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Solar-driven Supercritical CO2 Brayton Cycle (1-UFA004)

Project results and lessons learnt

Lead organisation:	CSIRO
Project commencement date:	1 November 2012 **Completion date:** 30 May 2017
Date published:	
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Executive Summary

Supercritical Carbon dioxide power cycles enable a significant increase in thermal efficiency over traditional steam Rankine cycles seen in the majority of current thermal power stations both fossil fuelled and solar thermal. The increase in efficiency is achieved by operating the turbine at higher temperatures (close to 700°C), while low compression ratios reduce the amount of worked required to pump the working fluid to the pressures required for the cycle to operate.

Applying the supercritical CO2 power cycle to a concentrating solar thermal system and taking into account the increased conversion efficiency, the solar collector system can be reduced in size for comparable electrical outputs. This translates to lower capital costs for the systems and overall a lower cost of production for the electricity.

This project looked at key components of the Supercritical Carbon dioxide power cycle, and addressed components required to implement the cycle with solar energy. The project demonstrated for the first time a directly illuminated solar receiver with high pressure supercritical carbon dioxide (sCO_2), developed and tested the required balance of plant, demonstrated a new sCO_2 pump, high pressure recuperators and with scope for future work testing sCO_2 turbines.

The project also demonstrated the use of a thermal storage system that allowed the sCO_2 flow loop to be commissioned in a controlled environment. This storage can be charged with either solar or combustion heat sources.

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Project Overview

Project summary

This project targeted a combination of advanced components to produce a levelised cost of electricity of less than 10c/kWh within five years. It adopts radical new technology in the form of a closed loop supercritical CO_2 turbine, combined with high efficiency receivers and small footprint thermal storage to provide a marked change of direction for CSP power that could transform the CSP sector. By taking previously disconnected areas of technology development and combining them into a new system, CSP can be reduced in scale, reduced in cost with increased efficiency, provided that the technical challenges can be met.

This technology affords such a step change due to particular properties of carbon dioxide. In its supercritical state CO_2 is able to exhibit liquid-like properties such that the power required to compress the fluid is halved. The net effect is that cycle efficiencies of 55% are possible at turbine temperatures of 700°C compared with typical Brayton cycle turbines of 35% at 1,000°C. The CO_2 circulates around a closed loop, so it is simply a working fluid, and is not released.

Efficiency improvement is one of the most fundamental and important ways in which the cost of solar electricity can be reduced. An improvement in efficiency offers capital cost reduction in all parts of the system – for example if efficiency is doubled then only half the mirror area is required, receivers and towers are smaller, the balance of plant cost is reduced and operation and maintenance costs are also reduced. With this particular cycle, turbines are much smaller than normal and are expected to eventually be cheaper also.

The other major attraction this cycle affords is the lower operating temperature. Typically Brayton cycles would need to operate above 1,000°C, and though solar towers can reach these temperatures, commercial operation is challenging due to exotic materials, thermal stresses, etc. This cycle operates with high efficiency at temperatures at which thermal storage is viable, thus enabling dispatachable solar electricity.

This technology will have great application for Australia. It can be installed in smaller more modular unit capacities which increases the opportunity for deployment and improves financing possibilities. It requires no water for operation and with the inclusion of storage is a highly flexible solar option. It offers the possibility of one of the most competitive zero emission technologies.

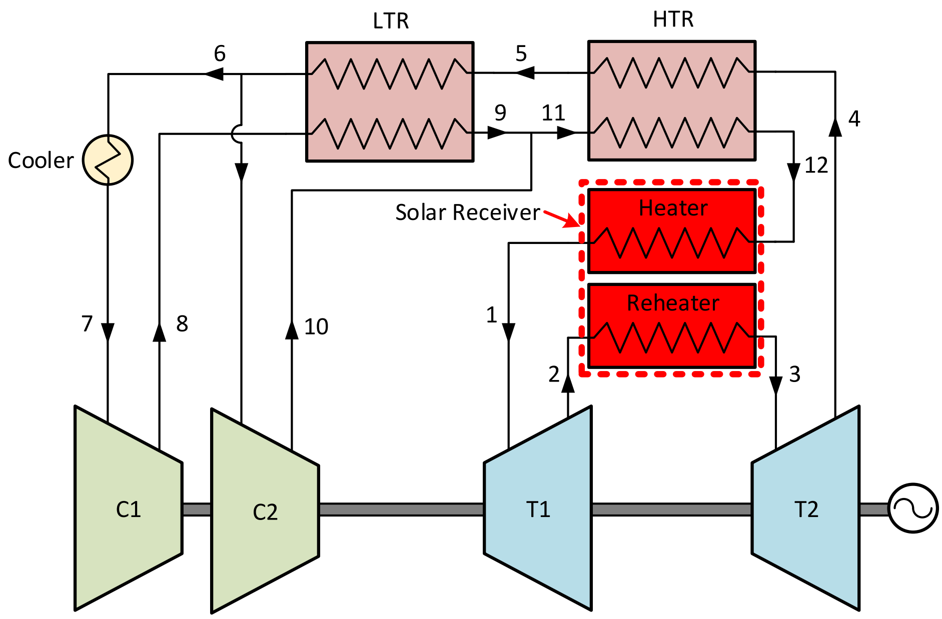
Partners in this project include the two key CSP research labs in the US - Sandia and NREL - who, together with CSIRO’s expertise in high performance solar towers and receivers, will make a very strong team to ensure this technology has the maximum chance of success. The project will also benefit from the expertise of the University of Sydney and Queensland University of Technology.

Project scope

This technology is at an early stage of its development and thus the objectives are based on understanding the performance boundaries of each of the major components within the typical operating conditions imposed by likely solar sites. Once known these component models are used to build an overall system model and examine the technoeconomics of full systems under annual solar conditions. The objectives were:

1. Map the operational envelope of the closed loop S-CO2 Brayton cycle under simulated solar conditions and analyse heat exchanger configurations to optimise performance.
2. Determine the performance attributes of receivers that are directly or indirectly heated by solar energy.
3. Design, build and test on sun an experimental receiver where S-CO2 is used directly as the heat transfer fluid.
4. Design build and test the production of heated S-CO2 from the discharge of thermal storage.
5. Comprehensively model the technology and examine economic optimisation using the findings above in addition to the knowledge held by Sandia, NREL and CSIRO on other components such as heliostats.
6. Assess the benefits and opportunities of modular CSP MW to the grid.

The most common configuration of the sCO2 cycle is known as the recompression cycle, in this cycle the flow is split after the Low temperature recuperator (LTR) with one stream recompressed and added back into the high-pressure side of the cycle. This eliminated a major heat transfer limitation in the standard cycle and will be the basis for the project.



Outcomes

The most significant outcome of the project was the successful development of the sCO2 flow loop and on sun operation at the Newcastle CSIRO solar thermal faculty. The system was designed at the CSIRO in conjunction with a wide range of international suppliers (for components such as the sCO2 pump), incorporates technology developed from the University of Sydney (Heatric Recuperators) and local engineering and fabrication service companies. These can be seen in Figure 1.

Figure 1 Completed Solar receiver (LHS) before installation, sCO2 Flow System (RHS)

The Solar sCO2 receiver and flow system achieved the first on sun demonstration of a supercritical Carbon dioxide implemented under conditions expected in a large scale solar thermal power station. The system was operated at temperatures of 650°C and pressures of 20MPa.

Figure 2 Operation of the sCO2 solar system.

Transferability

The project has delivered a number of breakthroughs increasing the technology readiness of components within the sCO2 cycle. Heat transfer information will aid future designs of solar receivers, recuperators and coolers. A significant analysis of the material involved in the process have also be achieved with the impact of carbon dioxide at high pressures and temperatures on steels used in the construction. Additionally, work on low temperature components in the form of seals has shown that more work is required to develop materials that will provide the longevity required for future applications.

In the immediate future, the CSIRO materials work will continue in collaboration with a demonstration project with the US DOE. The sCO2 flow system at CSIRO will continue to be utilised for long term testing of the solar receiver, recuperators, pumps/pump seals, valving and instrumentation.

The CSIRO facility will be utilised to integrate work being completed within ASTRI (Australian Solar Thermal Research Institute) as research is readied to be scaled upwards towards more commercial offerings, a great example is the sCO2 turbine being developed within the ASTRI program. In addition, CSIRO will continue to work with equipment developers to test new equipment witan the loop.

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Conclusion and next steps

The next steps for the project include the continued on sun activities within CSIRO to further experiment on the sCO2 system. The flow loop and equipment will become a key part of scaling ASTRI technologies and hopefully be part of the future sCO2 power system powered by solar thermal power.

Lessons Learnt

Lessons Learnt Report: Materials for supercritical CO2

Project Name: Solar-driven Supercritical CO2 Brayton Cycle

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar Thermal
State/Territory:	NSW

Key learning

The conditions under which Supercritical CO2 (sCO2) is required to operate within the power cycle result in short life spans for traditional seal materials. This was identified within the reciprocating pump seals and valve seats, which were observed to deteriorate at an advanced rate.

Implications for future projects

The implication is that industry is currently underprepared to supply components for the sCO2 power cycle that will meet the longevity and performance requirements a commercial plant.

Knowledge gap

While significant information exists for carbon dioxide compatibility on most materials at normal pressures and temperatures, under supercritical conditions, CO_2 becomes a solvent that can attack most seal materials.

Background

Objectives or project requirements

The triplex plunger pump uses an electric motor to drive a crank shaft via a speed reducing belt drive. The crank case part of the pump (the part of the pump painted blue) contains the crank shaft, oil bath, oil pump, one connecting rods for each of the three plungers, a piston guide tube and the pony rods. Each pony rod in term connects directly to the plunger.

Each of the three plungers is a stainless-steel cylinder measuring 45mm diameter x 200mm long is pushed into the pump head to displace the internal volume inside that particular pump head chamber. There are three chambers each connected to a common inlet and outlet header via a pair of non-return disc valves. The plungers have a stroke of 80mm and with the crank shaft turning at 197 rpm at 100% motor speed, the pump is capable of a flow rate of 73 litres per minute.

The entire pump head, the pony rods and the plungers are made from stainless steel with exception for the brass valve supports and seal housing adjustment nuts. The plungers are each sealed to contain the high-pressure contents, liquid CO_2 at up to 300 bars against atmospheric pressure. The plunger seals, which are the active part of the pump sealing system, allow the plungers to slide with very little loss of content. The plunger seals are made from a system of four compression packing rings 8mm square and 45mm inside diameter, which in turn are held together around the plunger via a pair of polymer anti-extrusion rings, a pair of stainless steel support rings, a loading spring inside the seal housing containing O-rings for sealing the housing in the pump head and a wiper seal to keep the plungers clean from the external environment. Each of the seal housings are connected to a common vent line so that any CO_2 that leaks through the seals is vented to a common point.

The crucial part of sealing the pump head around the moving plungers are the compression packing which are made from a flexible braided fibre rope impregnated with a lubricating and sealing compound.

Process undertaken

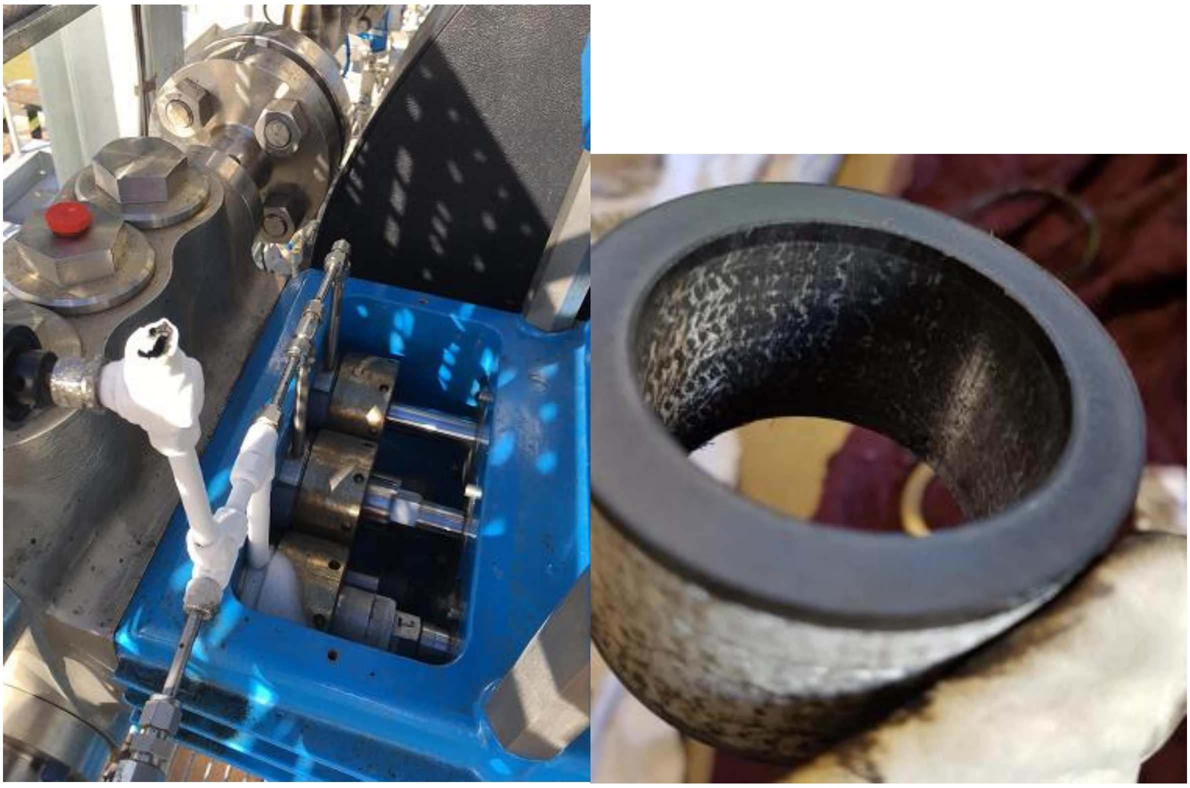

Figure 3 LHS - sCO_2 pump in operation showing expanding CO_2 freezing the vent pipe. RHS - Compression packing from the pump plunger.

CSIRO developed a concern about the nature of the PTFE based lubrication paste embedded in the seal compression packings. If it is a hydrocarbon based wax or grease it will dissolve in the CO_2 (either liquid or supercritical).

The black paste was considered to be derived from the carbon-impregnated PTFE anti-extrusion ring. The mechanism for removing the carbon from the PTFE is simply the PTFE swelling and allowing the carbon particles to be dislodged. PTFE doesn’t really stick to anything (low friction coefficient) so the carbon particles are “suspended” within the PTFE matrix rather than being firmly held.

The grease like black paste seen on the seal vent line was considered the likely result of the two effects above. The dissolved “wax” matrix from the PTFE paste drops out of the liquid CO_2 as it turns gaseous during escape. The black particles are carried out with the fluid flow.

CSIRO researched the compatibility of polymers with liquid CO_2 and CO_2 will work as a solvent for most polymers. Both liquid and supercritical CO_2 are “good” solvents for organic compounds. This solvent behaviour also extends to “solvent swelling” of elastomers and polymers. This is what makes it such a challenge to utilise.

In regards to pumping liquid or supercritical CO_2, CSIRO concluded that any polymer soft enough to be used as a sealing material is likely to show signs of swelling and so will not reseal very well after the first depressurisation. PTFE based polymers are certainly in this category. The use of any hydrocarbon oil, grease or wax is also likely to compromise the polymer. Which leaves us with the graphite-based sealing materials.

Ongoing activities

CSIRO continues to experiment with the sCO_2 system and is working with manufacturers of pumps and developers of seal materials to better understand the behaviour and mechanisms of attack for sCO_2 in the presence of carbon based seals materials. CSIRO is also investigating the configuration and layout of the seal with a mixture of materials to take advantage of specific properties of individual components and materials to combine and work to provide a long lasting seal.