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An Overview of the Rolls-Royce sCO_2-Test Rig Project at Cranfield University

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ABSTRACT

An experimental facility is currently under development at Cranfield University, aiming to explore supercritical carbon dioxide as a working fluid for future bottoming power cycle applications for Rolls-Royce. The initial objectives of this experimental program are to de-risk and demonstrate the robustness of a closed loop system, as well as to prove the function and performance of individual components and various measurement and control modules. This paper describes the planning and development phases of the test facility and summarises the lessons learnt from the component specification and component interface processes.

INTRODUCTION

The combination of high fuel prices and more stringent emissions legislation (particularly IMO Tier III [1]) has led to an increasing interest in waste heat recovery technologies across the marine sector. Gas turbines reject a large quantity of heat to the atmosphere compared with their reciprocating counterparts. Therefore recovering this heat using bottoming cycles, which have the potential to increase combined cycle efficiencies and offer additional electrical/mechanical power, is a topic of special interest in the marine propulsion community. The potential of a supercritical carbon dioxide (sCO_2) bottoming cycle is reasonably well documented in the literature. However, there are limited instances of demonstration and a single publicized commercial offering. Three UK related entities: Rolls-Royce plc, Heatric Meggitt and Cranfield University, have formed a collaborative consortium in order to generate data to validate a business case capable of reducing the level of technical and commercial risk associated with this novel and potentially valuable technology.

Despite the general enthusiasm about the unique advantages that supercritical CO_2 power systems could offer, it has been recognized that there is a need to address a wide variety of technological challenges before achieving a commercial prototype. The areas identified as critical for success were:

- Control of the working fluid throughout the thermodynamic cycle, recognizing “real gas” effects
- World-class transient modelling capability and turbomachinery design
- Identification or development of high-temperature materials fit for purpose
- Development of the auxiliary systems that are needed to realize the cycle

Additionally, the consortium believes that it has identified an important gap between the advanced research efforts reported by others. Consequently, the consortium has been exploring the technologies and resources that will be required to close this gap. The consortium has also discovered that it is necessary to assess the capability and capacity of the UK supply chain to provide goods and services for supercritical CO_2 waste heat recovery technologies.

Carbon dioxide applications are already known in the oil & gas and refrigeration industries and therefore important lessons can be learned from them. The challenge is to correctly scale equipment and control methods to be used for each stage of the experiment. Rig tests are bespoke by their nature, with associated technical and budgetary risks. Scaling introduces a risk because of the reliance on system and control modelling in the design of systems and components. Specifically, there is a risk that results generated from a ‘scaled’ rig will not be directly applicable to the design of a full scale system. We note that the Naval Nuclear Laboratory has already demonstrated [2] that over sizing components (to account for unknowns) will not guarantee a controllable off-design transient performance. After evaluating the lessons learned from existing CO_2 test facilities of this type [3] - [12], the consortium concluded that (noting budgetary constraints) the focus should be on testing compressors and main heat exchangers (MHEX) suitable for systems within a range of 100 to 300 kWe.

During the assessment of technologies where CO_2 in the supercritical state is used as a working fluid, it was found that pumps and valves for applications such as carbon capture and storage and carbon capture and utilization, are technically mature and reliable. However, the specified mass flow, component size and costs for the available equipment are not ideally suited to exploratory research. By contrast, the refrigeration industry, driven by incremental regulation on the sale of equipment containing fluorinated green gas (F gas) since 2007, has been moving towards low cost technologies using R744 refrigerant (Carbon Dioxide). Equipment, designed for application in food retail refrigeration and domestic heat pumps, comprises technologies where the CO_2 can be operated in either subcritical or transcritical states. From an experimental research viewpoint, one advantage of this equipment is the size: typically larger than those used in laboratories but commercially available and relatively compact. The initial configuration of the facility at Cranfield University has been designed to capture the key elements of operability and controllability of CO_2 as a working fluid through the use of a transcritical circulation loop intended for use in refrigeration systems.

This paper describes the planning and development of the modular test facility designed by the consortium to be a reliable source of carbon dioxide in a supercritical state.

TEST RIG DEVELOPMENT ROADMAP

The aim of this project is to design, build and commission a closed loop sCO_2 system to enable critical component testing and whole cycle demonstration of a representative waste heat recovery system. As a starting point, a simple recuperated Brayton cycle has been selected as a baseline reference system. This design choice allows interfaces with data acquisition and control systems to be designed for progressive step wise development and implementation of ever more complex configurations; such as simple recuperated split shafts or nested expansion configurations.

The step wise development progression of the facility will be as follows:

1. Development of a baseline sCO_2 closed loop facility and specification of required components and operating processes.
2. Development of a high-pressure gas-to-CO_2 compact heat exchanger.
3. Design and development of a sCO_2 compression system. This includes system and mechanical design definition for the system and components in the main gas flow path.
4. Development and implementation of data acquisition and rig control systems for operating the test loop:
    - Compressor speed / recirculation valves
    - Cooling flow
    - Start-up/shut-down procedures
    - CO_2 inventory control

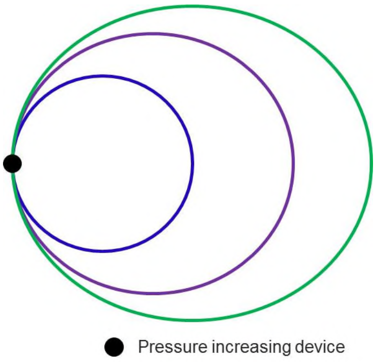


Figure 1 – Parabolic pencil pattern example

The design of the test rig has adopted a modular approach. The main requirement behind this approach was to isolate major equipment components (i.e. heat exchangers, compressors) or control loops (i.e. flow split, bypass valves) for testing. The modular approach followed a "parabolic pencil" pattern (shown in Figure 1), meaning that each testing branch (including equipment to be tested, pipes, minor valves and instruments) are tangent to each other at a single point (i.e., the pressure increasing device).However, this single point or equipment, could be varied accordingly.

This approach enables independent development and testing of each individual component with bespoke boundary conditions to demonstrate component operability prior to interfacing them with each other. Figure 2 shows the modular and staged development followed under the parabolic pencil pattern. Presently, it comprises four stages, targeting TRL 4 in some of the subsystems. The anticipated outcomes of each stage are shown in Table 1.

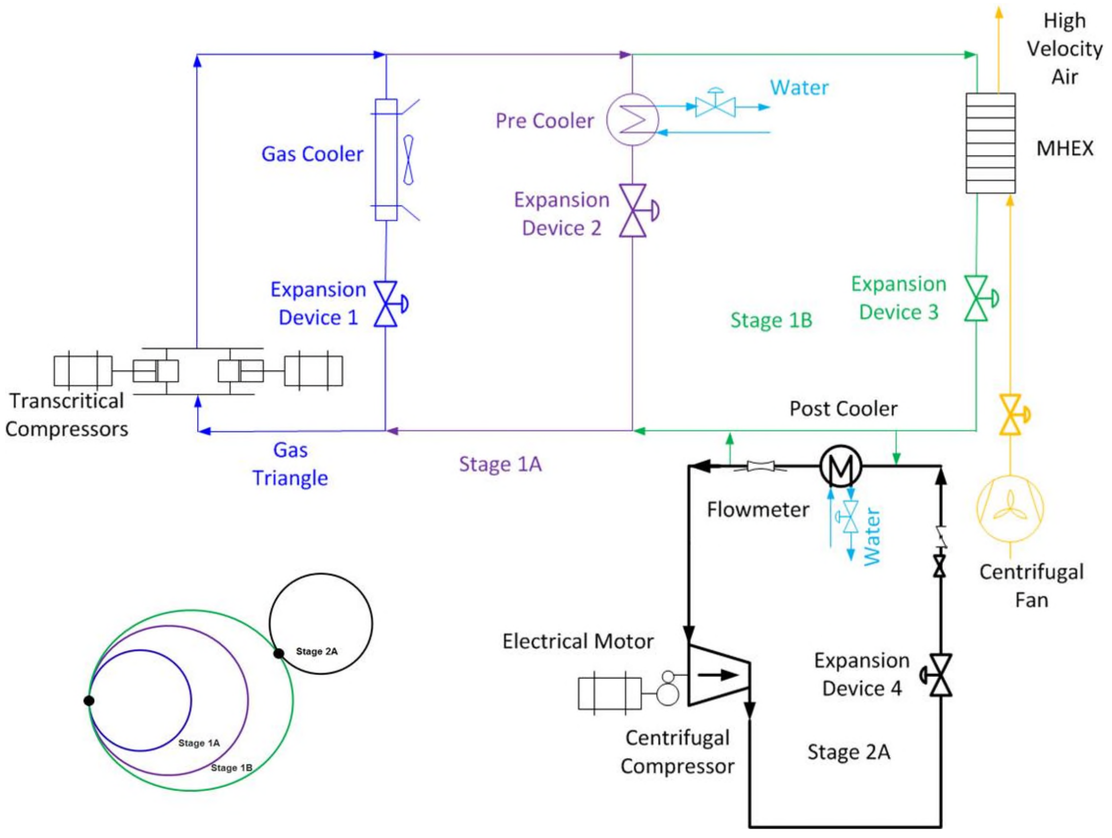


Figure 2 – Modular and staged development concept

Table 1- Roadmap of the test rig development and its outcomes

Stage	Components	Outcomes
GT	Circulation compressor, gas cooler, expansion device 1 (refrigeration)	- De-risk sCO_2 loop. - Demonstrate component/rig robustness and proof of concept. - Verify transcritical compressor performance. - Assess procedures for filling / starting up / shutting down. - Demonstrate pressure and temperature acquisition data at supercritical state.
1A	Circulation compressor, pre cooler, industrial expansion device 2	- Verify contractual performance of high pressure facilities. - Characterize pre cooler performance. - Validation of SIMULINK models. - Demonstrate pressure and temperature control cooling system. - Assess control system for inventory control
1B	MHEX, fan, circulation compressor, expansion device 3	- Test MHEX performance (cold run – only air). - Assess key technical issues for further development (thermal expansion).
2A	Centrifugal compressor, post cooler, expansion device 4	- De-risk compressor installation. - Characterize pre cooler performance. - Develop supporting technology of the turbomachinery design: • Bearing type, thrust loading, bearing cooling, sealing technologies, and rotor windage losses. - Validation of SIMULINK models. - Demonstrate pressure and temperature control at supercritical state. - Demonstrate compressor performance at representative PR.

RIG DESIGN CONSIDERATIONS

The work undertaken by SANDIA [8] was reviewed as a prelude to generating the specifications for the test rig at Cranfield. With their sCO_2 compression test loop, SANDIA have shown [8] that (from a systems control point of view) the ‘real gas’ effects of operating close to the critical point are challenging. Achieving simultaneously set-points, for the expansion pressure and water temperature, demand the development of a relatively complex control system. However, when decomposing the problem, it was identified that the loop process consisted of three steps: compression, expansion and heat rejection. Although the steps are in a different sequence, these steps are the same for testing reciprocating compressors in the refrigeration industry. Hence, the consortium elected to use positive displacement compressors sourced from the refrigeration industry for the first configuration of our rig test. We have called this step the ‘gas triangle’ (see below). In this arrangement the working fluid is compressed, cooled and then expanded. This approach has allowed us to build the control system for the test rig gradually (and independently). Hence, the control algorithms for the first stage (expansion device and cooling water) will be developed using only the transcritical compressors. Control algorithms for the rig with the MHEX and for the compressor will be developed later. Figure 3 illustrates the principle behind operating transcritical compressors in a “gas triangle”.

The ’gas triangle’ approach allows us to test different technologies for heat exchange and gas expansion, as shown in Figure 2. Additionally, it allows us to operate the rig with a low cost source of CO_2 (commercially available R744: 99.9% purity carbon dioxide with a moisture content of 10vpm).

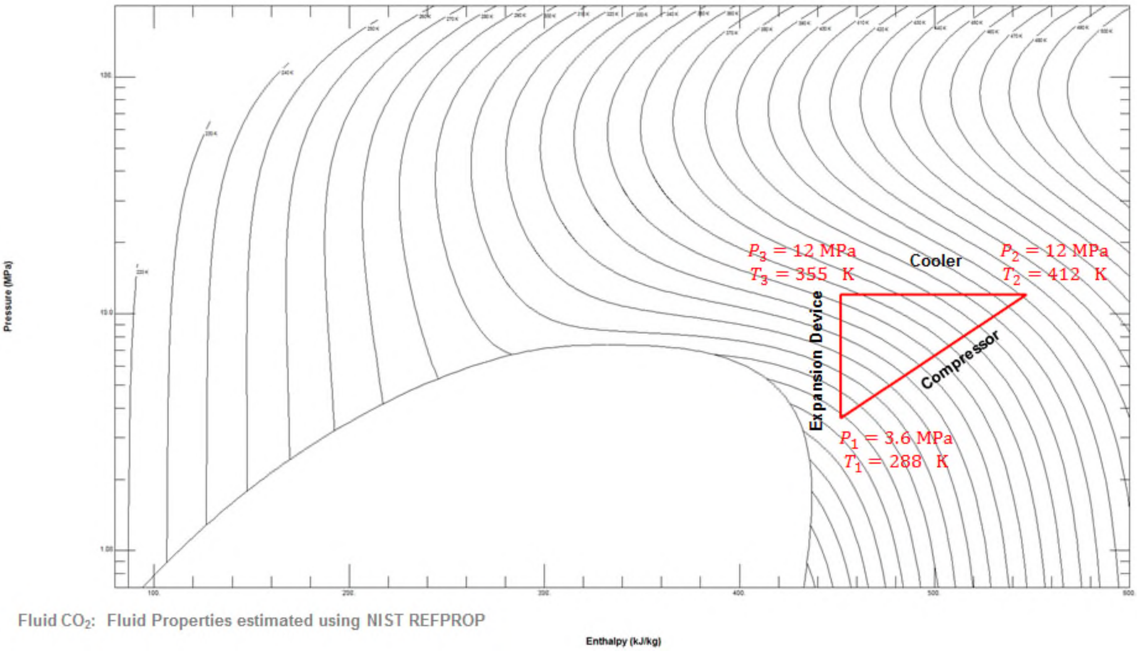


Figure 3 – Test rig development: Gas Triangle concept

DESCRIPTION OF THE EXPERIMENTAL LOOP

The combined conceptual schematic diagram is shown in Figure 4. The loop comprises a main heat exchanger, an expansion valve, pre and post gas cooler heat exchangers and two transcritical compressors. Ultimately, a centrifugal fan will provide the required air for testing the main heat exchanger. The heat sink is an evaporative cooling system. Later stages will configure the rig to integrate a centrifugal compressor with a recirculation anti-surge valve. We anticipate that the final configuration of the rig will allow fully coupled operation of the compression and expansion systems. Table 2 summarizes the main operating parameters of our sCO_2 facility. A series of flow mixing and splitting points shown in Figure 4 will be used for temperature control across the system.

The initial phases of the commissioning process for the rig will address closed loop system robustness, monitoring and controllability of gas properties across the system, CO_2 inventory management and health and safety considerations. Operation of the transcritical pack will provide input for the design of the rig control system for later stages (replication of functionalities from the refrigeration control system).

The next step is to reconfigure the rig to expand the ‘gas triangle’ with an additional loop. This loop is designed entirely in SS316L for the CO_2 side. It comprises a printed circuit heat exchanger coupled with a pneumatic control valve. Once in operation, assumptions for flow velocities in the pipes and pressure drop in the fittings will be tested and verified. Insulation and its effect on the thermal balance of the system will be also reviewed. The water side comprises an arrangement of medium density polyethylene pipes, fittings and a control valve; connected to a cooling tower (heat sink). A suite of instrumentation has been specified to characterize the transient response of the heat exchanger, as this is considered to be valuable information for establishing control of the post-cooler operation in the later stages.

The objective for the reconfigured rig is to test the main heat exchanger (MHEX). The MHEX design is a “hybrid” between printed circuit (PCHE) and formed plate heat exchanger (FPHE) technologies (see Southall et al. [12]). The former has been used in recuperation applications, including sCO_2 test rig at high pressure (SANDIA [8] & [13]; Bechtel [9]). The latter is more applicable to low pressure applications because mechanical integrity at high-pressure is questionable. Combining these technologies extends the applicability to high pressure systems. Testing using our rig will follow guidelines from the ASME PTC 12.5 [17], and will be limited to “cold runs”: CO_2 vs air. However, we are undertaking a thermal piping analysis to assess loading in the manifolds and nozzles to prepare for potential “hot runs”: CO_2 vs hot exhaust gases.

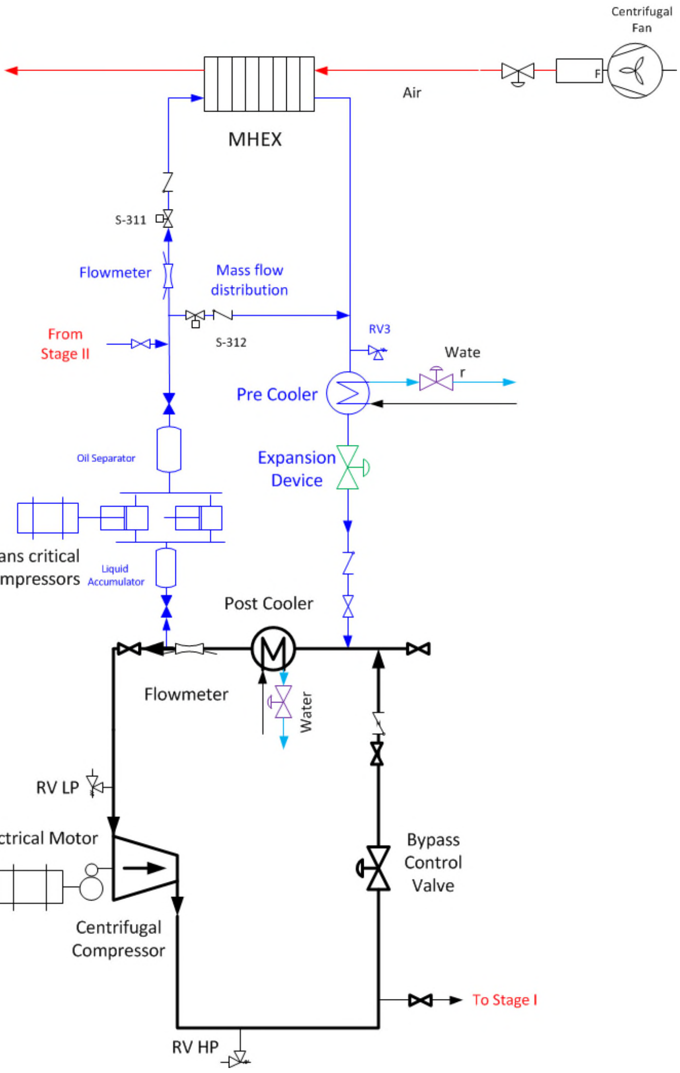


Figure 4 – Schematic of the envisaged S-CO2 test rig. Blue: Stage 1 loop, Black: Stage 2 loop

Table 2- Design parameters for the S-CO2 rig test facility.

Parameter	Stages 1A / 1B	Stage 2
Overall Pressure Ratio	2.66	1.95
Top pressure [MPa]	12	15
Top temperature [K]	440	350
Bottom pressure [MPa]	4.5	7.7
Inlet compressor temperature [K]	294	305
CO_2 mass flow [kg/s]	<1	5
CO_2 mass flow to MHEX [kg/s]	0.3	

Transcritical compressors sourced from the refrigeration industry deliver the specified flow rate of 1 kg/s for the first configuration of the rig. The compressors are assembled into a pack rack, similar to the ones used in refrigeration, as shown in Figure 5. The pack includes a brazed plate evaporator and a gas cooler (not shown in the picture). The intent of the evaporator is to assure vaporization of liquid CO_2 during the start-up process. This arrangement (evaporator and compressors) is being assessed as an option for the supply of supercritical CO_2 in more complex test rigs. The gas cooler is a 200 kW fin fan cooler, installed to help us to understand how to operate a test rig with CO_2 as working fluid.

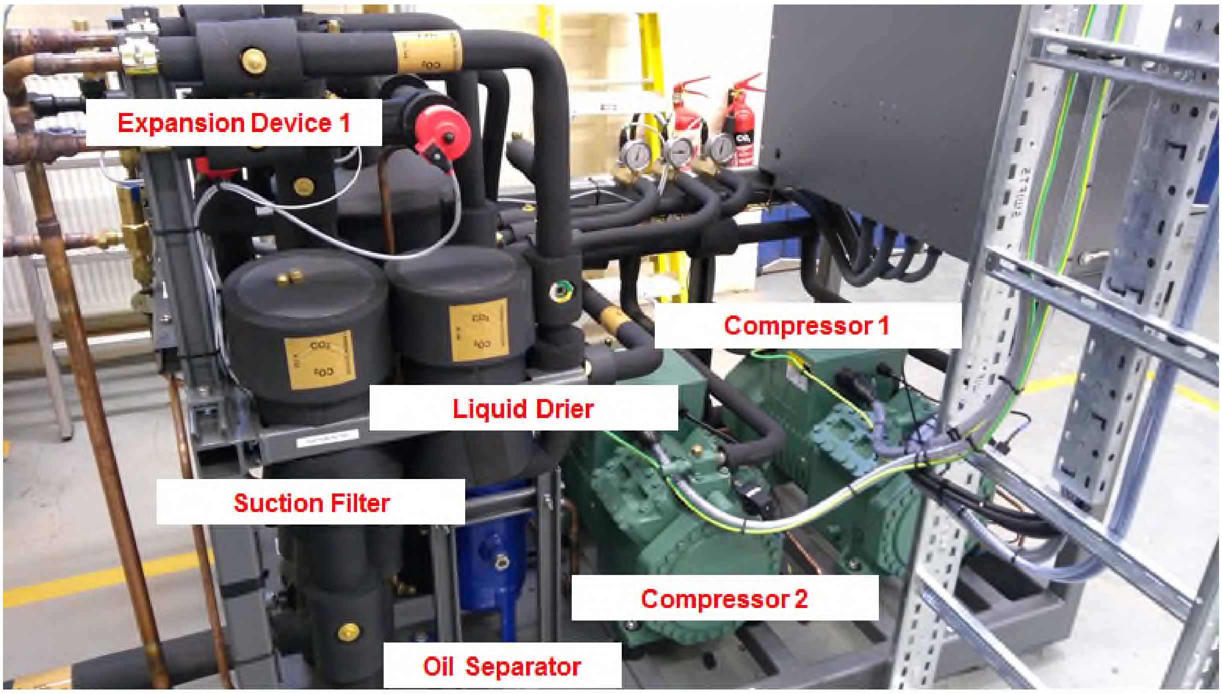


Figure 5 – Transcritical CO_2 pack at Cranfield University

As can be seen in Figure 5, the transcritical pack design offers two advantages: it is transportable and uses standard tube connections. Current applications for supermarket refrigeration systems use tubes and fittings made of high-strength copper alloy (Wieland K65). K65 is a high strength material, which is offered commercially permitting operating pressures up to 12 MPa. The composition of K65 allows silver (hard) brazing to be used in system construction without restrictions.

A bespoke, supercritical centrifugal compression system will be commissioned and tested during a later stage of the facility development. Some elements of the ASME PTC 10 [19] have been considered in the design and planning for the compressor testing. Lessons learned from previous stages will allow us to implement the most appropriate measurement techniques at optimal points in the system. For compressor testing, pressure and temperature measurements will be introduced at key loop 'stations' including compressor inlet, compressor outlet and post cooler inlet. In addition, static pressure measurements will be taken from the surface shroud adjacent to the gas path and at several locations along the leakage path, in order to verify predictions and enable reactive system protection. Based on desired temperature measurement accuracy, 'Class A' (±0.2 K) platinum resistance temperature sensors will be used. Finally, for mass flow and density measurements, Coriolis mass flow meters will be installed in the inlet to the compressor. The selected flow meters will be looking to achieve an accuracy of ±0.1% on flow measurement

LESSONS LEARNED AND DISCUSSION

This project anticipated that reducing the level of technology risk currently associated with sCO_2 waste heat recovery implies three fundamental activities:

- Verifying claims of potential technology performance
- Understanding cost of investment for a full research program
- Identifying customers and supply chains for the exploitable output

We are in the process of addressing the first of these but, thus far, we have only partially addressed the other two. For the last two, we have not reached a point where further investment could be justified. However, our design and modelling of different cycles shows that there is commercial potential providing that our assumptions and methods can be validated. This is all taking us in the right direction but there are a number of milestones we need to hit before we can claim to have de-risked the business case. Recognizing this, alternative applications for supercritical CO_2 (beyond WHR) are currently under assessment.

Some examples of lessons learned to-date include:

- Costing of key components is easier than costing of their auxiliary systems
- Identifying an appropriate supply chain requires a systemic approach
- The challenges of managing the procurement processes across industrial and academic partners in a consortium are not trivial.

The following paragraphs discuss more specific lessons.

General operation of R744 systems

The following items are lesson learned from the design and pre-commissioning of the circulation loop with transcritical compressors:

- If liquid can be trapped between valves, these sections of the system should include high-pressure protection; i.e.: pressure-relief valve (PRV)
- For CO_2 leaks,
    - It is necessary to set system gas leak detection alarms levels
        - 5,000 ppm for initial alarm (warning)
        - 15,000 ppm for main alarm (evacuation)
    - A large escape of CO_2 in confined areas has the potential to kill
- Dedicated lubricant system
    - Polyolester (POE oil) lubricants are hygroscopic – harmful to aquatic life
    - Avoid exposure to air
    - Evacuate air and back-fill oil to the compressor under a vacuum
    - A crankcase heater so that the oil temperature is maintained within a specified range (to reduce oil carry-over and R744 solubility)
- Charging directly from the cylinder
    - Prevent ice formation and thermal shock: charge gas (from cylinders) until the system pressure is slightly above the triple point (0.42 MPa)
    - Slow process, need to allow the system to equalise (to avoid PRV discharge)
    - PRV lift would cause pressure decrease and loss of (wasted) CO_2
    - Efficiency of charging operation is dependent on the gas cylinder pressure and the ambient temperature
- Relief of R744
    - Expansion of liquid R744 from any pressure level, and the expansion of gaseous R744 from pressure higher than 3.5 MPa, will lead to the formation of dry ice if the final pressure is lower than about 0.52 MPa
    - Avoid pipe lengths that could be plugged by dry ice formation (due to pressure expansion)
    - Pressure-relief valve: Select high-lift types to prevent dry ice blockage
- Retrieving R744 directly from the pack

    - Online recovery system (vessel & expansion regulator): risk of freezing
- Elastomer seals
    - When elastomer seals are depressurised, any absorbed R744 rapidly evaporates, causing explosive decompression and damage to the seal
- Running the system for the first time
    - Do not attempt to charge an R744 system when the amount of refrigerant in the system is unknown
    - Unlikely that all CO_2 will be able to be charged into a system without running that system first
    - Make sure that there is no moisture in the system
- Storage
    - R744 should be stored in ventilated areas
    - Cylinders need to be stored below 50 °C

One observation that has arisen, that will be relevant to the specification of any future design of WHR marine systems, is that ship engine room temperatures can exceed the critical point of CO_2. Hence, even the low pressure side of a WHR system will need to be designed to withstand a pressure of 8 MPa (at system idle).

Modelling

Both Sandia National Laboratories and Knolls Atomic Power Laboratory started their CO_2 projects with developed simulation codes (RPC-SIM [13] and IST TRACE [14] respectively). Our project began with no available simulation tool and we needed to fast-track development of a simulation code to support the project. PRO II was our chosen as the tool to develop and model steady-state cycle architecture and design point selection. In parallel, both steady-state and transient cycle modelling of the test rig architectures were performed using MATLAB Simulink®. Two sets of off-the-shelf libraries were used: Thermolib® and Simscape®. Currently, most of the performance calculations are being performed using Simscape because it is able to incorporate ‘real gas’ effects. CO_2 gas properties were calculated from NIST miniREFPROP 9.1 [15] using the Span and Wagner equation of state [16].

The Span and Wagner equation of state is the approach that is routinely used by other researchers currently studying supercritical CO_2. This approach works well provided that the flow domain remains above the saturation line. The flow cannot be modelled below the saturation line as some flow properties, such as speed of sound are not defined. Hence, the sub-critical region was modelled as a metastable subcooled vapour. Metastable properties are based on direct extrapolation of the NIST REFPROP Span and Wagner equation of state model.

In the immediate vicinity of the critical point two issues are expected: Two-phase effects are expected to become more prominent as the limit of metastability is exceeded; and a singularity in the speed of sound occurs.

Rolls-Royce has developed a CFD approach and code, using property tables, which allow the flow to be modelled as a metastable gas when it becomes subcritical. Rolls-Royce refers to this model as “the real gas model”. Rolls-Royce real gas modelling comprises the Span and Wagner equation of state implemented in an internal code with the use of lookup tables which, for CO_2, can be generated by REFPROP software (developed by NIST). REFPROP can be used to calculate metastable vapour properties up to the Spinodal limit by extrapolation. This approach has yet to be validated by experiment but does provide a method of generating thermodynamically consistent tables of properties for compressibility factor, enthalpy and speed of sound as required by the internal code.

The Spalart-Allmaras turbulence model with wall functions [16] was used in all simulations. Viscous wall surfaces were used for the impeller blades, hub and casing. Lower and upper periodic surfaces were also used to reduce the size of the domain to a single blade and splitter pair.

Although the development of transient models for the first rig configuration is well advanced, modelling as a whole continues (noting that we consider that auxiliary systems require better characterization). We also intend to verify our Simscape models incorporating real data from different configurations, as and when such data is available from the rig.

The following lessons have been learned for modelling to-date:

- The effect of lubricant carry-over into the CO_2 stream was not accounted during the top level modelling of the transcritical loop. This has an impact on performance and should be considered
- Potential pressure losses for operation near the critical point must be understood and managed – this is fundamental to the successful operation of the cycle / test rig
    - Pressure drop correlations should be properly selected to cover off-design conditions
- Assumptions for the thermal inertia of PCHEs has an important effect on calculating CO_2 temperature changes near the critical point
- Control of cooling water temperature becomes a critical factor to avoid CO_2 condensation
- Selection and characterization of control valves may prove to be inconsistent with CO_2 'real gas' effects; noting that variation of gas properties through the valve has not been assessed by suppliers

Main Heat Exchanger

Heatric Printed Circuit (PCHE) technology is ideally suited to the recuperator duty in the supercritical carbon dioxide Brayton cycle [12], as this cycle requires a heat exchanger with good mechanical integrity and a high surface density; to achieve good thermal performance while remaining as compact as possible. The disadvantage of this technology is that it has not been optimised for recovering heat from the low pressure gas (or vapour) side of the heat exchanger when there is a high volumetric flow. Hence, this technology would not be economically viable for such applications.

Heatric also use Formed Plate Heat Exchanger (FPHE) technology, which is better suited to the lower pressure gas in the exhaust of a gas turbine, but this technology does not currently achieve the same mechanical integrity as PCHE (noting that the high pressure side of a supercritical carbon dioxide power conversion cycle can be greater than 200 Bar).

One technical solution to this challenge is to use a “hybrid” design, with a PCHE configuration for the high pressure CO_2 and a FPHE configuration for the lower pressure gas turbine exhaust. This reduces the back pressure on the gas turbine, reduces efficiency losses and reduces the overall size of the heat exchanger. The hybrid design therefore allows an economically viable solution for the Main Heat Exchanger to be developed.

This project has allowed Heatric to develop this technology, previously considered for an intermediate heat exchanger in a Sodium Fast Breeder nuclear power plant, in a low risk environment.

Diffusion bonding is a complex and difficult process, especially when two different heat exchange geometries need to be combined. Heatric have therefore developed new procedures and techniques for the revised geometries, to facilitate the development of this hybrid technology for application in this Waste Heat Recovery rig. Numerical tools were also developed and tested to produce three preliminary designs:

- Small scale hybrid (c. 140x180x105 mm)
- Medium scale hybrid (c. 300x600x300 mm)
- Large scale hybrid (c. 600X1500x600 mm)

Two of the three configurations were selected to be manufactured and mechanically tested. Different combinations of materials, fin specifications and bonding conditions were tried until a successful set of parameters was identified that allowed a robust sample to be produced. This work has allowed Heatric to down-select a design and manufacturing methods for the MHEX and the MHEX has now been released to manufacture.

COMPRESSOR DEVELOPMENT

Impeller

Figure 6 – Impeller

Rolls-Royce has designed a radial impeller (Figure 6) for inlet conditions just above the critical point for CO_2 (306K, 7.70MPa). The design point stagnation pressure ratio is 2.0. The design point mass flow is $5kgs^{-1}$. An impeller design speed of 50k RPM has been selected, giving an impeller diameter of 70.4mm.

For the impeller, one objective for the rig test is to determine how close to the critical point the compressor can operate efficiently. The goal is to determine whether the predicted higher cycle efficiencies for operating close to the critical point can be achieved.

In order to account for flow uncertainties, Rolls-Royce has taken a conservative approach to design of the impeller. In particular, a radial impeller has been coupled with a vaneless diffuser. Rolls-Royce believes that a radial impeller will operate stably with little or no pressure drop when it enters stall and a vaneless diffuser will be less susceptible to stall under low flow conditions (compared with a vaned diffuser).

Rolls-Royce recognises that condensation may occur in the impeller, but considers that the risk is low and can be managed. In particular, the impeller has been designed without an inducer to minimise the residence time when the flow is subcritical (and at risk of condensing). When condensation does occur, the density difference between the fluid and the gas will be sufficiently small such that the effect will be far more benign than cavitation in a water pump.

Rolls-Royce considers that the compressor could choke because the speed of sound drops by a factor of 6 around the critical point. The rig will be used to explore this effect by experiments operating close to the critical point.

Computational Fluid Dynamics

The known challenge for Computational Fluid Dynamics (CFD) analysis of a supercritical CO_2 flow is the singular behaviour of the gas at the critical point. At the critical point, the CO_2 exhibits significant non-ideal behaviour meaning that real gas models are needed for the analysis. For compressors designed to operate near the critical point, phase change effects become important. There is potential for condensation in the region located near the leading edge of the compressor, where expansion occurs. However, if residence times are sufficiently low, expansion leads to non-equilibrium condensation and the CO_2 becomes a metastable subcooled vapour. This remains true whilst the thermodynamic state is outside of the spinodal limit. Unfortunately, experimental measurements of metastable properties are not available. However, they can be obtained by extrapolating the gas properties onto the two-phase domain. Rolls-Royce is currently developing a method to model the CO_2 flow in the supercritical and metastable regions. This work will explore different methods of extrapolating gas properties, real gas CFD and the challenges of modelling CO_2 near the spinodal limit.

Figure 7 and Figure 8 (next page) illustrate outputs from the CFD.

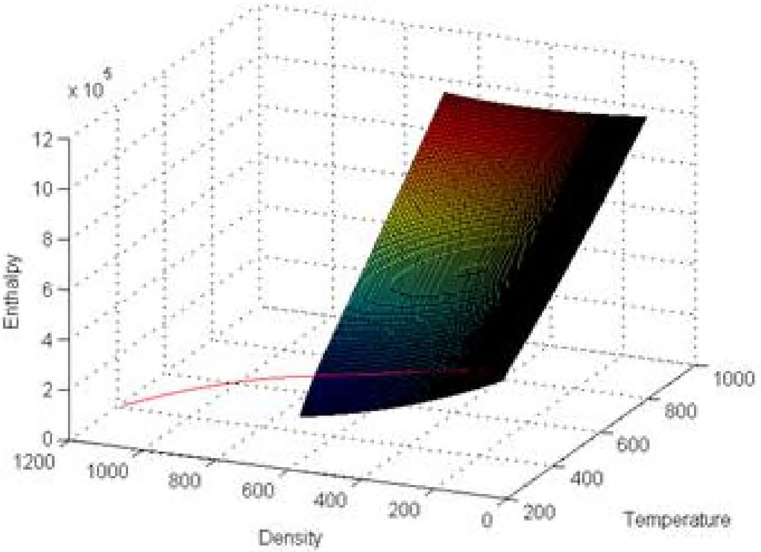


Figure 7 - Thermal properties of sCO2 under the ‘saturation dome’ extrapolated from the gas region

Figure 9 (next page) illustrates the Rolls-Royce simulations steps on a T-S diagram. Results of a simulation are used as initial conditions for the next simulation. This ensures stability and enables simulations closer to the critical point. Blue lines show the setup with theoretical calculations for efficiency and purple lines show the boundary condition properties and efficiencies recalculated by CFD. The inset view on Figure 9 shows a scattered entropy plot obtained from a random 30000 points in the CFD domain (with red and blue indicating simulations for two different inlet conditions). This illustrates that, for inlet conditions close to the critical point, some parts of the flow around the leading edge of the blade enter the two-phase region.

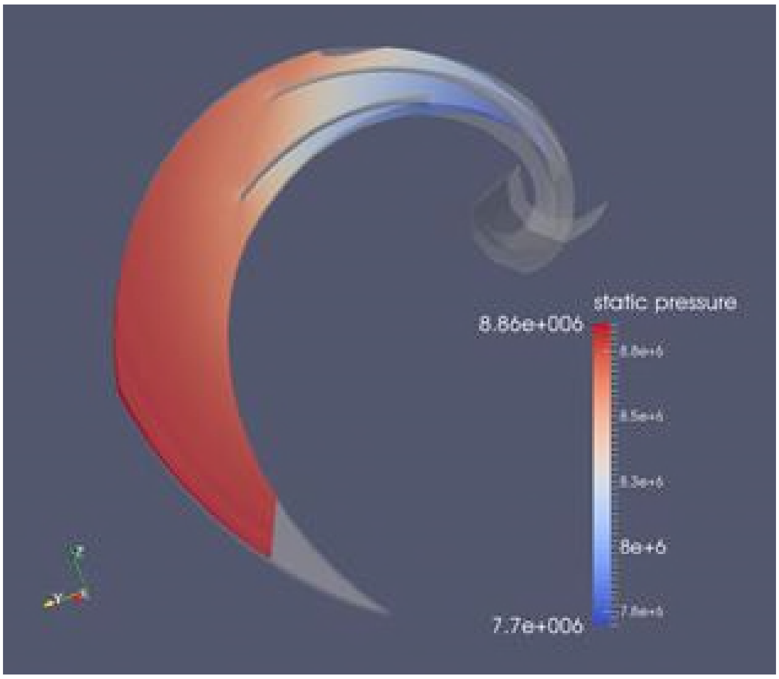


Figure 8 - Preliminary simulation results using the “real gas” model at inlet conditions of P = 7.7 MPa, T = 691.2 K

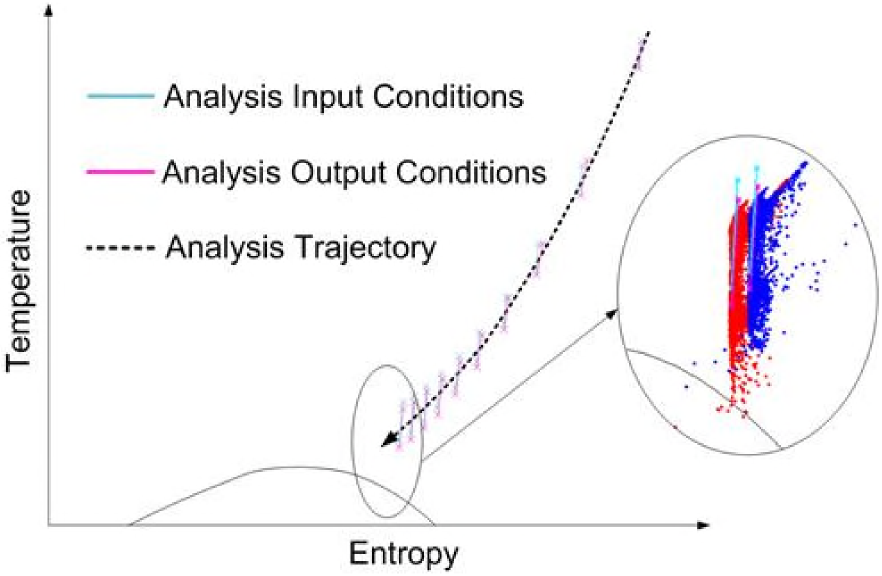


Figure 9– Summary of Rolls-Royce CFD Simulations

Compressor Design

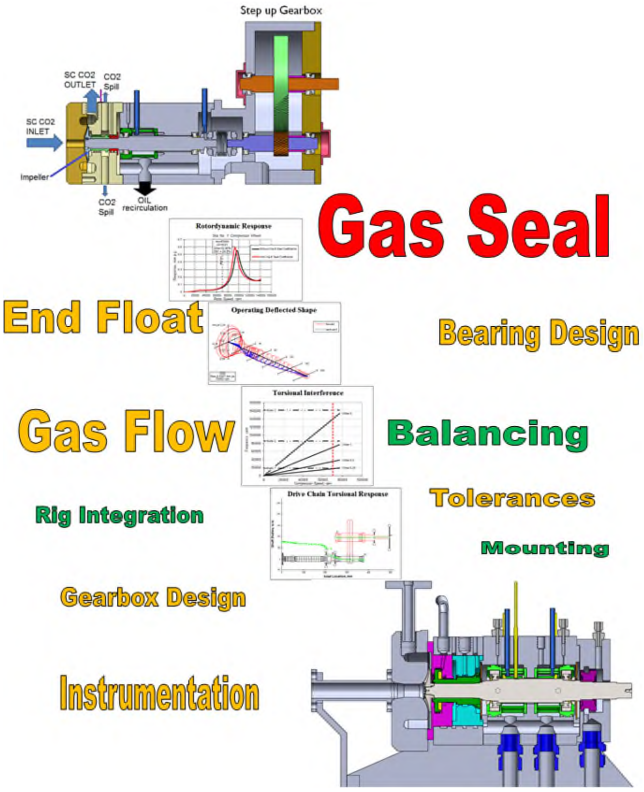


Figure 10 – Compressor development path

Figure 10 illustrates the development route toward integrating the impeller into the compressor. This is a work in progress but a design has been established that the consortium has accepted can be developed for integration into the test rig.

A number of compromises have been necessary in order to identify the most suitable compressor for the rig and it has been necessary to redefine the shaft seal. This became necessary as it was clear that the rate of gas leakage from the original design would have been excessive. We have now engaged with a seal supplier to optimise a seal for the compressor design and operating conditions.

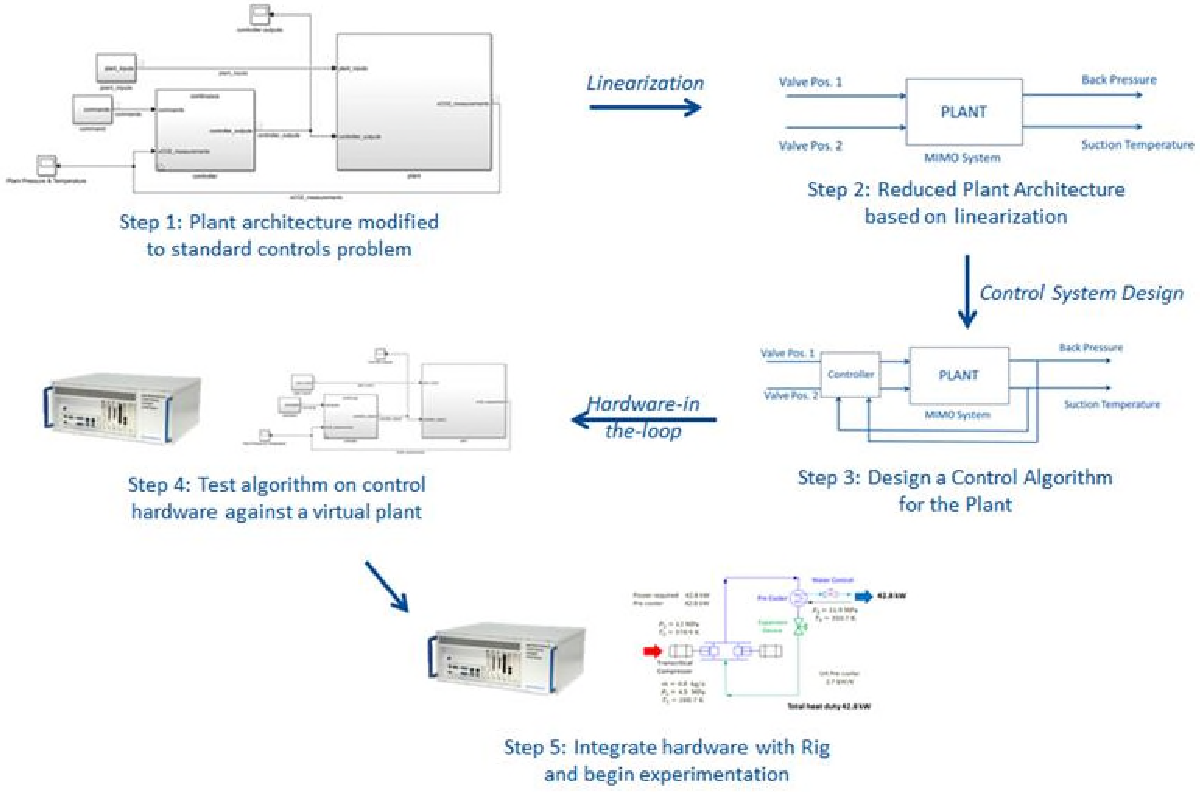
The use of a single sided centrifugal impeller means that there will be an axial load created by the pumped flow. The design therefore includes features that will assure axial location of the impeller under all load conditions, whilst providing assurance that bearing limits are not exceeded.

Control System

Rolls-Royce is developing a control system for the test rig (Figure 11 – next page), which aims to control the system to ensure that (except for the compressor) CO_2 is always supercritical and never enters the two phase region. As illustrated in Figure 12 (next page), the rig has been modelled in MATLAB, using Simscape® libraries.

The model consists of two control inputs, expansion valve and cooling water valve, with the objective of precisely controlling the pressure and temperature of the CO_2 entering the compressor. The expansion valve is in the CO_2 loop, controlling the back pressure through a valve area PID control mechanism.

The cooling water valve, in the cooling water loop, controls the amount of flow by PID control of the valve area, controlling the temperature after the pre-cooler. The control mechanism is two SISO systems (one for temperature and the other for pressure). Even though each input affects both outputs, this effect has been ignored because pressure and temperature have very different system response times (slow and fast respectively). To design a robust control system, the plant architecture has been linearized to find the relationship between the individual inputs and outputs. With plant transfer functions obtained via linearization, the controller was tuned to obtain stable characteristics and response behaviours. Ultimately, the controller will be connected to the rig using a Speedgoat target computer.



Step 1: Plant architecture modified to standard controls problem

Step 2: Reduced Plant Architecture based on linearization

Step 3: Design a Control Algorithm for the Plant

Step 4: Test algorithm on control hardware against a virtual plant

Step 5: Integrate hardware with Rig and begin experimentation

Figure 11– Rolls-Royce Control System

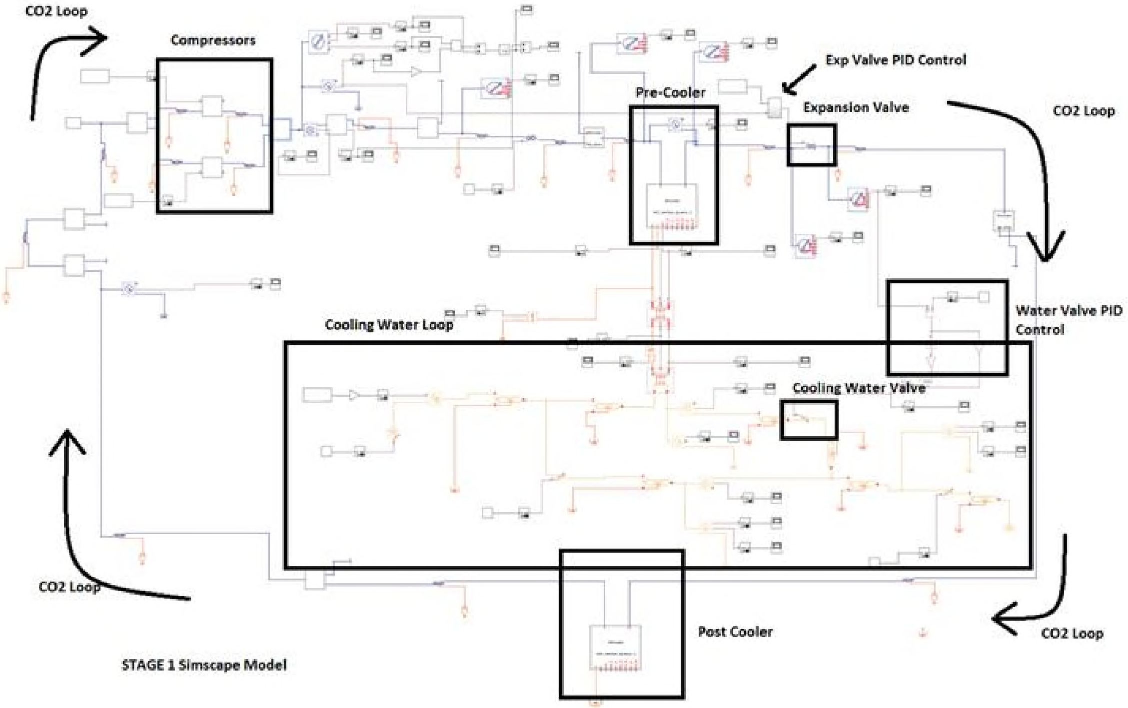


Figure 12– Rolls-Royce MATLAB Model

SUMMARY AND FUTURE PLANS

This paper describes the development phases of a supercritical CO_2 closed loop system to enable testing of key components of a representative waste heat recovery system. The consortium objective for this test rig is not linked with specific cycle architectures or system designs, but rather to de-risking the design, manufacture and implementation of components and systems. The sCO_2 closed loop test rig being developed at Cranfield allows us to de-couple testing of the main heat exchanger and the compression system by means of separately controlled sub-loops. Commissioning of the circulation loop is currently planned for early 2018 with initial tests planned for later in the year. It is hoped to publish results from the tests in due course.

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LIST OF SYMBOLS

FHPE	Formed plate heat exchangers
GT	Gas triangle
IMO	International Maritime Organization
MHEX	Main heat exchanger
NIST	National Institute of Standard and Technology
PCHE	Printed circuit heat exchangers
PR	Pressure ratio
PRV	Pressure relief valve
TRL	Technology readiness level

Meet the authors	Working for the research project called: Supercritical CO2 Waste Heat Recovery for Marine Gas Turbines, which has received funding from Innovate UK under project reference 101982. It comprises a consortium of three partners: Rolls-Royce plc (lead participant), Meggitt (UK) Limited and Cranfield University.
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	Professor Vassilios Pachidis is the Director of the Rolls-Royce University Technology Centre for Aero Systems Design Integration & Performance at Cranfield University. He also heads the Gas Turbine Engineering Group within the Propulsion Engineering Centre. He is the Principal Investigator of the Innovate UK funded consortia. He holds a MEng from The University of Liverpool and an MSc and a PhD from Cranfield. His main research focus is on gas turbine performance and certification, novel cycles, turbomachinery experimental, analytical and computational aerodynamics, propulsion system integration and environmental performance.
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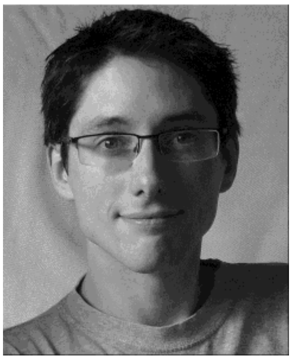	Michael Johnston MEng CEng is a chemical engineer specialising in compact heat exchanger development. Michael currently works for the Heatric division of Meggitt designing Printed Circuit Heat Exchangers. He has also worked designing and developing heat exchanger technologies for use in aircraft engines whilst working for Meggitt Control Systems. For the past 3 years Michael has been developing new heat exchanger technologies for use within a supercritical CO_2 waste heat recovery system as part of the Innovate UK funded consortia. Michael has a MEng in Chemical Engineering and has assisted with process modelling and safety reviews of the test rig as part of this project.

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An overview of the Rolls-Royce sCO2-test rig project at Cranfield University

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