Supercritical CO_2 Controls Strategies for a Fixed-Speed Recompression Closed Brayton Cycle

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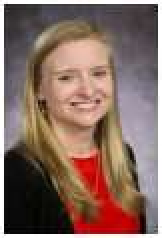

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Patrick Bishop leads a group of engineers that provide instrumentation and controls support to commercial and R&D projects in GTI's Energy Supply and Conversion division. His areas of expertise include process control systems, instrumentation, data acquisition systems and system integration. These skills have been used in an 800 ton/day demonstration plant of GTI's RGAS coal gasifier which included the design and specification of startup and shutdown sequences, SIS specification, safety and process interlock logic and instrumentation requirements. He also has assisted in the development of the control system design, specification and installation for the 10 MWe STEP supercritical CO_2 power cycle test facility.

ABSTRACT

Supercritical carbon dioxide (sCO_2) power cycles vary in many ways from conventional steam power cycles. As a result, designing and implementing a control system for an sCO_2 cycle presents numerous unique challenges that must be overcome in order to ensure safe and efficient operation of the plant. In a closed-loop cycle, a process upset can quickly move from the source of the problem to components downstream, causing further damage. Ensuring that controls are in place to avoid the risk of cascaded process upsets is critical to plant safety. With high temperatures and pressures in the loop, equipment and personnel safety become a key consideration in designing shutdowns to minimize damage and reduce risk. This paper will present a proposed control strategy for a fixed-speed Recompression Closed Brayton Cycle (RCBC). This paper delves into the controls considerations of each component and its associated auxiliary systems. Additionally, interactions between components are discussed.

INTRODUCTION

A Supercritical Transformational Electric Power project (STEP) is underway to design, construct, commission, and operate a 10 MWe sCO_2 power cycle. The project team is led by Gas Technology Institute (GTI), Southwest Research Institute® (SwRI®), and General Electric Global Research (GE-GR). Objectives of STEP include the demonstration of the operability of an RCBC sCO_2 power cycle, demonstration of potential for greater than 50% thermodynamic cycle efficiency, and turbine inlet temperatures in excess of 700°C [1]. The STEP team has been designing and validating the closed loop controls necessary for stable operation of the pilot plant through the use of steady state and transient modeling [2]. The design of these controls strategies is inherent in equipment and personal protection considering the extreme fluid properties of greater than 700°C and 250 bara at peak performance

A simplified layout of the STEP 10 MWe pilot plant is shown below in Figure 1. The main process is comprised of two compressors, one turbine, two recuperators, two coolers, and one heater. The main compressor is responsible for the majority of the mass flow while the bypass compressor mitigates a possible pinch point if a single recuperator were used as in the Simple Cycle configuration. With the introduction of the bypass compressor, the recuperation duty is split between the High Temperature Recuperator (HTR) and Low Temperature Recuperator (LTR). The main cooler is used during steady state and is in the primary flow path while the bypass cooler is used during transients only. The turbine and bypass compressor share a common shaft which is also connected to a generator through a gearbox. The main compressor, meanwhile, is controlled by a motor and VFD. The facility is controlled and protected by a Distributed Control System (DCS).

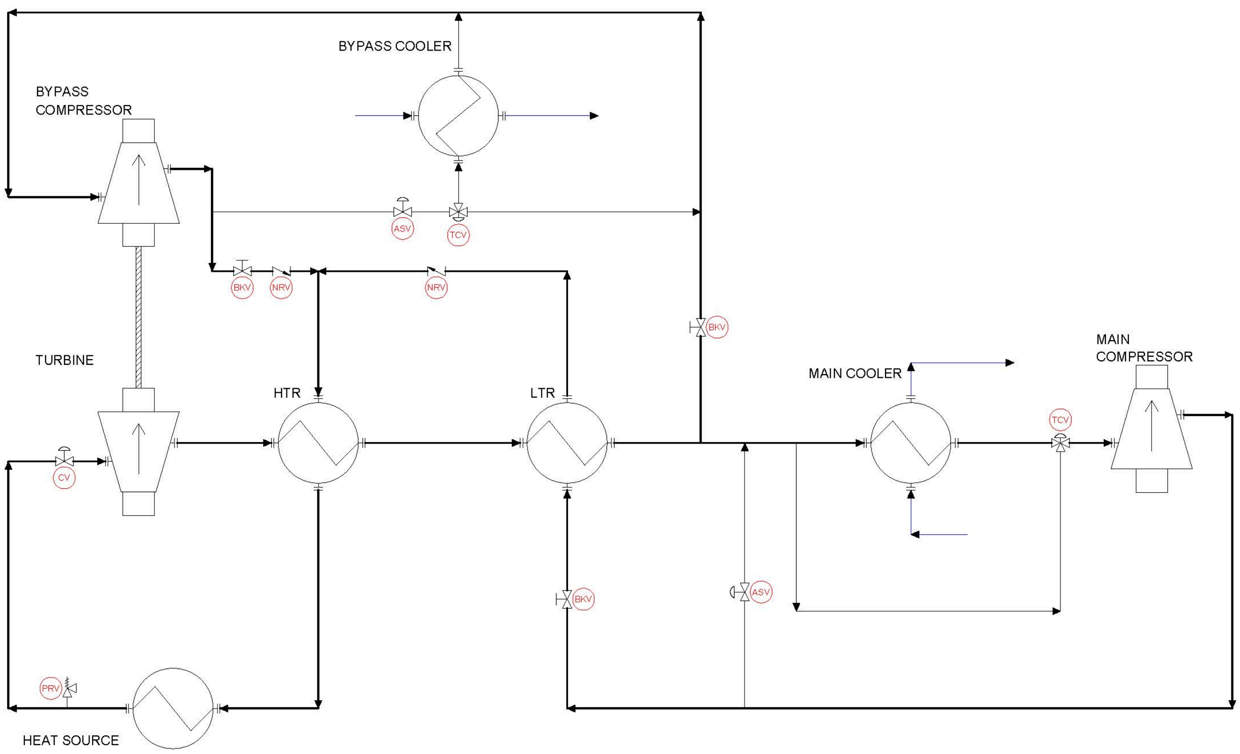

Figure 1: Recompression Closed Brayton Cycle Layout

MAIN PROCESS CONTROLS

The closed loop nature of the RCBC poses a unique controls problem: any given independent variable will influence multiple dependent variables. This lends the system to unstable behavior and requires careful selection of what closed loop controls to implement. The following control loops have been designed for steady state operation of the main process.

Turbine Inlet Temperature

The turbine inlet temperature is a critical system parameter for performance in the RCBC configuration. The temperature at the turbine inlet is closely coupled with the heater outlet temperature during steady state operation. Insulation of the process piping between the heater outlet and turbine inlet will minimize the temperature drop, and throttling of the turbine control valve will have minimal impact from isenthalpic cooling at the operating conditions. The heater firing rate, achieved by the natural gas fuel control valve, will maintain a closed loop control of the turbine inlet temperature.

High Side Pressure

The system pressure boundaries during steady state operation are at the compressors, turbine, and anti-surge valves as shown in Figure 2. While both main and bypass compressor inlet guide vane (IGV) positions directly affect the system high side pressure, it has been shown that the main compressor IGVs have a more effective control. For this reason, the main compressor IGV position is used to close the loop on system high side pressure.

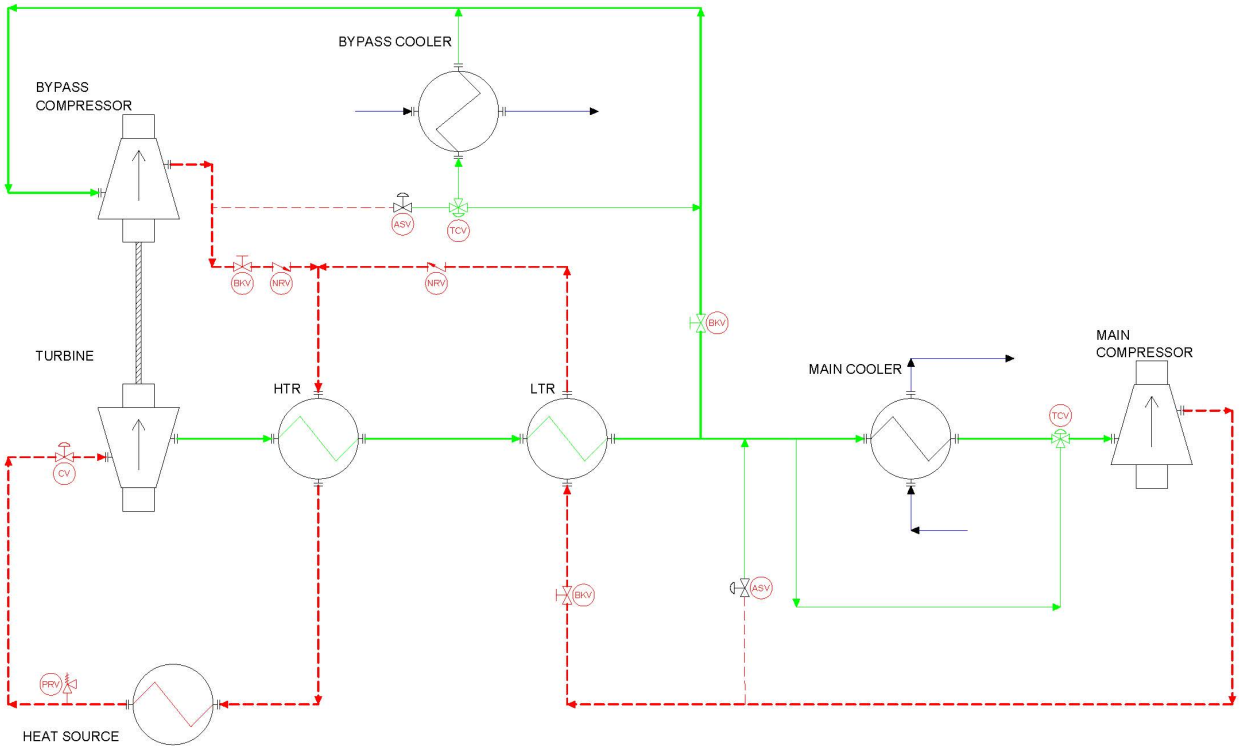

Figure 2: The System High and Low Side Pressures during Steady State Operation. The Dashed Lines Shown in Red Represent the High Pressure While Solid Green is Low Pressure.

Mass Flow Split Fraction

For any high side pressure, as controlled by the main compressor IGV, the bypass compressor IGVs have been sized to allow for multiple possible solutions while maintaining parallel operation. This additional degree of freedom allows the bypass compressor IGV to be used to control the mass flow spit fraction. Mass flow split fraction is defined as the mass flow rate through the bypass compressor relative to the combined mass flows of bypass and main compressors. This variable has a large influence on the system's recuperation and can be used to optimize system performance.

Main Compressor Suction Temperature

During steady state operation, the main compressor inlet temperature will be controlled via a main cooler CO_2 bypass line and a three way temperature control valve (TCV). This requires the cooler leg to be cooled below the desired main compressor inlet condition. The bypass cooler will not be utilized during steady state operation.

Low Side Pressure

With process temperatures and high side pressure controlled by other variables, the system mass will be closely tied to low side pressure. An Inventory Management System (IMS) will control the low side pressure [3]. This will be achieved by adding mass on the low pressure side of the loop or removing mass from the high pressure side.

Additional Control Variables

The turbine control valve and both compressor anti-surge valves are other critical process variables that are not included in closed loop controls during steady state, grid connected operation. These variables play a large role in system transients, however.

EQUIPMENT PROTECTION

Critical process variables, including pressures, temperatures, vibrations, and speed, are monitored around the loop by the DCS for operator information and automated trips. The trip levels for specific process variables are carefully determined to not only protect the specific piece of equipment, but also prevent a cascaded failure. Each of the primary pieces of equipment in the loop has dedicated hardware that allows it to promptly shut down and to avoid cascaded failure modes.

Main Compressor

The primary concern for the main compressor is surge. An anti-surge valve has been designed as the primary recycle valve to ensure the system resistance can be lowered quickly enough to avoid surge during rapid transients or process upsets. The compressor discharge flow rate and inlet/outlet pressure and temperature will be instrumented and monitored for surge avoidance. The main cooler and suction temperature control play a critical role in maintaining suction temperature during prolonged operation in recycle. Additionally, the main compressor's variable IGVs allow a wide range of safe operation outside of surge and choke.

Bypass Compressor

Similar to the main compressor, the bypass compressor is primarily concerned with surge. The bypass compressor also has a dedicated anti-surge valve as the primary recycle valve with similar instrumentation to monitor surge. While in recycle, the bypass compressor will also use the bypass cooler during prolonged recycle to manage inlet temperatures with a diverting three way valve. The bypass compressor variable IGVs also expand the range of safe operation outside of surge and choke.

There are check valves, or NRVs as shown in Figure 1, downstream of each compressor's discharge. These check valves aid in parallel operation of the compressors by preventing one compressor from inducing surge in the other compressor. These check valves also help the anti-surge valves by stopping the backflow of a large volume of high pressure fluid during emergency trips. The bypass compressor also has an isolating block valve, or BKV as shown in Figure 1, on the suction side of the loop. This isolating valve aids in start-up, but also allows the bypass compressor to be isolated from the main compressor if deemed necessary during emergency shutdown.

Turbine

The primary protection for the Turbine is the Control Valve, or CV as shown in Figure 1, that is close coupled to the suction. This valve has been designed for throttling control as well as fast acting isolation. The valve is responsible for speed control of the turbine shaft and will protect the turbine from overspeed events.

Heater

The heater will have a pressure release device, or PRV as shown in Figure 1, immediately downstream of the exit. This valve will protect the heater from over-pressure events.

Dry Gas Seals

The compressors and turbine use Dry Gas Seals (DGS) which require a constant supply of CO_2 above low side pressure for sealing. The IMS has been designed to provide continuous and passive back-up DGS supply in emergency scenarios, including seal supply boosters for settle out events [3].

CHALLENGES

There are two primary concerns when tripping a piece of equipment in a closed loop: temperature migration and settle out pressure. The piping and equipment from the HTR high pressure section back to the HTR low pressure section have been carefully designed for the high temperature application of greater than 700°C [4]. The other components and piping around the loop have not been designed to this high temperature to reduce the risk of high costs due to over-designed components. Therefore, it is critical that controls be implemented to protect the low temperature equipment. Similarly, low pressure equipment and piping identified in Figure 2 are not rated to full compressor discharge pressure. Before controls can be implemented, it is critical to understand what cases would cause a temperature migration or elevated pressure.

Temperature Migration

Multiple scenarios can lead to the migration of high temperature CO_2 to components that are not rated for the full temperature of the cycle. Any rapid change in CO_2 mass flow through the heater will quickly increase the heater outlet temperature to levels beyond the rating of the downstream piping and turbine. For most RCBC testing, “a range of about 30-36% flow split to the bypass compressor is optimal” [2]. This means that if either compressor were to rapidly enter recycle through the ASV for surge avoidance or otherwise, the mass flow through the heater would drop substantially, introducing the risk of over-temping. Additionally, if the turbine performance were to drop off due to throttling of the turbine CV or a decrease in speed, the Turbine would extract less of the energy from the CO_2 and the exit temperature would quickly rise, subjecting downstream components to elevated temperatures

Low temperatures can also pose a risk to the system. The Turbine, in particular, is at risk for shock cooling. If the Turbine casing has been fully heat soaked at conditions in excess of 700°C and the heater trips, relatively cold fluid would be forced through the casing, imposing excessive thermal stress on the equipment. Therefore, if the heater trips at or near the design point, the Turbine must be protected from this cold flow. After this hot shutdown event, the DGS supply to the Turbine must also be reduced to a minimum flow rate so as to not shock cool the casing. The Main Compressor is also at particular risk of a low temperature transient due to its proximity to the critical point at steady state conditions. If the inlet temperature of the Main Compressor were to drop below the critical point of 31°C there is an increased risk of liquid formation at the impeller along with drastic swings in fluid density. These droplets and swings in density are dangerous for the impeller and could quickly cause damage.

Settle Out Pressure

The entire system will reach a single settle out pressure if the turbomachinery is allowed to coast down to 0 RPM without rapidly closing the turbine CV. This uncontrolled settle out pressure is above the design pressure of many of the components, and piping runs on the low pressure side of the loop, if it is initiated from the steady state points identified for RCBC [[2], [5]]. This single high settle out pressure, however, can be segregated into two sections with the use of the check valves on the compressor discharge legs and a rapid closure of the turbine CV. Isolating, fast acting block valves are used upstream of the check valves for redundancy. This segregated settle out condition is depicted in Figure 3. The high pressure section identified in dashed red below also effectively traps the high temperature fluid, limiting the temperature migration beyond components that are rated for this condition. This hot bottle up scenario becomes imperative for equipment protection any time the full system settle out pressure exceeds the pressure rating of the components on the compressor suction side or the heater has achieved a temperature beyond the ratings of components downstream of the turbine.

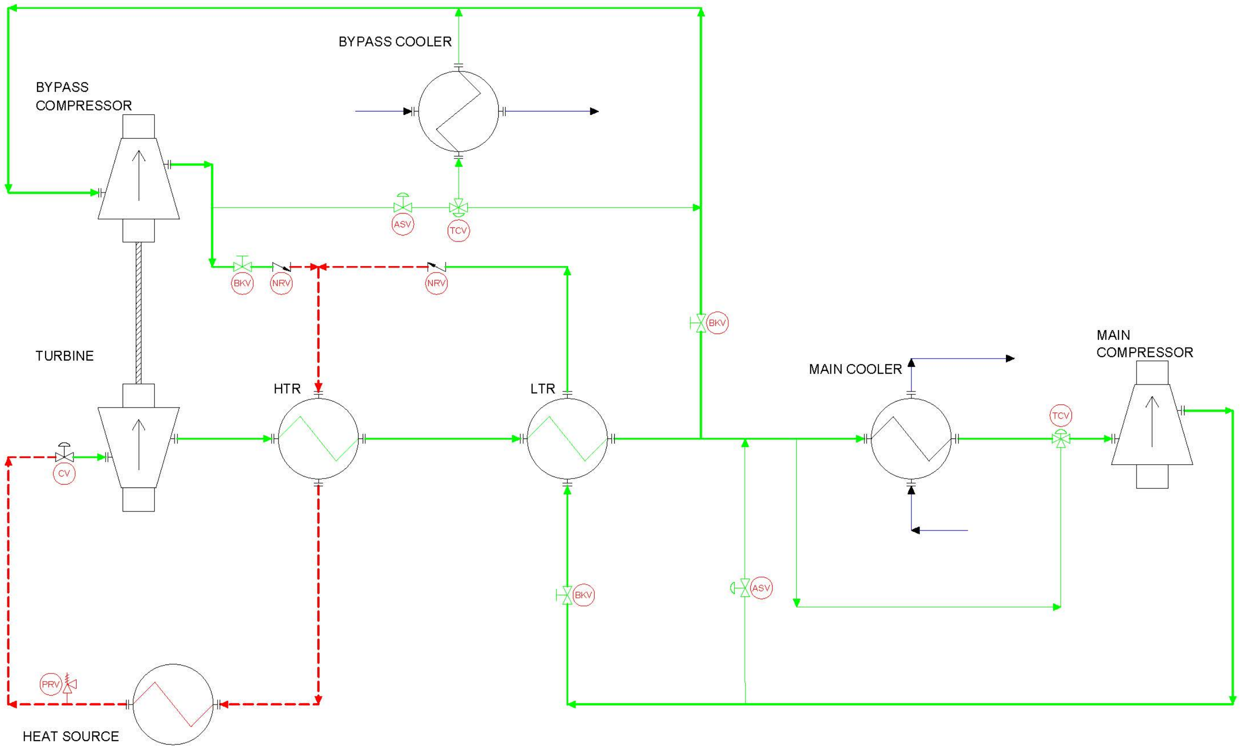

Figure 3: The System High and Low Side Pressures After Rapid Closure of Turbine CV. The Dashed Lines Shown in Red Represent the High Pressure While Solid Green is Low Pressure.

SYSTEM SHUTDOWNS

The DCS will use automated trip sequences to protect the equipment from the challenges discussed above. The main compressor, turbine, and heater trips result in the same shutdown sequence. This sequence has been defined as a Level 1 (L1) trip. During a L1 trip, the main compressor remains at full speed in full recycle. This is the only difference to the main compressor trip where the motor is commanded to zero speed. This main compressor shutdown sequence is defined as a Level 2 (L2) trip. After a L1 trip, the main compressor is left at full speed in full recycle while the operators diagnose the trip condition. This allows for a prompt restart if possible. Otherwise, the main compressor can be shut down. During a L1 trip, the bypass compressor is isolated with the BKV and allowed to spin down with the turbine.

Main Compressor Trip – L2

The following actions will be taken by the DCS if the main compressor initiates a trip:

- Trip the turbine by closing the turbine CV
- Trip the heater by closing the fuel control valve
- The anti-surge controller will open the ASV to avoid surge in the main compressor
- Trip the main compressor motor
- The anti-surge controller will open the ASV to avoid surge in the bypass compressor
- Isolate the high temperature section by closing both BKVs upstream of check valves
- Isolate the bypass compressor suction with BKV
- When the turbine speed reaches 0 rpm, reduce DGS flow rate

Turbine, Bypass Compressor, or Heater Trip – L1

The following actions will be taken by the DCS if the turbine, bypass compressor, or heater requires a trip:

- Trip the turbine by closing the turbine CV
- Trip the heater by closing the fuel control valve
- The anti-surge controller will open the ASV to avoid surge in the main compressor (note that the main compressor maintains its speed setpoint)
- The anti-surge controller will open the ASV to avoid surge in the bypass compressor
- Isolate the high temperature section by closing both BKVs upstream of check valves
- Isolate the bypass compressor suction with BKV
- When the turbine speed reaches 0 rpm, reduce DGS flow rate

CONCLUSION

The sCO_2 RCBC has great potential to increase the state of the art in thermodynamic efficiency. To realize this efficiency benefit, however, the closed loop dynamics need to be closely studied with conservative measures in place for protection. Each piece of equipment, many of them novel in their design, are already being pushed to their design limits at the steady state operating points. This provides very little margin on transients which are rapid and cascading in the closed loop. The DCS must be able to respond in a reliable fashion that allows for the system to return to a safe state. Passive equipment protection needs to be implemented where possible with automated controls where it is not. Understanding the effect of independent variables on the system is inherent in designing these conservative shutdown sequences.

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