Transient oscillation phenomena during cool, pressurized start-up of sCO2 compressor

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ABSTRACT

Supercritical CO2 compressors are likely to be started in a pressurized condition. Depending on the pressure and temperature conditions before start up, there may be liquid CO2 in portions of the loop. Special start procedures must be utilized to vaporize the liquid in the loop. The DOE STEP 10 MWe Pilot Scale sCO2 Power Plant utilizes slow speed operation of the compressor to avoid damage from potential liquid droplets until conditions show that all liquid is gone. Data collected during pressurized start-up of the compressor show transient oscillations in discharge pressure and temperature that dampen out over time. This paper describes the observed phenomena and seeks to provide an explanation for the behavior.

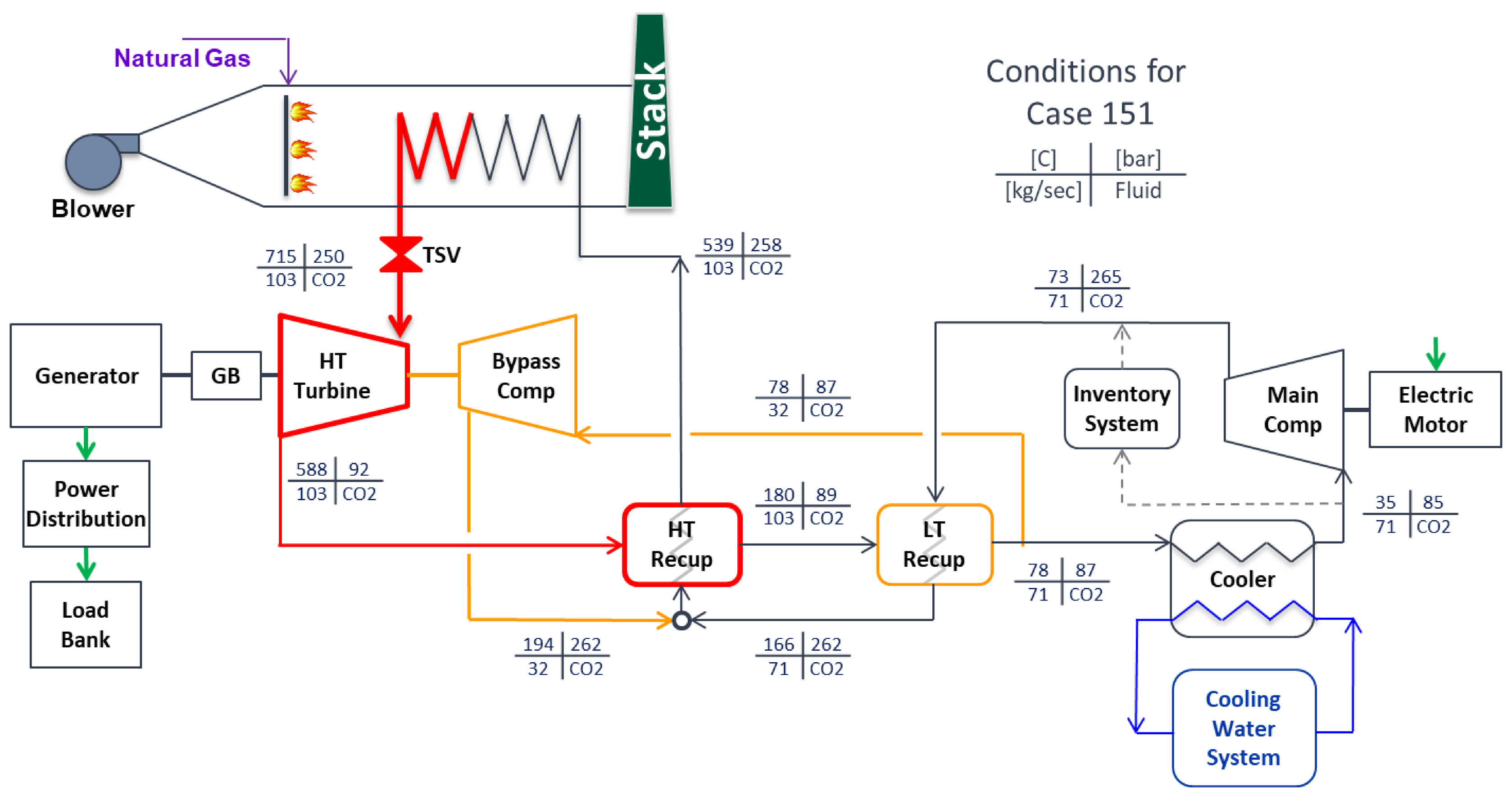
INTRODUCTION

Supercritical CO2 power cycles take advantage of the fluid properties of CO2 near the critical point to help maximize cycle efficiency. As conditions approach the critical point (for CO2, 31 degC and 73.8 bar), the density increases rapidly to near-liquid magnitude, and compressibility decreases. This lowers the required compression work to achieve a given pressure rise, increasing cycle efficiency. However, approaching the critical point is not without risk, as doing so also means approaching the liquid-vapor dome. If conditions cross into this dome, dense liquid droplets can form and wreak havoc on the compressor's high-speed rotating impeller, causing erosion, high vibrations, and loss of performance.

The plant control system must have means to prevent the formation of liquid CO2 during operation. When the plant is shut down or tripped while still pressurized, however, it is possible, and even unavoidable in certain conditions, to form liquid CO2 in certain sections of the system. Thus, when the plant restarts, there is risk of running liquid CO2 droplets or slugs through the high-speed rotating machinery.

The DOE STEP 10 MWe Pilot Scale sCO2 Power Plant utilizes a low-speed start up sequence, running the compressor first at 9,000 rpm to break up and vaporize liquid present in the loop before accelerating to its full 27,000 rpm operating speed. During several pressurized start-up instances of the compressor loop (full recycle) at the plant, compressor discharge pressure and temperature showed oscillatory fluctuations that slowly dampened out during the 9,000 rpm operation period. This poster aims to explain this phenomenon through careful examination of the data.

Figure 1 – STEP Recompression Brayton Cycle



RESULTS AND DISCUSSION

Figure 2 shows compressor discharge pressure, temperature, and flow rate alongside operating speed for one 9,000 rpm startup instance. Shortly after the compressor began to accelerate, flow rate and pressure increased while temperature decreased. When the compressor is at rest, the measured discharge temperature typically increases to the dry gas seal supply temperature of approximately 80 degC due to the fact that the discharge nozzle is pointed upward at an angle, and the warm seal gas leaking through the static seals enters the discharge pipe and encounters the temperature measurement locations. By the time the compressor reached 9,000 rpm, the effect of the trickle of warm seal gas had been overcome by the temperature of the now-flowing CO2.

Once the compressor reached a steady 9,000 rpm, significant oscillations became visible in the discharge conditions. These oscillations had a period of approximately 45 seconds and dampened out to negligibility in approximately six cycles.

Figure 3 shows the suction conditions for the same event. Note that there is a similar effect from the warm dry gas seal flow on the suction temperature as for the discharge temperature due to upward-facing suction piping. Prior to start-up, suction pressure is higher than the critical point. However, as the compressor begins to spin, suction pressure drops below the critical point. Plotting the data for this start-up on a p-H diagram (Figure 4) shows that the conditions in the suction piping very closely approached the vapor dome, but it does not appear that they crossed into the dome. It is possible that liquid is forming in the compressor inlet due to pressure drop from the inlet geometry after the suction piping temperature measurement. Even if liquid is not forming, Figure 4 still does show the magnitude of the changes in density – approximately doubling from prior to start up until the disappearance of the oscillations.

Figure 2 – Main Compressor Discharge Conditions

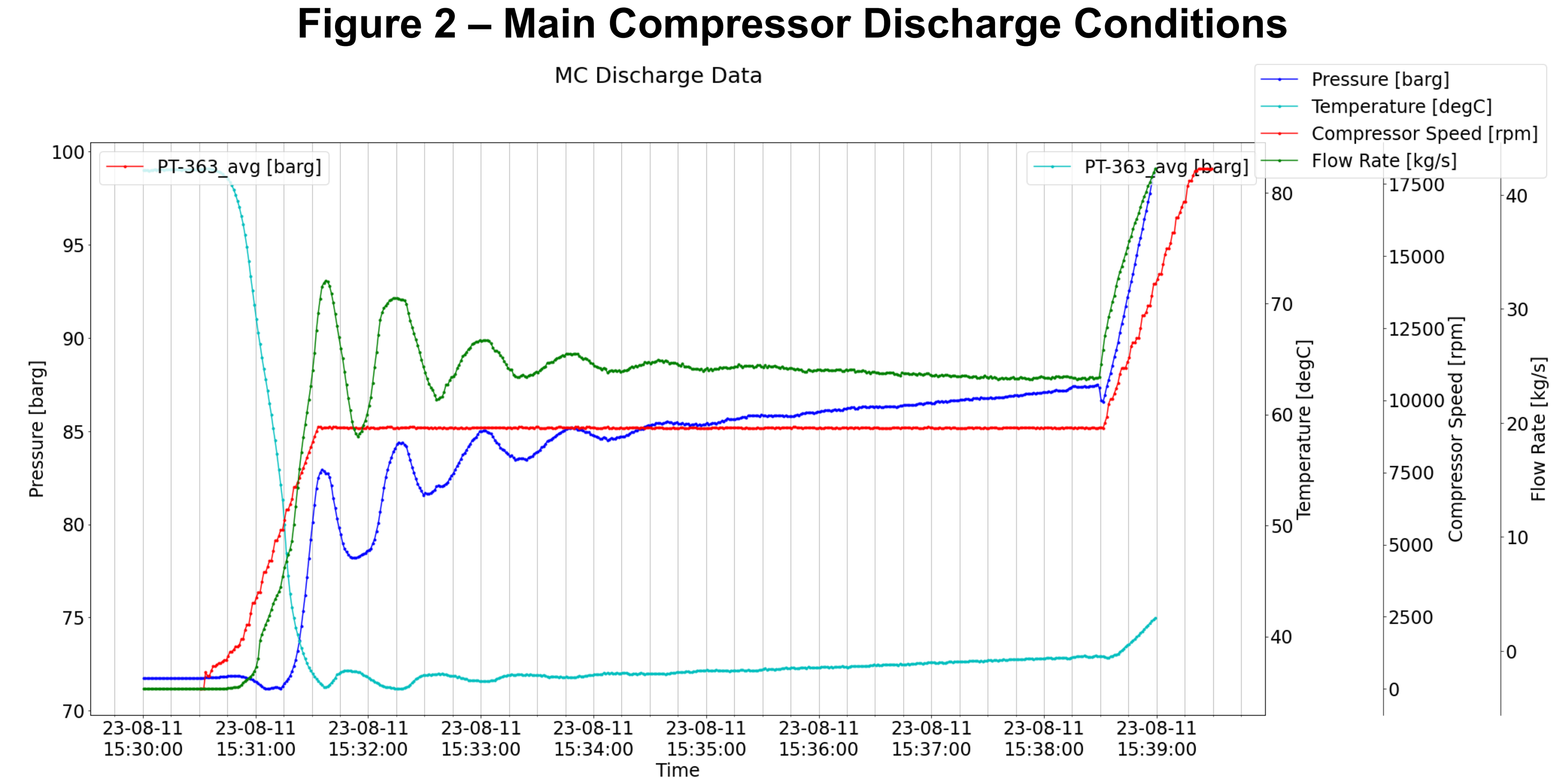
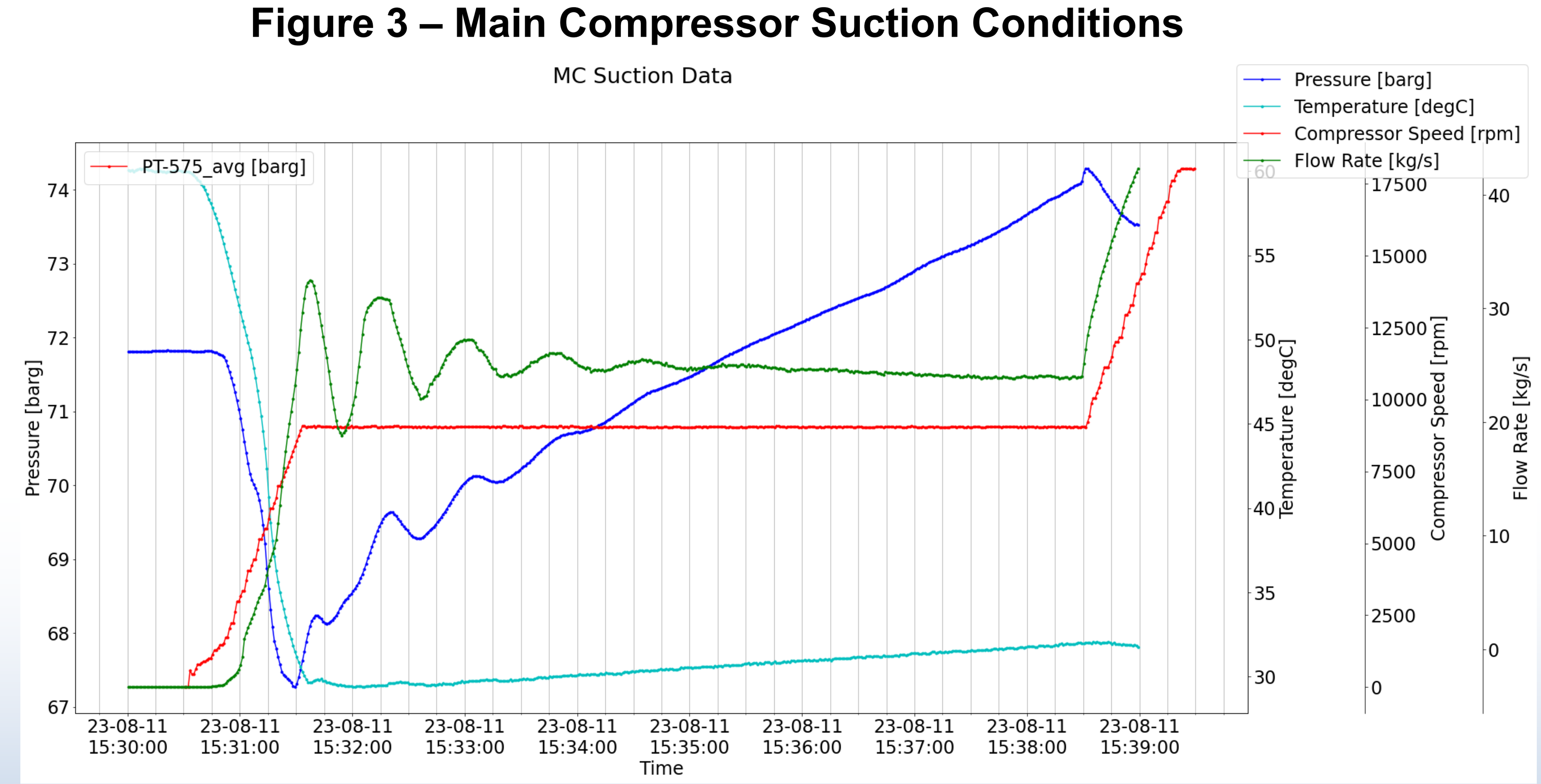


Figure 3 – Main Compressor Suction Conditions



Using known piping geometry and operating conditions, it is possible to calculate the round-trip travel time of fluid through the compressor loop. Mass flow rate is known, as is density from temperature and pressure. Thus, one can divide the mass flow rate by the density and known cross-sectional area of each section of piping to get the velocity in each section of piping. With length known for each piping section in the loop, it is then possible to calculate the transit time for each section as well as the entire loop. The period of the observed oscillations closely aligned with the transit time of the loop. One possible explanation is that "packets" of fluid originating in different sections of the loop at start-up result in oscillating conditions when the packets traversing through the compressor are alternately hotter or colder, and thus less or more dense. The pressure ratio of a centrifugal compressor should increase when the fluid density increases, as will its mass flow rate. This trend is seen in Figure 1 and Figure 2. As the compressor loop runs over time, fluid mixing and temperature control logic around the suction cooler would be expected to result in steady operating conditions, which was observed as the oscillations diminished following several transit cycles of the loop.

CONCLUSION

While liquid conditions were not directly observed during this event, the slow speed start up sequence of the compressor did appear to successfully mix out differences in fluid temperatures and densities and reach a steady state operating condition following a pressurized start command. Thus, slow speed operation seems a reasonable approach to mitigate the risk of liquid entrainment into a high-speed CO2 compressor during start up.

REFERENCES

[1] Marion, John, et al. The STEP 10 MWe sCO2 Pilot Plant Demonstration. Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, 2019.

ACKNOWLEDGEMENTS

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Figure 4 – Compressor Suction Conditions Plotted on p-H Diagram