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Evaluation on the rapidity of sCO2 cycle power up and down events using the STEP dynamic simulation model

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ABSTRACT

The $STEP_{USA}$ dynamic simulation model was successfully used to predict transient shut down and start up events in a sCO2 Recompression Brayton Cycle (RCBC) cycle power plant. The dynamic simulation model was developed to support design and operation of the 10 MWe supercritical CO2 $STEP_{USA}$ Demo pilot plant in San Antonio, TX which GTI Energy is leading with prime funding from U.S. DOE and many project partners. The start-up and shutdowns simulated are intended to be indicative of the ability of a sCO2 energy conversion system to closely follow potential quick startup and shutdown power generation patterns expected for a power plant in planning by the United Kingdom Atomic Energy Authority (UKAEA). The system shutdown takes less than five minutes paced by the inertia of the rotating equipment. The shutdown puts the system into a hot standby condition. Start up to power from hot standby takes less than 5 minutes paced by the rotating inertia of the turbine and compressors. This paper discusses the dynamic model of the $STEP_{USA}$ plant, limitations on rapid power & temperature changes found in start-up and shutdowns and shows simulation results.

INTRODUCTION

Fusion energy is often described as the "holy grail" of power generation. Fusion energy holds the promise of clean, sustainable, and predictable power which could be the ultimate energy solution, globally. Fusion can be thought of as the opposite of fission – combining lighter atoms rather than splitting heavier ones.

The United Kingdom Atomic Energy Authority (UKAEA) researches fusion energy and related technologies, with the aim of positioning the United Kingdom (UK) as a leader in sustainable nuclear energy. UKAEA is an executive non-departmental public body, sponsored by the Department for Energy Security and Net Zero within the UK government.

Spherical Tokamak for Energy Production ($STEP_{uk}$) is a project currently being pursued by UKAEA. The $STEP_{UK}$ project seeks to "deliver a UK prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion". This project will be performed in 3 phases. The first of the three phases seeks to develop a concept design for a first of a kind prototype power plant by 2024. The following phases will be focused on maturing the design and constructing the power plant.

The $STEP_{UK}$ prototype power plant relies on a fusion energy device to provide thermal heat. This thermal heat will then be converted into electrical power using a thermodynamic cycle. This thermodynamic cycle must be both flexible and highly efficient. The fusion energy device producing thermal heat is a Spherical Tokamak. The Spherical Tokamak is variant of the conventional tokamak which seeks to magnetically confine a high temperature plasma that enables fusion of two hydrogen isotopes maximizing energy yield.

The sCO2 thermodynamic cycle is currently being investigated as a technology which can add a number of benefits that can be advantageous to $STEP_{UK}$. One benefit is the potential ability for the sCO2 cycle to be more adaptable in dynamic scenarios.

In 2022, UKAEA commissioned GTI Energy to use their dynamic model to further understand key dynamic aspects of an sCO2 cycle.

Dynamic modeling of a Recuperated Brayton Cycle version of a sCO2 cycle was performed to investigate how well the power cycle electrical generation profile could follow a power input with rapid shutdowns followed by startups shortly thereafter. The $STEP_{USA}$ digital twin (dynamic simulation model) was used as the starting point and was shown to work well. The model was created by GTI Energy to support design and operating planning for the $STEP_{USA}$ (Supercritical Transformation of Electrical Power) sCO2 Facility. This is a 10 MWe net sCO2 Brayton test facility on the Southwest Research Institute (SwRI) campus in San Antonio, Texas. Modeling improvements were made to improve the understanding of the thermal transient impact on the High Temperature Recuperator (HTR). Further model improvements were identified.

The modeling provided temperature, pressure, and flow conditions for the sCO2 cycle components throughout the simulated events. The thermal transients were evaluated against limits of the existing $STEP_{USA}$ components as being indicative of limits for other plants.

RESULTS AND DISCUSSION

Fusion power plants

Fusion power generating challenges

There are distinct and unique variants of fusion machine designs. Nonetheless, as a thermal power source these devices (including the $STEP_{UK}$ device), typically pose several challenges:

- Significant parasitic loads and demand for high efficiency
- Rapid, frequent, and significant transience (linked to pulsed machines and the nature of plasma generation)
- Integration of different grades of heat
- Commercial and economic viability

Fusion power generation systems

Governmental and private fusion entities are investigating the feasibility of fusion power plant concepts. Many of these include the use of dedicated power generation systems. The paradigm for fusion power generation systems has remained the steam Rankine cycle for multiple decades.

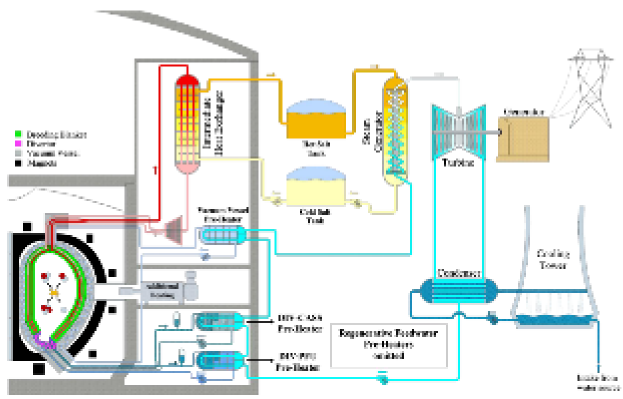

Figure 1: Overview of the HCPB ICD BoP using steam Rankine cycle configuration [1]

The advancement in the sCO2 Brayton technology has opened up new possibilities for modern concepts evaluating the generation of power from a fusion heat source. While the TRL of this power generating technology is low, there are some distinct differences when compared to a steam Rankine cycle which makes the sCO2 technology compelling and competitive; by uniquely addressing the challenges listed [5].

Among other advantages the sCO2 cycle offers distinct benefits regarding the following aspects of fusion energy power generation:

- High efficiency at elevated operating temperatures
- Highly responsive and able to operate with rapid transience
- Able to integrate heats at different grades
- Compact and competitive

UKAEA's STEP is a unique program seeking to generate net power on the grid, targeting 2040. This program has evaluated multiple cycle technologies to understand how power may be generated. The program continues to assess these cycle technologies for their benefits and drawbacks.

Fusion power plant dynamics

One key aspect that UKAEA wished to explore was the ability for the sCO2 cycle to handle rapid transience of the fusion heat source at a power plant scale. There are multiple reasons for this:

1. Rapid start up shut down

The fusion heat source is expected to start up and shut down very rapidly. This is linked to the physics of the plasma contained within the Spherical Tokamak and a desire to limit the amount of time whereby the fusion power plant "recirculation power" (electrical load) is supplied (and purchased) from the grid. The Spherical Tokamak will generate thermal power in a much more rapid manner compared to traditional heat sources (coal or fission power plants) – and it will do so in an uncontrolled manner. This is a cause for concern when considering the incumbent Steam Rankine cycle which can notoriously take up to several hours to start up [6] with a steady ramp up profile.

Being able to rapidly start generating power and limiting the time period between plasma start up (aka plasma burn) and internal power generation is incredibly valuable to any fusion power plant designer as can be seen in the following figure:

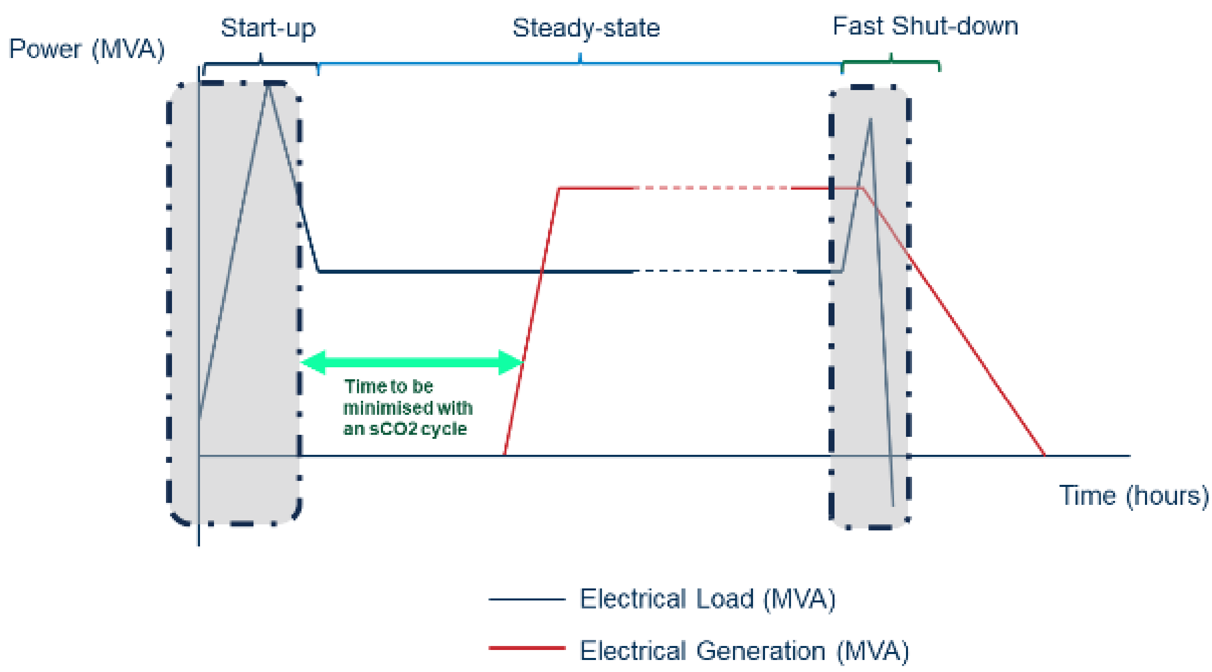

Figure 2: Fusion power plant load profile and generation profile

2. Pulse power

Fusion devices (such as JET) currently operate in pulsed power modes. The length of pulse achievable will vary between machines, as will the dwell time between pulses. The ITER device will demonstrate longer pulses (circa 15 minutes), and ultimately the European DEMO program expects to operate with pulse times around 2 hours. The pulse time for $STEP_{uk}$ is undefined at the time of writing, however the Spherical Tokamak plasma physics does *theoretically* enable the plasma to run indefinitely. While a worthwhile goal, running a plasma indefinitely is highly ambitious, hence the $STEP_{uk}$ program anticipates some degree of pulse/dwell operations for its initial prototype machine. This highly dynamic system requires a power generation system which in turn is highly responsive and can manage both these rapid startups and shutdowns as well as multiple cyclical operations.

3. Prototype machine

The $STEP_{uk}$ power plant to be operational in the 2040s will be a first of a kind *prototype* power plant. Hence, it is expected that this prototype plant will operate with many trips both within the reactor and within the plant. Frequent losses of the thermal source, as a result of a trip or other conditions is expected. Hence, there is a need for a power generating system which can manage these, potentially frequent, trip events, and ideally recover from them easily.

The requirement for a power generating system which can handle highly dynamic scenarios is critical to a responsive power plant. While this can be managed with the incumbent steam Rankine cycle (when other systems are included such as molten salt thermal storage – this is akin to the DEMO design), it was the ambition of UKAEA to understand just how an sCO2 cycle could address these dynamic requirements.

RCBC sCO2 Cycle Model Description

$STEP_{USA}$ Description

The $STEP_{USA}$ sCO2 Facility is a 10 MWe net sCO2 Brayton test facility on the Southwest Research Institute (SwRI) campus in San Antonio, Texas, Figures 3 & 4. The effort to design, construct, and build this facility has been led by GTI Energy and funded by the U.S. Department of Energy (DOE), National Energy Test Laboratory (NETL). The objectives of this project and for this facility are to demonstrate the operability of the sCO2 cycle, verify the performance of components (turbines, recuperators, and compressors, etc.), show the potential for producing a lower cost of electricity in relevant applications, and demonstrate the potential and pathway for a thermodynamic cycle efficiency greater than 50% in large scale (100 MWe and greater) power generation applications [2].

Steady state modeling has been performed for both the Simple Cycle and Recompression Brayton Cycle (RCBC) configurations of the facility [3]. The RCBC configuration utilizes two compressors in parallel to increase cycle efficiency. The purpose of the steady state model was to provide the input for the technical specifications for each equipment unit in the facility to ensure successful targeted performance operation. Sizing and optimization of the components were based on the design point case of a 10 MWe RCBC cycle configuration with 715°C turbine inlet temperature. The RCBC sized components were then used in the off-design cases for both the RCBC and simple cycle configuration to determine the range of boundary conditions for each equipment unit so that the procured equipment would meet these specifications. Since testing will first be done in the simple cycle configuration, followed by reconfiguration to the RCBC configuration, the equipment needed to work for both configurations, with optimization for the design point case.

Transient modeling is being performed for each configuration of the facility using the Flownex program [4]. The purpose of the transient model (digital twin) is to provide numerical results to aid in the operational analysis of the test facility. Transient operations, such as startup, shutdown, load level changes from 10 MWe to ~5 MWe and back, etc. are modeled. Control loop algorithms have also been incorporated to support definition of the distributed control system (DCS) requirements. Results of the transient model help determine best control methodologies for the facility.

Figure 3: $STEP_{USA}$ facility building (middle), cooling towers (right), heater and stack (middle), load banks (left)

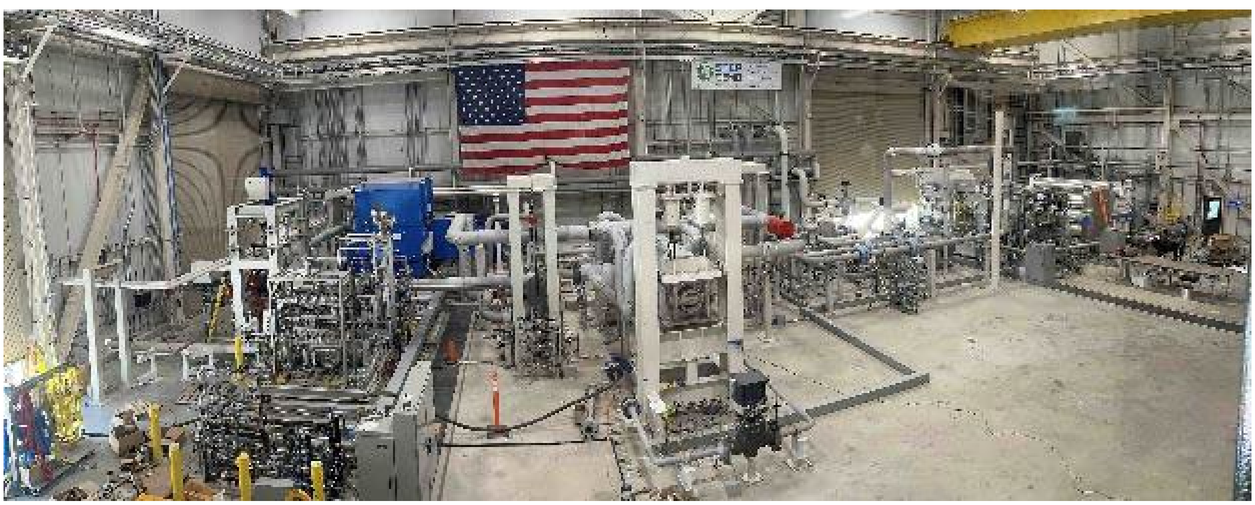

Figure 4: Power cycle equipment

Flownex Model Description

A simplified diagram of the $STEP_{USA}$ RCBC configuration is shown in Figure 5 below. In the RCBC configuration, sCO2 is heated in the heater to desired conditions for that experimental case. The sCO2 passes through the turbine stop and control valve (TSV) and is then expanded through the turbine. Heat is recovered in the high temperature recuperator (HTR) and the low temperature recuperator (LTR) before the flow is split to the main compressor or the bypass compressor. The flow split controller is connected to the bypass compressor IGV; by changing the IGV position and thus the flow from the bypass compressor the ratio of the flows is controlled. The main compressor is driven by a Variable Frequency Drive (VFD) electric motor to control the speed of the compressor, and the bypass compressor is driven directly by the turbine. Since the bypass compressor and turbine are connected to a gearbox and the generator all on the same shaft, this shaft has roughly five times the inertia compared to the main compressor shaft driven by an independent motor. Prior to entering the main compressor, the sCO2 is cooled in the main cooler. Prior to entering the bypass compressor, the sCO2 can flow through the bypass cooler or around the bypass cooler. Bypass loops, which include the flow path from the compressors to the recycle valves and through the coolers, are provided for both compressors to allow for them both to be started independently, as well as to provide anti-surge protection. The exit stream of the main compressor then flows through the LTR where it mixes with the discharge of the bypass compressor. The mixed stream flows through the HTR and then re-enters the heater.

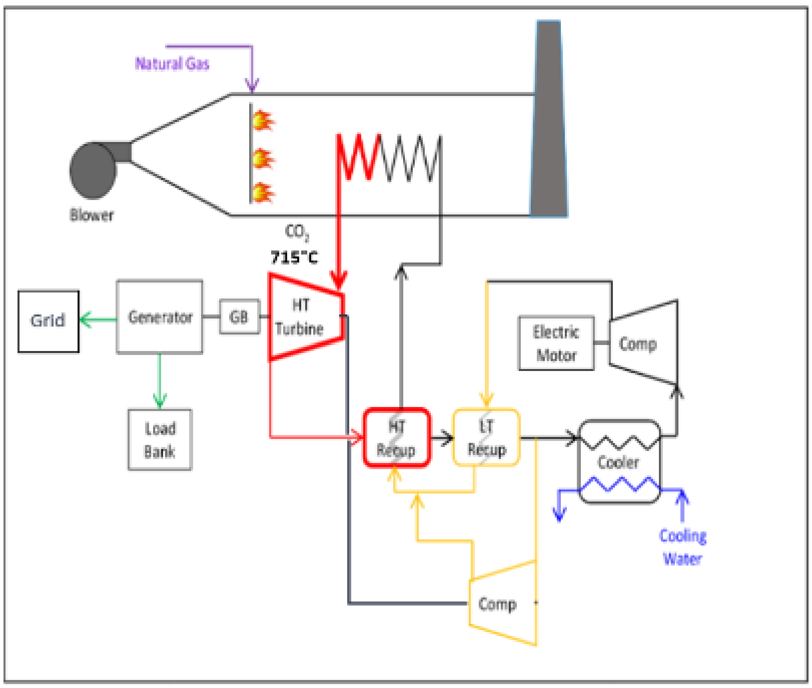

Figure 5: Simplified diagram of recompression Brayton cycle configuration [2]

The property method chosen for the dynamic model is REFPROP, which is the best property method available for calculating sCO2 properties at temperatures and pressures required for high efficiency Brayton cycles. The main area of concern in terms of accurately predicting properties is upstream of the main compressor, in which the operating conditions are extremely non-ideal. REFPROP is the most accurate in predicting properties in this region.

Component geometries from vendor datasheets and operational constraints have been incorporated into the model. Individual component models have been benchmarked against vendor predicted performance data. Custom models have been built for the recuperators that incorporate adjusted heat correlations to align with the vendor predicted results. Results from the individual component models align well with vendor predicted performance. Results from modeling have been used to guide overall control logic and methodology. Validation of the model on a system level will be performed with the data from the facility during testing.

RCBC Modelling Results – Start-up & Shutdown

The following section describes the modelling (digital twin) results for the two event simulations of $STEP_{USA}$ developed in support of $STEP_{UK}$. The simulation starts at the normal operating condition, followed by a shutdown of the heat source for its one hour powered down period and shutdown of the sCO2 power system. The shutdown is similar to a system trip where the heater shuts off and the TSV closes quickly causing the hot, high-pressure CO2 in the region of the heater to become bottled up. Once the system is shutdown, it is in a standby hold condition for approximately one hour, after which the system is re-started to the full power normal operating condition while keeping plant equipment within operating limits.

Shutdown from normal operating condition (roughly 700°C/250 bar turbine inlet, 35°C/86 bar main compressor inlet)

In the simulation, shutdown from the normal operating conditions starts with the $STEP_{USA}$ gas fired heat source, heat input side ramping down from full flow to zero flow over one minute. It was found that the heat source shutdown must lead the shutdown of the other components to avoid the CO2 flow through the heat source stopping first causing the heater heat exchanger metal to increase in temperature. This is not desirable as it causes the CO2 to increase in temperature during restart and leads to the HTR inlet metal temperature increasing above its design limit of 600°C. Once the heat source, heat input side flow has stopped, the system continues to run and produce power for 90 seconds, which allows the heat source metal temperature to cool down.

Figure 6 shows the CO2 temperatures throughout the system. The turbine inlet temperature is initially at 700°C. The heater starts to shut down and flow decreases starting at t=60 seconds and ending at t=120 seconds, the heat source heat input side was kept at 855°C to model an indicative boundary condition of a fusion energy application. The system continues to run and the CO2 at the turbine inlet decreases to 625°C before shutdown of the remainder of the system begins. During the turbine spin down, the dry gas seal flow to the turbine was increased from its normal operating temperature of 70°C to 630°C which is an average of the turbine pipe wall temperatures. This was done since the Flownex model does not have sufficient fidelity of the dry gas seal flow passages and heat transfer through the turbine, nor does Flownex calculate diffusion, which caused the turbine inlet temperature to initially drop and then later rise due to heat transfer from the pipe walls. To avoid confusion and better represent reality, the change was made resulting in the gradual decrease of the turbine inlet temperature.

Figure 7 shows the CO2 pressure throughout the system. The turbine inlet pressure is initially around 250 bar. Once the heater is shutdown, the pressures start to decrease until the remainder of the system shuts down. Once the compressors spin down, the high outlet pressure decreases, and the system reaches a settle out pressure. The high pressure between the turbine stop valve and check valves can be seen with the grey data points.

The net electric power output, which is the turbine shaft power minus the main compressor and bypass compressor shaft power multiplied by the shaft, gearbox, and generator efficiencies. As the turbine inlet temperature decreases from 700°C to 625°C the turbine power output decreases from 12 MWe to 10.7 MWe. After that it decreases quickly as the turbine stop valve closes and the turbine ceases to generate power.

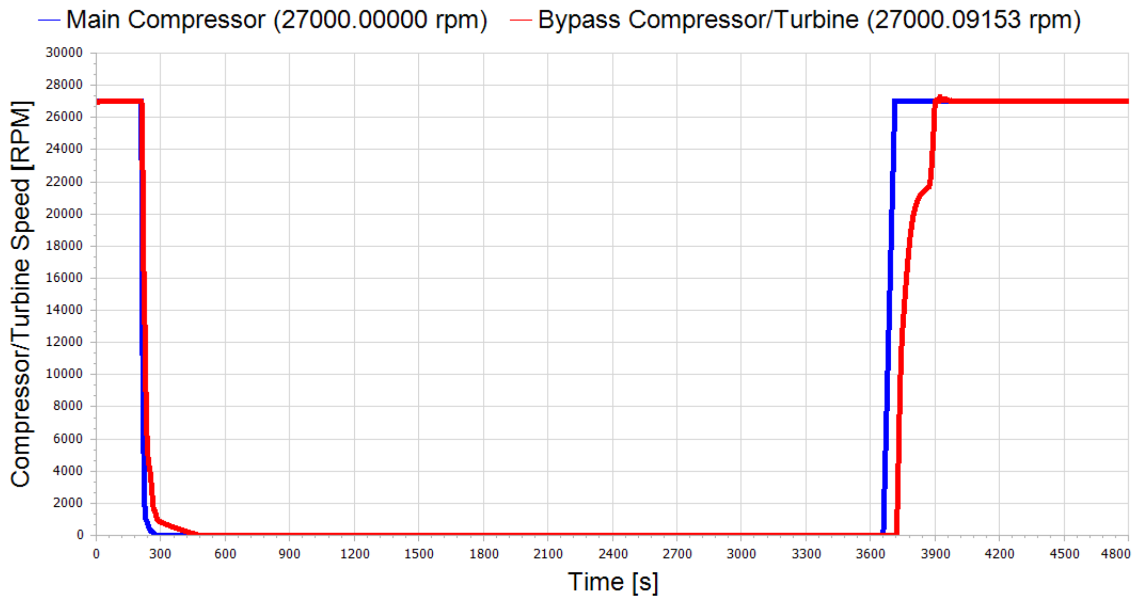

Figure 6: Main compressor and turbine/bypass compressor shaft speed

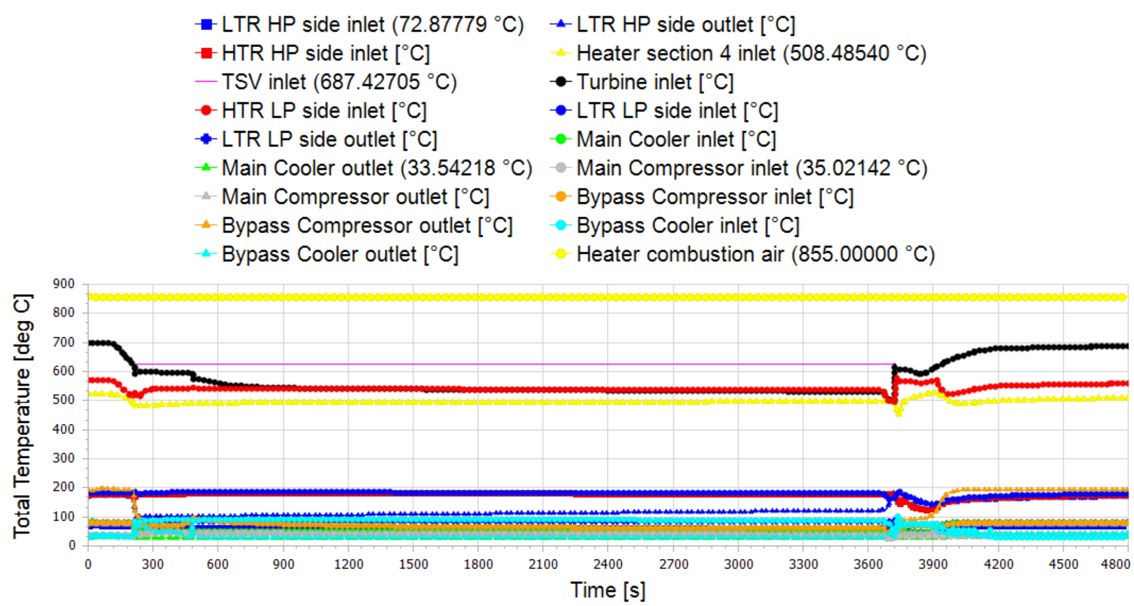

Figure 7: CO2 temperatures throughout the system

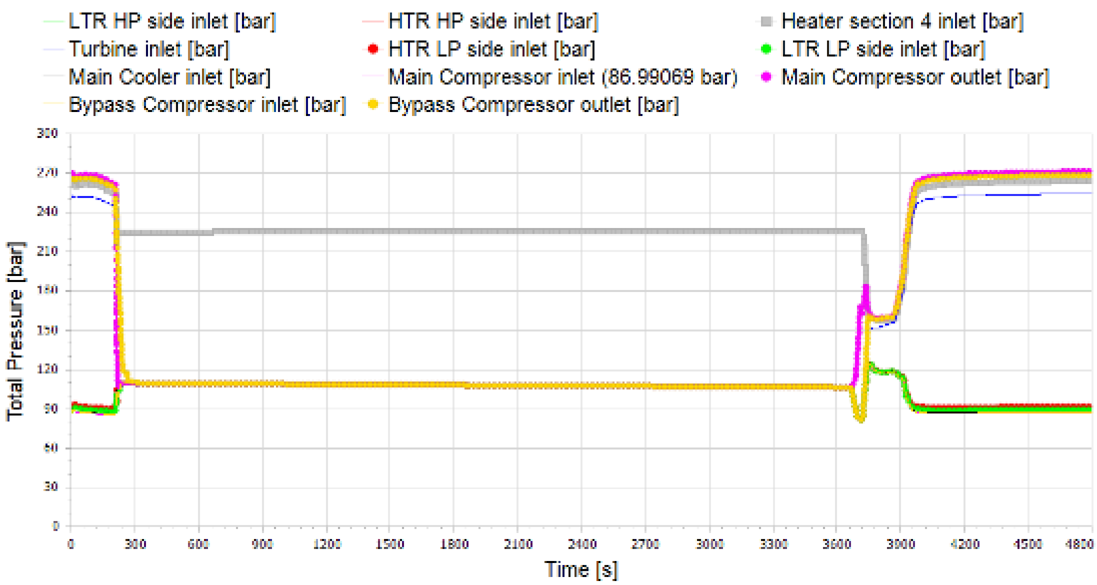

Figure 7: CO2 pressures throughout the system

System changes during 1 hour shutdown

During the one-hour shutdown, there is no CO2 flow. Due to diffusion within the CO2, we would expect heat in the CO2 to migrate from higher to lower temperature areas. However, the Flownex modelling software does not have this capability, so temperature differentials of CO2 along pipe lengths will not be shown to decrease as might be expected.

During shutdown, the major source of heat transfer in the model is from convection and conduction from the CO2 through the pipe walls and insulation to atmosphere. Once the system is shut down around t=300 seconds, there is a general decrease in pipe inner wall temperatures as heat is transferred out to the ambient environment. Pipe temperatures at the outlet and inlet of the heater and the outlet of the turbine all decreased about 27°C, the pipe from the HTR to the LTR decreased 7°C, and the pipe from the LTR to the HTR decreased 4°C.

Start-up from the shutdown condition

Start-up from the shutdown condition is achieved by ramping the main compressor back up to full speed, followed by the turbine stop valve slowly opening starting at t=3720 seconds. The high-pressure CO2 then flows through the turbine and starts to spin the turbine/bypass compressor shaft, achieving a speed of slightly less than 22,000 RPM shown in Figure 6. The net power up ramp follows the command to start up by about three minutes. As seen in Figure 7, the high-pressure CO2 pressure starts to decrease as it flows through the turbine. When the main and bypass compressor outlet pressures exceed the decreasing pressure on the opposite side of their respective check valves upstream of the HTR, the check valves open allowing flow to the HTR. This brings the turbine speed up to 27,000 RPM, at which point the generator starts to control the shaft speed and generate power as seen in Figure 8. After these actions, the CO2 and metal temperatures continue to increase until they again reach their steady state values, which would be slightly longer than this simulation, which stops at time t=4800 seconds, shows.

Components seeing the highest thermal transients were evaluated against their limits. HTR hot side (low pressure) wall temperatures were evaluated to determine maximums and ramp rate during the startup transient. To avoid going over the 600°C metal temperature limit during re-start, for shutdown the system was allowed to cool slightly by first turning off the heater, followed by the remainder of the system. The rate at which the HTR bulk metal temperature increases during re-start, which should be limited to about 7°C/minute. A more detailed HTR thermal model was built into Flownex to analyze bulk metal temperatures. This provided a bulk metal temperature change of 428°C to 444°C in two minutes, or about 8°C/minute which is slightly above the limit but with a small temperature increase of only 16°C this is acceptable. From the restart period when the turbine starts to gain heat again from t=3885 seconds to t=4200 seconds, the turbine inlet pipe wall temperature increases from 614°C to 676°C, or a rate of 12°C/minute, which is less than the 23°C/minute metal temperature rate limit for the turbine.

Impact of study conclusions on sCO2 cycles

The results of the work documented here show the sCO2 cycle to be very responsive to input power transients including complete shutdown and startup when the intervening shutdown interval is an hour or somewhat more. The sCO2 system shutdown can put the system into a hot standby condition. During the hot standby hold system temperatures fall slowly as heat is conducted through insulation to the environment. This allows start up to power to take less than 5 minutes for a 10 MWe size plant paced by the rotating inertia of the turbine and compressors.

The $STEP_{USA}$ dynamic simulation model is a valuable tool for powerplant design & evaluations. The model can be the starting point for a large power plant sCO2 system model and should be used to explore the changes on plant startup time due to the higher rotating machine inertia found in larger plants. Continuous model improvement, including validation with data from $STEP_{USA}$ operation, will be pursued to make the model even more useful.

Component procurement specifications should include the transient environment. Thus, dynamic modeling must be done early in the sCO2 cycle power plant design process.

Impact of study on CO2 cycle applications in fusion

The study has shown that sCO2 cycles lend themselves well to fusion energy applications based on rapid transient performance. A sCO2 cycle is a robust system that can start up and shut down in much shorter timeframes than the steam Rankine cycle typically chosen for this application. With an sCO2 cycle, auxiliary equipment on the fusion power plant such as thermal storage which might otherwise be used to support a rapid plant startup can be dramatically reduced or even removed altogether, depending on the thermal inertia of the coolant and thermodynamic systems.

There will also be significant component analysis required to support rapid plant transients before a power plant scale system can be made operational with a fusion plant system, specifically the stop valve and turbine.

Conclusions

The $STEP_{USA}$ digital twin (dynamic simulation model) was successfully used to predict transient shut down and start up events in the sCO2 cycle demonstration power plant. The start-up and shutdown simulated are intended to be indicative of the ability of a sCO2 energy conversion system to closely follow a pulsed input, steady state period at power, then one hour off power generation pattern, indicative of a fusion energy application. The system shutdown takes less than five minutes paced by the inertia of the rotating equipment. The shutdown puts the system into a hot standby condition. During the one-hour hot standby hold system temperatures fall slowly as heat is conducted through insulation to the environment. Start up to power from hot standby takes less than 5 minutes paced by the rotating inertia of the turbine and compressors. The command to start up leads the net power up ramp by about three minutes. A short period of negative power is seen due power draw by the start-up of the motor driven compressor which leads the turbine/generator in beginning operation. The profile of the power command signal and resulting verses time for these events on Figure 8 shows how well the system responds.

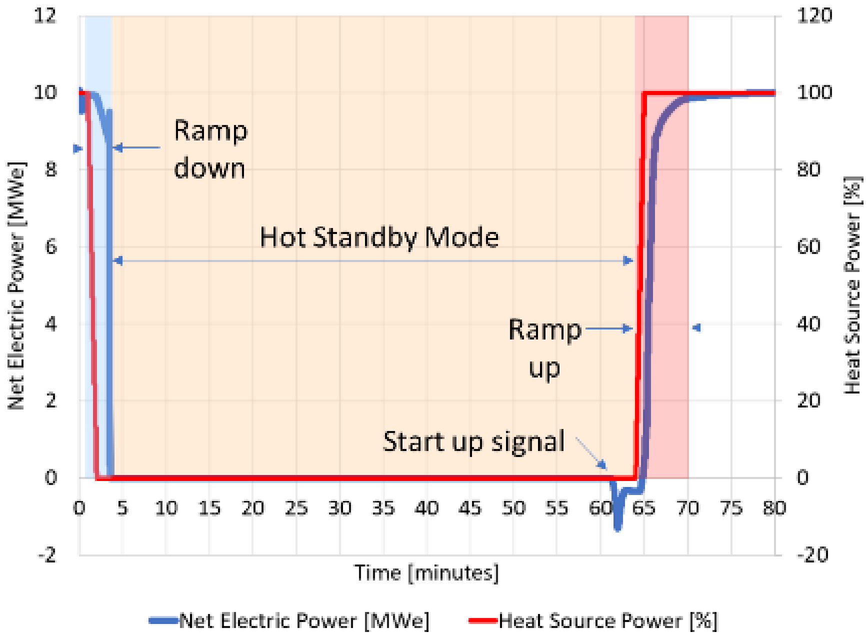

Figure 8: Rapid ramp rates of the $STEP_{USA}$ sCO2 power cycle effectively support fusion plant operation with one hour of standby time after steady state operation at power.

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