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Start-up and Emergency Shutdown Modeling for a Coal-fired 10MWe sCO_2 Power Plant

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ABSTRACT

As part of a Phase II Front End Engineering Design (FEED) study for the DOE Fossil Fuel Large-Scale Pilots program, investigations of novel start-up and emergency shutdown methods for a stoker-fed, coal-fired, 10MWe sCO_2 power plant proposal were performed. These investigations were performed using 1D transient system models of the plant created within the GT-SUITE system modeling platform. The system model components were created using vendor quotation data (heat exchangers), performance maps (turbomachines), or FMU models (fired heater).

Previously, Echogen Power Systems (Echogen) has used a sCO_2 power cycle start-up method that fills the system with liquid CO_2 to facilitate easy use of an electrically-driven start pump to transition the system from initial CO_2 fill to turbo-compressor initialization. The novel start-up method presented attempts this transition with a minimal filling of the system with liquid CO_2, to reduce the total CO_2 inventory required. This method leaves the start pump vulnerable to a two-phase inlet condition as system pressure is below the CO_2 saturation pressure for the condenser cooling water temperature (Tcw). System model cases at Tcw of 18°C, 26°C, and 32°C, corresponding to cold, design, and hot ambient days, were analyzed to determine if the SP inlet condition could be kept as a subcooled liquid and estimate the CO_2 inventory reduction amount.

Stoker-fed, coal-fired heaters continue to emit heat for some time even after emergency shutdown from events such as a power failure. This heat emission would lead to a failure of the fired heater, as the metal overheats, if the CO_2 flow is shut off. The emergency shutdown method presented utilizes CO_2 vented by a controllable vent valve (CRV) to provide CO_2 cooling flow to the fired heater. To determine the effectiveness of this method at keeping the fired heater peak tubing metal temperature below the ASME material temperature limit, for pressures below 5 MPa, of 816 °C, system model cases with CRV diameters ranging from 4” to 10”, and an alternative CO_2 vent routing with CRV size of 6”, were investigated.

INTRODUCTION

As part of the DOE Fossil Fuel Large-Scale Pilots program, the project team of Echogen; Riley Power, Inc; the University of Missouri; and the Electric Power Research Institute were awarded funding for a Phase II FEED study of a proposed stoker-fed, coal-fired, $10MW_e$ sCO_2 Economized Recompression Brayton Cycle Primary Power Large-Scale Pilot Plant (LSP) [1]. The purpose of the FEED study was to determine the technical scope and budget required to build the proposed $10MW_e$ sCO_2 Recompression Brayton Cycle primary power plant at the University of Missouri. As part of the FEED study, Echogen developed a novel start-up and emergency shutdown method for the LSP.

A previously facility tested Echogen sCO_2 power cycle for waste heat recovery achieved start-up by pumping liquid CO_2 into the system while slowly adding heat to the system CO_2 via a printed circuit heat exchanger (PCHE) serving as the primary heat exchanger (PHX) with the primary heat source flowing through the other side. This heat and mass addition pressurized the system until an electrically-driven start pump (SP) could be operated and used to drive the system to the required inlet pressure and temperature for the drive turbine, of the primary turbo-compressor, to achieve self-sustaining operation.

In the LSP power cycle, the extremely low CO_2 volume PCHE PHX was replaced by a dramatically higher CO_2 volume coal-fired heater. The coal-fired heater also had a more limited ability to manage heat output and an increased heat source temperature versus the waste heat recovery application. Application of the same start-up method used previously would require much of the fired heater tubing to be filled with liquid CO_2 before heat was applied to ensure proper cooling of the metal tubing. Due to the large volume of the fired heater, a large CO_2 inventory control (IC) tank would be required. The novel start-up method minimizes the CO_2 inventory required by using a three-step process to bring the system from an initial vapor fill to the required system state for the initialization of turbo-compressor self-sustaining operation.

Stoker-fed, coal-fired heaters, like the one used in the LSP, continue to emit heat from the coal even after the system experiences an unplanned shutdown due to events such as a power failure. Because of this, adequate cooling must be supplied to the fired heater tubing to prevent overheating failures. The system cannot be slowly ramped down during a power failure because the cooling water supply to the condenser stops. Echogen developed a novel method to supply cooling CO_2 flow to the fired heater after an unplanned shutdown through a CRV downstream of the fired heater, in the event of a power failure. An alternative routing variation that feeds CO_2 directly from the IC tank to the fired heater inlet was also investigated.

To test the validity of these novel methods, Echogen performed 1D transient model studies using the GT-SUITE 1D system simulation software package (GT-SUITE). A full power cycle system model was constructed and then simplified into three models that specifically matched the power cycle components and controls needed for the start-up and two emergency shutdown cases. Riley Power, Inc was contracted to create a Co-Simulation Functional Mock-up Unit of their LSP coal-fired heater design for use in Echogen GT-SUITE models.

DESIGN BASIS

The Recompression Brayton Cycle (RCBC) is advantageous for optimizing thermal efficiency in indirect fired sCO_2 primary power applications [2]. Recuperative preheating creates a narrow temperature range for heat addition. A recompressor introduces a partial recuperator bypass, minimizing exergy destruction in the recuperators and optimizing internal heat recovery. The combination of high average hot-side temperature and highly effective recuperation results in cycles with high thermodynamic efficiencies relative to steam.

An economized RCBC architecture (RCBC-E, configured with turbine-driven compressors) is shown in Figure 1. The main compressor, or low-temperature compressor (LTC), compresses relatively dense fluid after the final heat rejection step in the cycle. The re-compressor, or high-temperature compressor (HTC), compresses a lower density fluid that bypasses heat rejection. Drive turbines (LTC DT and HTC DT) power the LTC and HTC, respectively. Net and auxiliary electrical power are supplied by a synchronous generator driven by the power turbine (PT). Heat addition from the thermal resource occurs in a single primary heat exchanger (PHX). Heat rejection to the cooling fluid occurs in the cooling heat exchanger (CHX). Ambient-range cooling fluid temperatures limit the pressure ratio of the working fluid, such that the CO_2 leaves the turbines at relatively high temperatures. Two internal heat exchangers recuperate this energy to preheat the CO_2 entering the PHX. The high-temperature recuperator (HTR) preheats the full high-pressure flow. The low-temperature recuperator (LTR) preheats a portion of the high-pressure flow, minimizing the exergetic destruction associated with recuperation by closely matching the temperature glide between the hot and cold CO_2 streams.

The thermal resource is a combustion byproduct (flue gas) from a coal-fired heater. While ideal for optimizing power cycle efficiency, standard RCBC architecture, without an economizer, can restrict the efficiency of the fired heater and reduce the overall plant efficiency. Recuperative pre-heating of the CO_2 produces a high PHX inlet CO_2 temperature, limiting the enthalpy extraction from sensible thermal resources.

To increase net plant efficiency, the RCBC-E uses a sCO_2 economizer to increase the fired heater efficiency. In the flue gas stream, the sCO_2 economizer (PHX-2) is in series with the main PHX (PHX1), reducing the heat that is exhausted through the stack. In the CO_2 stream, PHX-2 is in parallel with the HTR, so that a portion of the total CO_2 flow bypasses high-temperature recuperation for low-temperature heat addition.

For heat rejection, a clean-water cooling loop with an intermediate heat exchanger (IHX) is used to transfer heat to an existing plant water loop and cooling tower. Water in both the intermediate and plant loops is circulated by pumps (WP1 and WP2, respectively). The heat addition system includes coal combustion (with natural gas co-firing) in a stoker-fired heater.

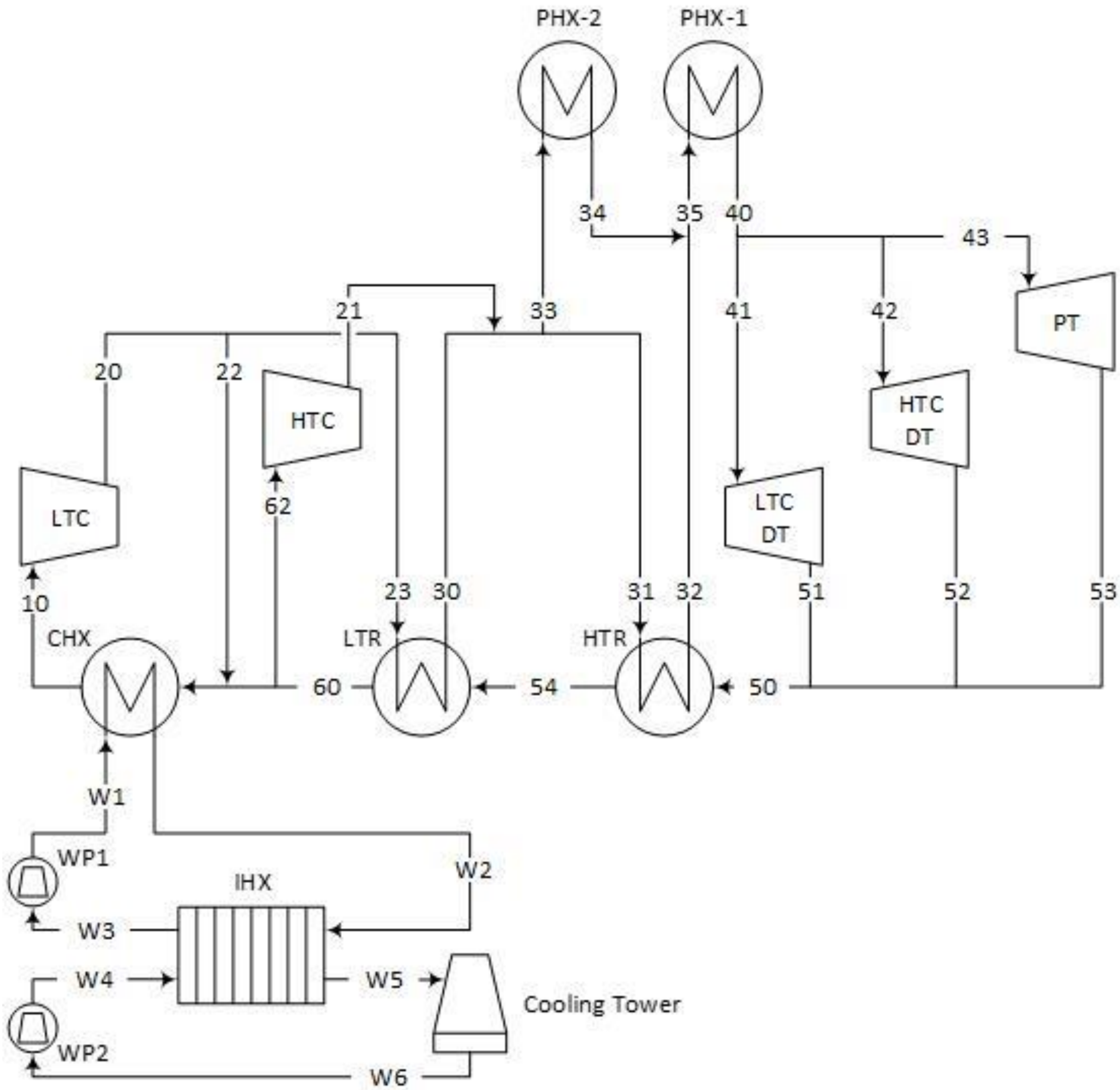

Figure 1: RCBC-E with a sCO_2 economizer (PHX-2)

MODEL DEVELOPMENT

Performance maps containing the pressure rise, flow rate, speed, and efficiency for the turbomachines at a fixed fluid inlet condition were provided by their respective vendors. The data from these maps was input into specific templates available within GT-SUITE. The GT-SUITE templates created new data maps that converted flow rates and speed into corrected values that can be used to predict turbomachine performance at different fluid inlet conditions. The LTC, LTC-DT, HTC, HTC-DT, and PT performance maps used isentropic enthalpy rise instead of pressure rise. Isentropic enthalpy change was used instead of pressure rise to account for the real gas effects of sCO_2. To use these maps, proprietary FORTRAN codes were written by Echogen that could be utilized by the GT-SUITE templates instead of the traditional template code.

Due to limited detailed geometric information for the heat exchangers, they were modeled as a general flow geometry with a lumped capacitance core structure. The vendor provided the heat transfer area, core size, and dry/operating heat exchanger masses. The characteristic length, flow area, and fluid volume were determined by a built-in genetic optimizer within GT-SUITE. The optimizer solved for fluid volume, channel area, and characteristic length of the channels. These values were then used to solve equations 1, 2, and 3, resulting in the needed flow geometry. The correlation equations selected for use in the heat exchangers were Dittus-Boelter [3], for single-phase and supercritical, and Shah, 1979 [4], for evaporation and condensation. Pressure drops in heat exchangers were calculated by use of the Fanning friction factor in the 1D momentum equation. The Fanning friction factors were calculated via an explicit approximation of the Colebrook equation [5].

A Co-Simulation Functional Mock-up Unit [6] (CS FMU) of the fired heater was developed by Riley Power Inc. Due to difficulties integrating the CS FMU within the GT-SUITE models, substitutions were required. In the start-up model, the fired heater model used a heat source input to the metal of the fired heater pipes. The heat source was controlled by a PID targeting the outlet CO_2 temperature. The PID gains were tuned to match the CS FMU performance during the initial fired heater start-up. Simple heat input to the fired heater piping was used for the emergency shutdown cases. To obtain the correct heat input profile, an iterative process in which the results from one model were used as either the flow (GT-SUITE) or heat input profiles (CS FMU) in the other model until the results converged on a solution.

Piping pressure losses were calculated with the same method used for the heat exchangers. All piping was modeled with an adiabatic exterior boundary condition that is justified by the high level of insulation applied.

START-UP

Methodology

The novel start-up method investigated used three steps to bring the system from the initial post vapor fill condition of CO_2 at 2.5 MPa and 20 °C to the required turbine inlet condition for self-sustaining operation of CO_2 at 250 °C and approx. 12.5 MPa at the turbine inlets.

In Step 1, the TP pumped 7 kg/s of liquid CO_2 from the IC Tank, held at -19.5 °C and 2 MPa, into the SP inlet piping. From there, the liquid CO_2 traveled into the outlet of the CHX, where it vaporized as heat is transferred from the warmer water supply to the CHX. This mass and energy addition built pressure in the system. Step 1 continued until the system pressure reached the saturated pressure of CO_2 at the temperature of the CHX cooling water. Figure 2 shows the active parts of the system during Step 1.

In Step 2, Figure 3, the SP began operating with a flow target of 8 kg/s; however, the actual SP mass flow rate could vary due to system conditions such as pump pressure rise. The PT bypass control valve (PCV0530) was used to provide flow the flow resistance that allowed the SP to build discharge pressure. The 8 kg/s flow target was determined by the minimum stable pump flow rate at the minimum speed. Since the CO_2 exiting the CHX at this point was superheated vapor, there was a risk that the CO_2 at the SP inlet may enter the two-phase region causing potential damage to the SP and system instability. To help prevent this, the TP remained operating at the same 7 kg/s flow target from Step 1. The HTC DT, LTC DT, and PT throttle valves (PCV0042, PCV0041, and PCV0433) were closed during this step to prevent flow into the turbines. At the same time the SP was activated, the fired heater auxiliary gas burners were lit. The fired heater was set to a target CO_2 outlet temperature of 100 °C during this step to minimize the risk of overheating the metal tubes.

Step 3, Figure 4, began once the pressure at the SP inlet reached a predetermined set point. The setpoint pressure was determined by an Echogen proprietary optimizer that calculated the optimal set pressure as a function of Tcw. An Echogen proprietary inventory control system (ICS) was then used to control the pressure at the SP inlet by adding or removing CO_2 mass from the system. The SP mass flow rate was increased to the design flow rate target of 20 kg/s. At this point, the pressure at the CHX reliably remained above saturation pressure causing the CHX outlet to be subcooled liquid, eliminating the risk of two-phase condition at the SP inlet. The fired heater CO_2 outlet temperature target was increased to 250 °C, the design point turbine inlet temperature (TIT) for the LTC DT, to begin LTC self-sustaining operation.

To observe the effect of Tcw on the start-up procedure, the model was run at three Tcw temperatures, 18 °C, 26 °C, and 32 °C, spanning the likely cooling water temperature range. The ICS pressure control targets were determined to be 6.87 MPa, 7.67 MPa, and 8.48 MPa, for the given Tcw cases.

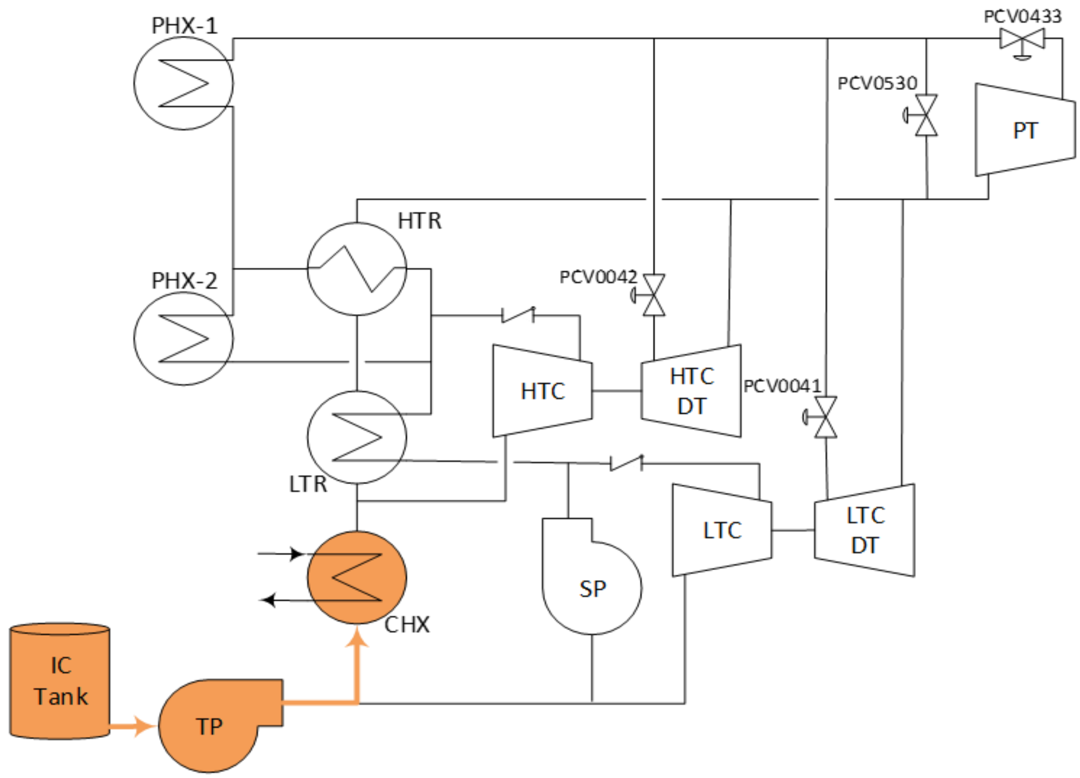

Figure 2: Start-up step 1 flow diagram. Orange arrows show the CO_2 flow path.

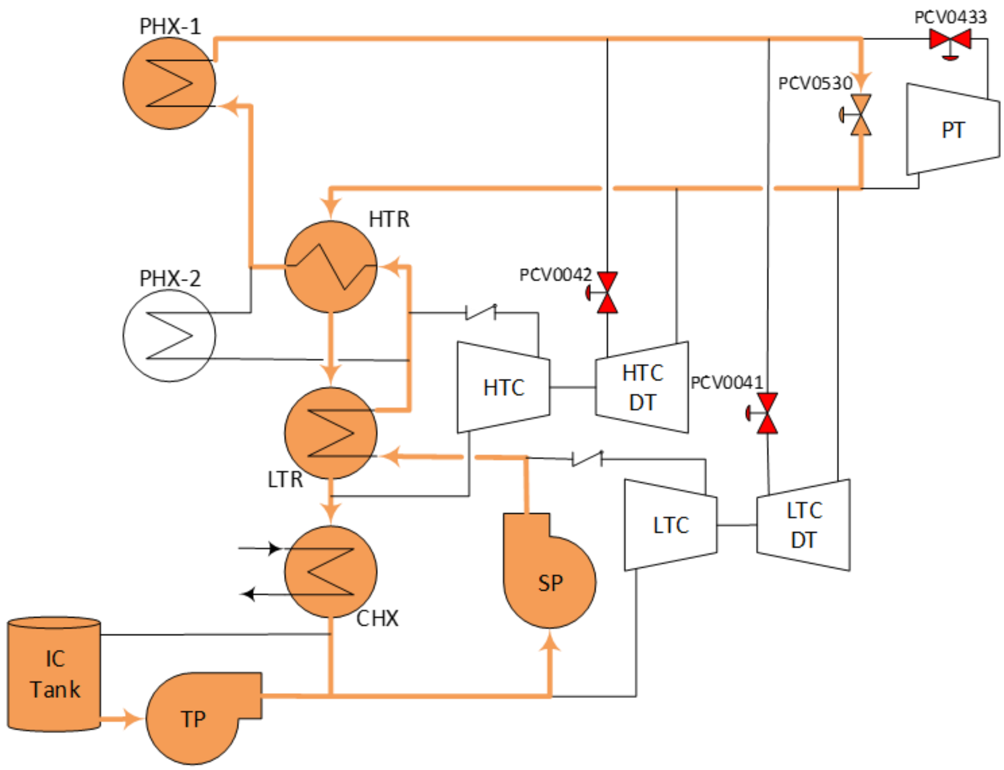

Figure 3: Start-up step 2 flow diagram. Red valves are closed. Orange valves are actively controlled.

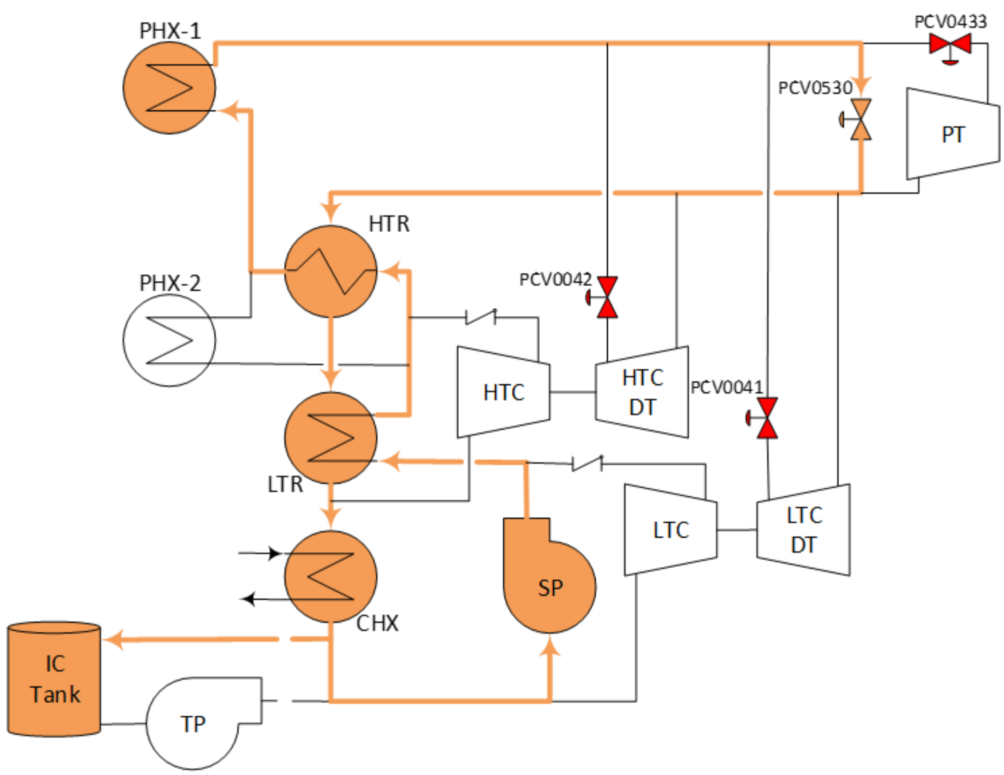

Figure 4: Start-up step 3 flow diagram.

Results

A plot of the SP inlet quality is shown in Figure 5 for each Tcw case. It is shown that the 18 °C and 26 °C experienced two-phase flow, quality greater than 0, at the SP inlet while the 32 °C case did not experience any two-phase flow. The two-phase inlet condition lasted 250 seconds for the 18 °C case and 110 seconds for the 26 °C case. Two-phase flow condition at the SP inlet is undesirable because it causes cavitation in the pump.

The cause of the two-phase flow was shown to be an excessively high SP mass flow rate at the start of step 2, as seen in Figure 5. This mass flow rate exceeded the sustainable level and drained the liquid CO_2 from the piping around the SP inlet until a two-phase inlet condition occurred. This spike in mass flow rate also exceeded the runout limit for the pump. The spike in mass flow rate occurred because there was little to no pressure rise from flow resistance across the pump when it is first activated. This was due to the large amount of available flow volume, filled with mostly CO_2 vapor, in the path from the SP outlet to PCV0530, which was used as the flow resistance controller. In order to build pressure rise across the pump, the CO_2 vapor in the flow path needed to be compressed by the addition of liquid CO_2 from the SP. Due to the large volume of CO_2 to be compressed, this process was relatively slow. The addition of a back pressure regulation valve close to the pump outlet would correct this problem by greatly reducing the flow path volume to the flow resistance controller, allowing for near-instantaneous buildup of pressure rise across the pump. Additionally, a slower SP speed ramp rate may also be implemented to reduce the maximum possible flow rate from the SP.

CO_2 mass within the system is plotted in Figure 6 for three start-up runs with cooling water temperatures of 18 °C, 26 °C, and 32 °C. The peak mass for each run is also tabulated in Table 1, along with a percentage CO_2 mass reduction versus flooding the system with liquid CO_2. It is estimated that filling the entire system with liquid CO_2 would require 44,850 kg of CO_2 given a system volume of 43 m^3 and liquid CO_2 density of 1043 kg/m^3. Given that 32 °C is the highest end of the Tcw range, it can be concluded from the simulation results that the method of start-up performed in this analysis would lead to a decrease in the required CO_2 inventory of at least 44.1% or 19,760 kgs.

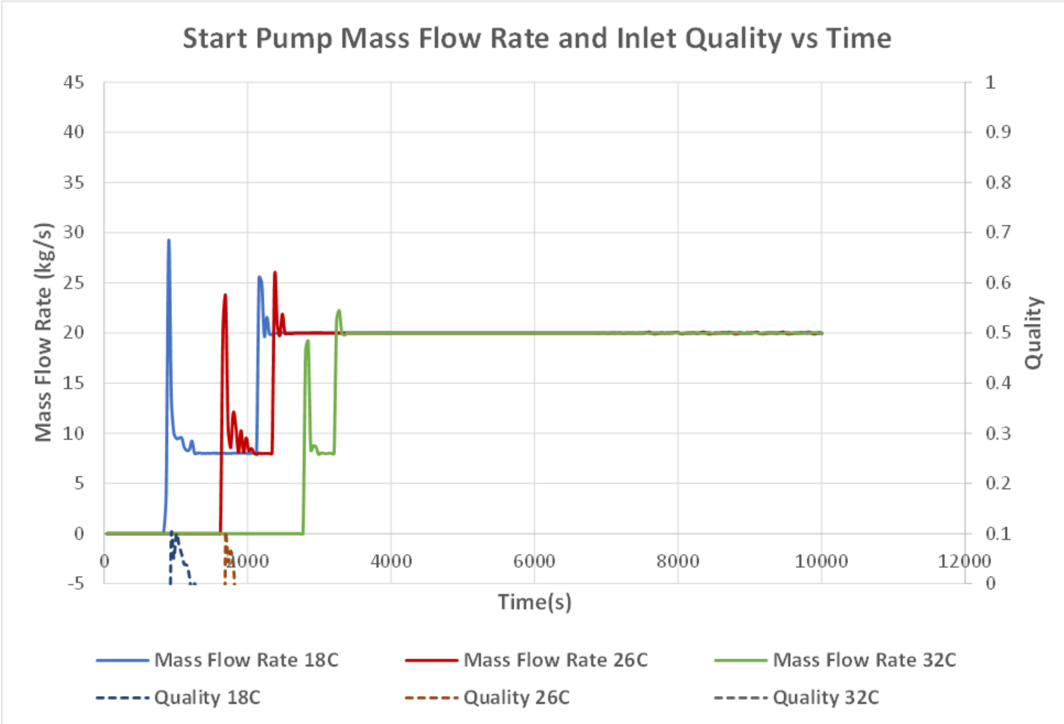

Figure 5: SP mass flow rate and inlet quality

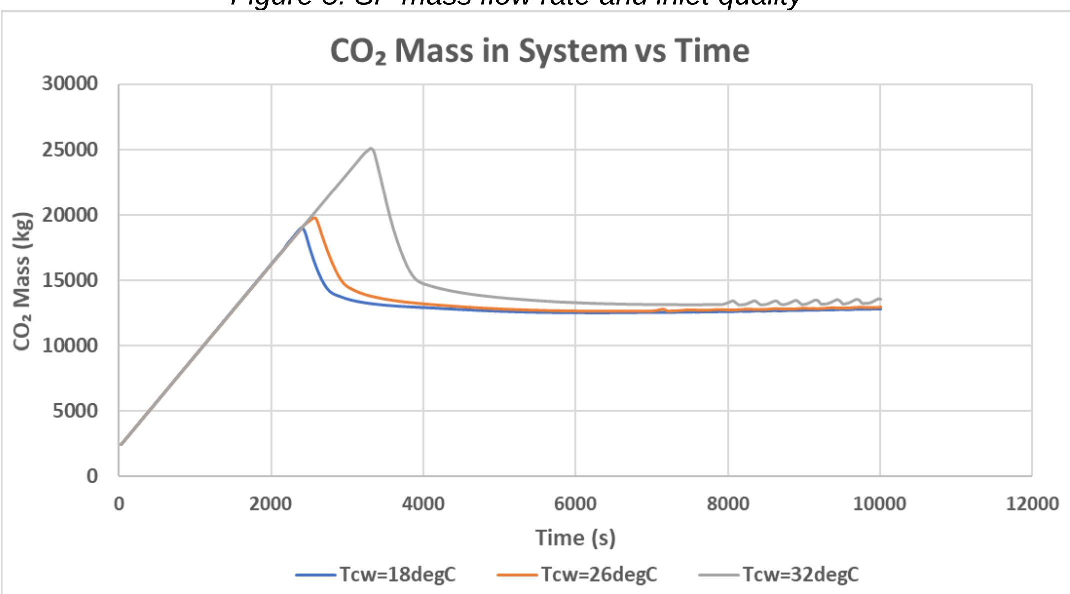

Figure 6: Mass of CO_2 in the system during start-up

Table 1: CO_2 mass in the system at specified Tcw

Tcw (°C)	CO_2 Mass in the System (kg)	% Decrease in Mass vs All Liquid Start
18	18998	57.6%
26	19766	55.9%
32	25093	44.1%

EMERGENCY SHUTDOWN

Methodology

The emergency shutdown method, as outlined in Figure 7, utilized an electronically controlled relief valve (CRV1003 or CRV), placed after the fired heater, to vent CO_2 once an emergency shutdown event was detected. The venting of CO_2 through CRV1003 forced the CO_2 in the system to flow through the fired heater, providing cooling for the fired heater tubing metal. The target temperature limit was set at 816 °C, the ASME temperature limit for the tube material below an internal pressure of 5.5 MPa. PCV0530, PCV0042, PCV0041, and PCV0433 as well as isolation valves before and after the SP (not shown) were closed to better direct flow through the fired heater.

An alternative venting strategy was developed to increase the CO_2 cooling of the fired heater during an emergency shutdown, Figure 8. This strategy adds a separate vent path from the IC tank (vapor side) to the PHX1 inlet. This separate path eliminates the friction losses from the CO_2 having to travel from the original tank inlet to the system (at the SP inlet) to the fired heater. It also greatly lowers the temperature of the CO_2 at the fired heater inlet, as the temperature of the CO_2 from the tank, -19.5 °C, is much colder than the temperature of the CO_2 already in the system.

The models were run at design load conditions until the system achieved a steady state. Once a steady-state was reached, a power failure event was initiated. The power failure caused the cooling water supply pumps to stop and the fired heater to cease supplying new fuel to the stoker grate. The valves and control system remained operational due to an uninterruptible power supply (UPS). Valves were then positioned according to Figure 7 or Figure 8, to ensure all CO_2 in the system was directed to the fired heater. CRV diameters of 4”, 6”, 8”, and 10” were tested for the original vent routing while one CRV size of 6” was tested for the alternative routing.

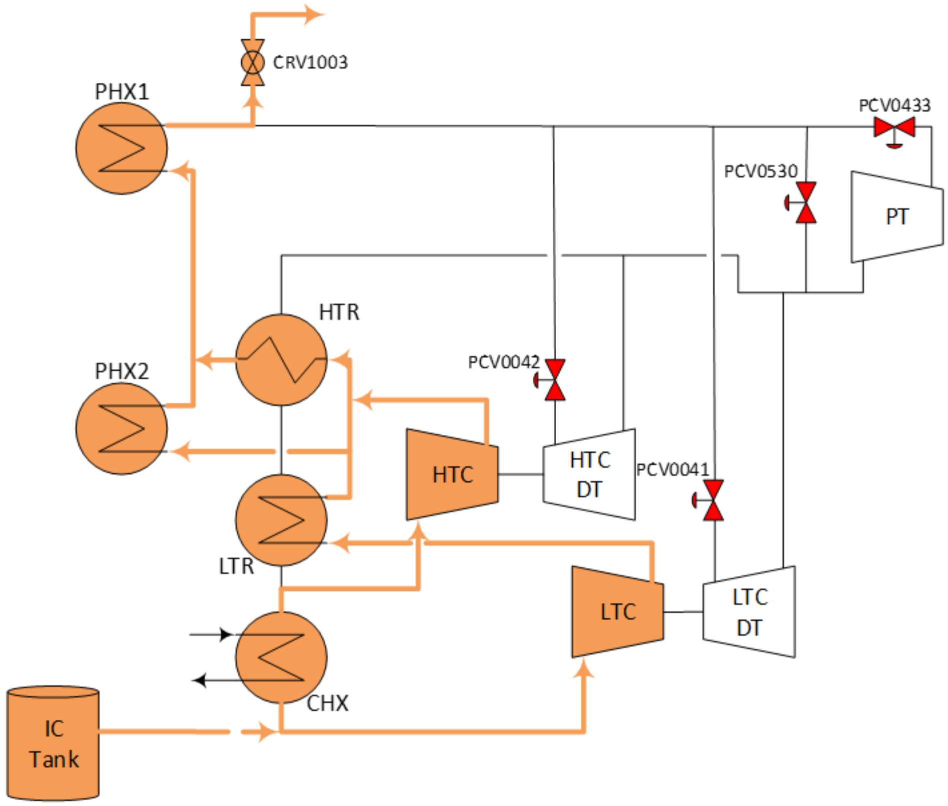

Figure 7: Emergency Shutdown Flow Diagram. Orange arrows show the CO_2 flow path. Red valves are closed. Orange valves are actively controlled.

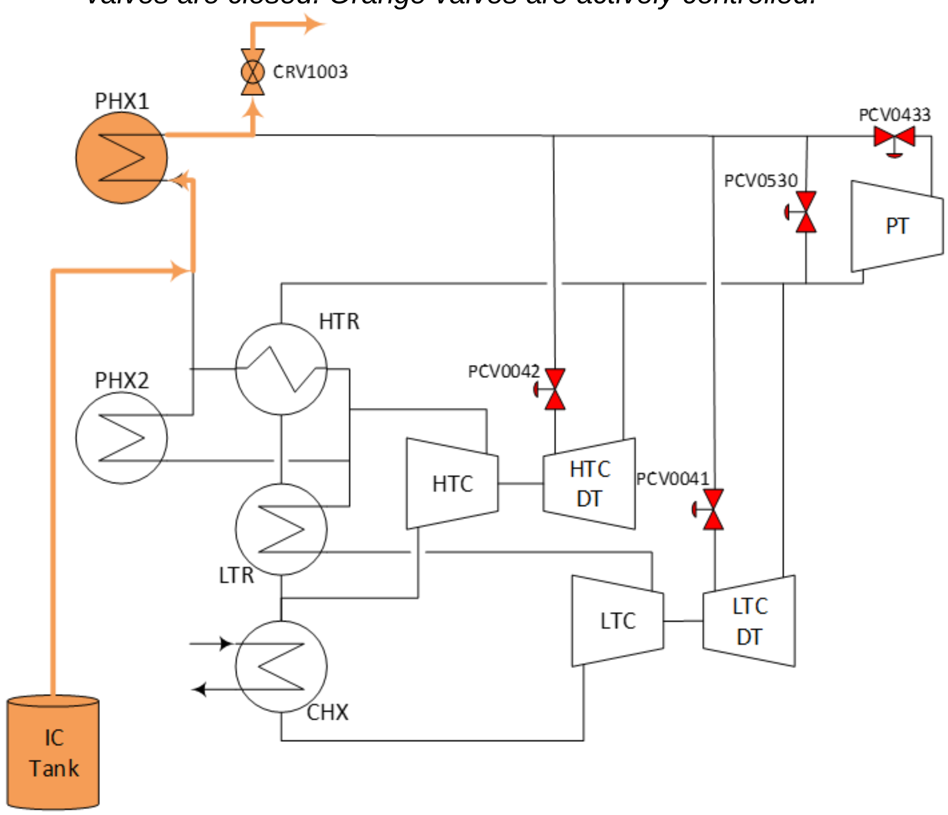

Figure 8: Alternative Routing Emergency Shutdown Flow Diagram

Results

Figure 9 shows the fired heater peak metal temperature from the original routing as well as the addition of a peak metal temperature from a 6” I.D. vent using the alternative direct routing method. As shown by Table 2 the 6” I.D. direct routing vent has a peak metal temperature of only 802 °C, a 30 °C decrease from the best original routing result (10” I.D.) and 39 °C better than the 6” I.D. original routing peak metal temperature.

Given that none of the vent diameters in the original vent routing condition could keep peak metal temperature below the target of 816 °C, the direct routing vent strategy would be required. The superior performance of the direct routing vs the original routing makes it possible to use a much smaller CRV1003 to reduce the costs incurred when adding piping and an isolation valve required to achieve the direct routing fired heater overheating prevention vent strategy. It is also possible that another overheating prevention strategy, such as quenching the fuel source, could be used to quickly dissipate the heat generated within the fired heater, preventing the need for CO_2 cooling of the pipe metal.

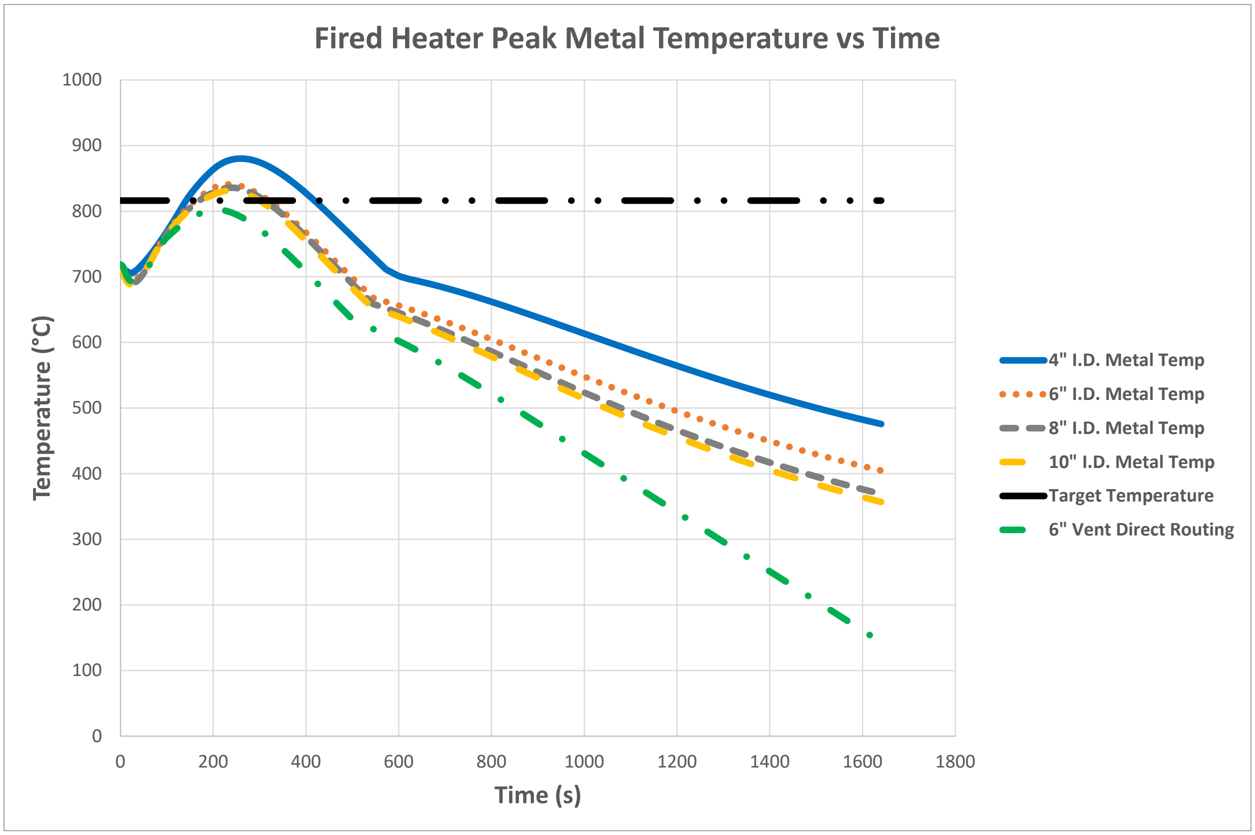

Figure 9: Emergency Shutdown Fired Heater Peak Metal Temperatures

Table 2: Emergency Shutdown Fired Heater Peak Metal Temperatures

Vent I.D.	Routing	Peak Metal Temperature (°C)
4"	Base	880
6"	Base	841
8"	Base	836
10"	Base	832
6"	Direct	802

CONCLUSIONS

Echogen Power Systems developed transient simulation models of novel start-up and emergency shut down methods for a proposed 10MW sCO_2 Economized Recompression Brayton Power Cycle for the Large Scale Pilot DOE program. The primary objectives of the start-up analysis were to determine if the start-up procedure could be accomplished without flooding the system with liquid CO_2 with the current TP and SP specifications, and if so, how much CO_2 mass would be required. The primary objective of the emergency shutdown analysis was to determine the size of the CRV required to prevent fired heater overheating or if a different strategy would be required to prevent overheating.

The novel start-up method showed a minimum reduction of 44.1% or 19,760 kg versus flooding the system with liquid CO_2. This result was observed in the start-up procedure using cooling water at a temperature of 32 °C. Reductions of 57.6% and 55.9% were shown at Tcw of 18 °C and 26 °C, but the maximum inventory required must be used for inventory tank sizing consideration.

The start-up modeling cases with cooling water temperatures of 18 °C and 26 °C had brief periods (250 and 110 seconds) of two-phase CO_2 at the inlet, but the run at 32 °C remained liquid or supercritical at all times. It was determined that the cause of the two-phase inlet was a large spike in mass flow rate at the initial activation of the SP (start of step 2) due to low flow resistance. To correct this, a slower RPM ramp rate or a back pressure control valve close to the SP outlet, allowing near-instantaneous control of SP flow resistance, could be utilized.

Simulation analysis of the base venting route for the emergency shutdown method was run at four CRV inner diameter sizes from 4” to 10”. The peak metal temperatures, in order from smallest diameter to largest, were: 880 °C, 841 °C, 836 °C, and 832 °C. All sizes failed to keep the peak metal temperature below the 816°C target and greatly diminishing returns were observed past 6” inner diameter CRV size.

An alternative vent routing, which placed a direct pipe route from the CO_2 IC Tank to the inlet of the fired heater, was tested. When tested with a 6” inner diameter CRV size, the peak metal temperature was 802 °C, below the 816 °C temperature target. This alternative vent strategy would be required to prevent fired heater tube overheating during an emergency shutdown if a CO_2 venting strategy was utilized. Otherwise, a new fired heater thermal management method would need to be developed, such as quenching the fuel source.

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