates at conditions different from the nominal ones. Consequently, it is necessary to verify the stability of the feedback system even at perturbed conditions. To this aim, the values adopted for the regulator parameters are defined such as to provide a sufficiently large phase margin. By providing a phase margin equal to 60° , the resulting control scheme will effectively damp disturbances.

When the gains of the controller are tuned, it is necessary to find a suitable solution such that acceptable control performance can be achieved, but at the same time the conditions of robust stability are met. As for the desired performance, they can be representing by the settling time, i.e., the time elapsed from the application of the initial step-wise perturbation to the input variable to the time at which the output variable has entered and remained within a specified error band (usually 2% or 5%), as shown in Figure 7.

Figure 7. Graphical representation of the step response of a second-order system. The settling time is outlined [9].

By adopting the described procedure, the following values for the PI controller gains were found (Eq. (8)).

$$K_p = 0.1, \quad K_I = 0.2 \text{ s} \quad (8)$$

As for the performance and the robustness stability figures of merit, the following values were obtained (Eq. (9)).

$$\varphi_m = 71.5^\circ, T_{settling} = -\frac{\log(0.05)}{\omega_c} = 34.2 \text{ s} \quad (9)$$

Before testing these values on the original nonlinear model, it is worth reminding that these values were derived starting from a time-continuous model. On the other hand, the GPASS model is a time-discrete simulation tool. Therefore, the found controller gains need to be converted accordingly. To this aim, the time-discrete representation of the control action performed by a PI controller needs to be defined (Eq. (10)).

$$u(k) = K_c \cdot e(k) + \frac{K_c}{T_I} \cdot \left(\frac{e(k) + e(k-1)}{2} \right) T_s + u(k-1) \quad (10)$$

where k is the instantaneous time step, and T_s is the sampling time (0.04 s).

By comparing this expression with the one reported in Eq. (6), we can come up with the following relationship between time-continuous and time-discrete gains:

$$K_p^{td} = K_p = 0.1, K_I^{td} = \frac{K_p \cdot T_s}{T_I} = 0.008 \quad (11)$$

Initially, the gains reported in Eq. (11) were adopted to simulate GPASS non-linear model controlled transients as well. Immediately, we realized that if a set-point variation larger than the one used for the LTI model identification is imposed, the feedback loop might turn unstable. This is due to the inherent non-linearity of the model which limit the effectiveness and the region of validity of the PI tuning. To ensure the asymptotic stability, the controller gains needed to be adjusted (Eq. (12)). The simulation outcomes corresponding to the controlled transient simulated with the GPASS non-linear model are shown in Figure 8 and Figure 9.

$$K_p^{td} = 7 \cdot 10^{-3}, K_I^{td} = 3 \cdot 10^{-5} \quad (12)$$

Figure 8. S-CO₂ temperature at the PCHE outlet response (blue curve) and corresponding set-point (red curve) during the simulated transient.

Figure 9. Water flow rate response during the simulated transient.

5 Conclusions

In this work, a model-based approach to design a PI controller for the operation of the S-CO₂ recompression cycle at SNL is presented. By relying on the one-dimensional control-oriented model of the pre-cooler developed last year, first the transfer function describing the influence of the water flow rate on the S-CO₂ outlet temperature was derived. Then, we found suitable values for the controller gains so that the Bode theorem conditions assessing the robust asymptotic stability of the feedback loop were satisfied. Finally, the gains were tested on the initial time-discrete non-linear model.

One of the goals of this fiscal year was the benchmark of the GPASS model against experimental data to assess its validity and accuracy. Unfortunately, the scheduled tests at SNL were delayed, and in the end they were not conducted. These tests are expected to be performed in FY19. At the moment, without a solid experimental benchmark validating the developed model, the outcomes of our analysis cannot be definitive.

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