Stress analysis of sCO2 Turbine Pressure Casing

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Introduction

Australia is well positioned to take advantage of developments in Concentrated Solar Power (CSP) technology, due to having substantial solar resources (Bahadori et al., 2013). Additionally, Australia has a substantial off- and fringe-of-grid market (BREE, 2013). These sites are characterised by the need for expensive remote generation or a requirement for high-cost network upgrades. These points are a challenge for common Variable Renewable Energy (VRE) options such as solar PV and wind generation, but present an opportunity for a Dispatchable Renewable Electricity options such as CSP (Lovegrove et al., 2018), including those plants using supercritical carbon dioxide (sCO2) power block configurations.

A focus of global research in CSP is the transition from steam-based power cycles to supercritical CO2 (Mehos et al., 2017). The opportunities presented by the sCO2 Brayton Cycle include improved efficiency when compared to the Supercritical Steam Cycle and greater compactness (Dostal et al., 2004) and suitability for air-cooling (Turchi et al., 2013). Current research and development efforts address on a number application areas, most notably in nuclear power generation, CSP, and fossil fuel-based generation (Gas Turbine Institute, 2018).

The Australian Solar Thermal Research Institute (ASTRI) funded the design of a prototype 1 MWe sCO2 Turbine Unit in 2019. The sCO2 Turbine Unit is configured as a dual-rotor, geared turbogenerator intended for connection to a synchronous generator (50 Hz, 3000 rpm). The design operating inlet conditions are 20 MPa / 700°C.

Configuration

The sCO2 Turbine Unit is configured as an integrally-geared Turbo-generator, with a number of subassemblies as shown in Figure 1. Key design features associated with the Casing will be described further.

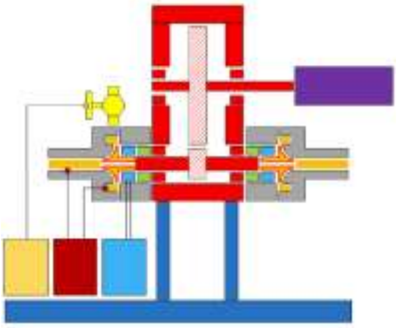


Figure 1. sCO2 Turbine Unit configuration with two opposed radial turbines

Casing Design Principles

It has been the practice of exemplar sCO2 turbomachines to comply with recognized Pressure Vessel standards (Allison and Moore, n.d.). Therefore, the sCO2 Turbine Unit Casing was designed in accordance with ASME BPVC principles. The design process occurred in two stages;

Stage 1: Design Concept generation according to “Design by Rules” principles (ASME BPVC Division 2) to establish the general requirements for the dimensions of simplified elements, and subsequent realisation using 3D modelling tools;

Stage 2: Analysis according to “Design by Analysis” principles (ASME BPVC Division 2) to determine the suitability of the Design Concept. Note that as the Casing operates in the creep range, assessment of Cyclic Loading was conducted per ASME BPVC Section III Division 1 Subsection NH (now Division 5) consistent with literature (Barua et al., 2020).

The Design and Operating parameters used are outlined in Table 1. These values were selected to be consistent with an RCBC-based Power Block that achieves a net efficiency of 50% or more. It is assumed that the Casing in constructed of Inconel 740H.

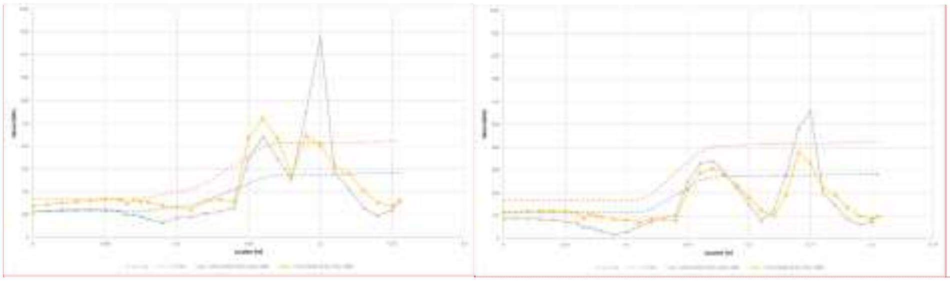
Table 1. Design and Operating Conditions for Casing

	HP Zone	LP Zone
$T_{max,operating}$	700°C	700°C
$P_{max,operating}$	20 MPa	14 MPa
T_{design}	725°C	725°C
P_{design}	24 MPa	17 MPa

Casing Analysis Results – Thermal Transient Zone (TTZ), Steady State

The combination of high-temperature turbomachinery with existing Dry Gas Seal (DGS) technology necessitates permanent thermal gradients within pressure boundary equipment. These regions may be termed “Thermal Transition Zones” (TTZ). These are cylindrical shells with high thermal stresses that persist in operation because the gradient must be sustained.

Figure 2 shows the membrane and bending components of stress, at the inner and outer walls of the Thermal Transition Zone (TTZ), for two configurations. Configuration A is the baseline design, and Configuration B is an extended TTZ (+25mm) that reduces stress by reducing the temperature gradient that must be sustained. The stresses are compared to a temperature-dependent value of the allowable stress per ASME Code Case 2702 for Inconel 740H. Note that the design assessment of temperature-dependent strength is formally considered in Protection against Cyclic Failure (Design-by-Analysis Stage 4) and not Protection against Plastic Collapse (Design-by-Analysis Stage 1), and the analysis shown here is indicative of the design principle only.



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Configuration A Case 3

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Configuration C Case 3

Figure 2. Stress (M + B) in TTZ (a) Configuration A (b) Configuration B

Casing Analysis Results – Casing Wall Transient Stress and Creep Life

The Casing is subjected to uneven heating, and this combined with the large section thicknesses lead to transient states where high thermal gradients, particularly in the axial direction, cause high stress in regions of the Casing. The effect is most significant for rapid and continuous temperature ramps, such as per the Design Cycle shown in Figure 3(a). To reduce the impact of these factors, a temperature hold at a lower temperature may also be introduced, as shown in Figure 3(b).

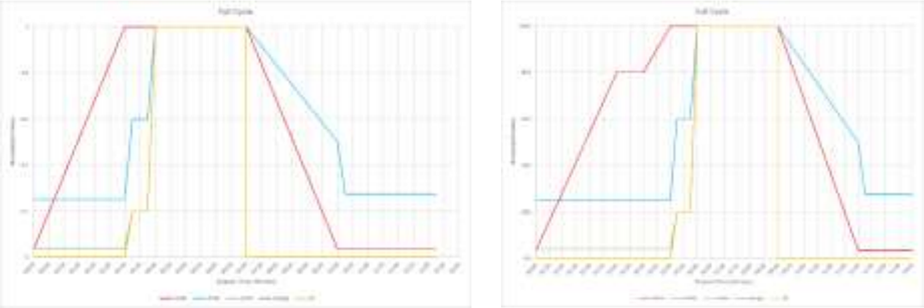

Figure 3. Design Cycle with (a) Ramp to 700°C (b) 560°C hold

Table 2a. Creep assessment (Design Cycle with Ramp to 700°C)

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	0	3	4	…	…	7	10	13.25	hr
Max Temp.	-	700	700	…	…	700	700	700	°C
Sk	0.0	333.7	331.5	…	…	149.7	306.6	304.8	MPa
Sk/K'(=0.9)	-	370.8	368.4	…	…	166.4	340.7	338.6	MPa
(Td)k	-	1619	1697	…	…	100000	2591	2658	hrs
Δtk	-	3	1	…	…	3	3	3.25	hrs
Δtk/Td	-	1.85E-03	5.89E-04	…	…	3.00E-05	1.16E-03	1.22E-03	-

Table 2b. Creep assessment (Design Cycle with 560°C Hold)

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	0	3	4	5	6	9	12	15.25	hr
Max Temp.	-	600	600	700	700	700	700	700	°C
Sk	0.0	365.7	360.2	313.7	312.5	198.7	165.5	166.8	MPa
Sk/K'(=0.9)	-	406.3	400.2	348.6	347.2	220.7	183.8	185.4	MPa
(Td)k	-	100000	100000	1663	1620	87303	100000	100000	hrs
Δtk	-	3	1	1	1	3	3	3.25	hrs
Δtk/Td	-	3.00E-05	1.00E-05	6.01E-04	6.17E-04	3.44E-05	3.00E-05	3.25E-05	-

Tables 2a and 2b show the assessment of creep life consumed in each segment of the Design Cycle, for the 700°C ramp and 560°C hold options respectively. Stresses (von Mises, maximum value of stress within the interval) are obtained from 3D transient FE analysis of the Casing during a simulated Design Cycle. The Design Cycle is simulated by the application of temperature boundary conditions on the hot gas paths; convective heat loss on the exterior of the insulation; and fixed-temperature conditions at the supports. Two key differences are observed; firstly, while stresses remain high during the start-up phases of both cycles, the segmentation of the start-up sequence means that a smaller creep damage fraction (Δtk/Td) is consumed (for example, 3×10^{-5} vs 1.85×10^{-3} in the first 3 hours). Secondly, the assessment shown in Table 2b shows the results from a different assumption regarding the cool-down phase. Rather than assuming that rapidly-cooling CO2 would be circulated (per the results of Table 2a), it was instead assumed that the Casing would be isolated from new inflows and thus be allowed to cool naturally through external convection. This assumption resulted in a dramatically slower rate of cooling, with commensurately lower thermal stresses.

Conclusion

The conclusion of the work outlined is that the progression to very high temperature (>560°C), high-pressure (20 MPa) turbomachinery, such as is associated with the supercritical CO2 Recuperated Brayton and Recompression Brayton Cycles (RCBCs), present significant challenges for designers to deliver robust equipment whilst working within established methodological frameworks.

The key issues noted are related to (i) high stresses caused by the steady thermal state in operation, which curtails design flexibility; and (ii) the degree to which useable life of pressure-boundary components are consumed by high stresses incurred during start-up and shutdown, which may place limits on the operation of equipment.

References

Allison, T., Moore, J.J., n.d. SwRI Webinar: sCO2 Turbo Machinery Design Concepts Various Applications.

Bahadori, A., Nwaoha, C., Zendehboudi, S., Zahedi, G., 2013. An overview of renewable energy potential and utilisation inAustralia. Renewable and Sustainable Energy Reviews 21, 582–589. https://doi.org/10.1016/j.rser.2013.01.004

Barua, B., McMurtrey, M., Rupp, R.E., Messner, M.C., 2020. Design Guidance for High Temperature Concentrating Solar Power Components (No. ANL-20/03, 1582656). https://doi.org/10.2172/1582656

BREE, 2013. Beyond the NEM and the SWIS: 2011-12 regional and remote electricity in Australia. Bureau of Resources and Energy Economics, Canberra.

Dostal, V., Driscoll, M.J., Hejzlar, P., 2004. A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors. The MIT Center for Advanced Nuclear Energy Systems.

Gas Turbine Institute, 2018. 10 MWe Supercritical C02 Pilot Power Plant.

Lovegrove, K., James, G., Leitch, D., Ngo, A.M.A., Rutovitz, J., Watt, M., Wyder, J., 2018. Comparison of dispatchable renewable electricity options 188.

Mehos, M., Turchi, C., Vidal, J., Wagner, M., Ma, Z., Ho, C., Kolb, W., Andraka, C., Kruizenga, A., 2017. Concentrating Solar Power Gen3 Demonstration Roadmap. NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States)).

Turchi, C.S., Ma, Z., Neises, T.W., Wagner, M.J., 2013. Thermodynamic Study of Advanced Supercritical Carbon Dioxide Power Cycles for Concentrating Solar Power Systems. Journal of Solar Energy Engineering 135.