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Development of an experimental S-CO_2 loop for bottoming cycle applications

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Abstract: This paper describes the design of a supercritical carbon dioxide [S-CO_2] rig for bottoming power cycle applications. The final envisaged layout of the facility includes a fully coupled compressor-turbine system, a number of heat exchangers to enable heat management of the cycle and a control system for start-ups, shut-downs, inventory control and transient operation of the loop. The objective of the preliminary design phase is to experimentally de-risk the robustness of the closed loop system as well as prove the purpose of individual components and various measurement and control modules.

1. Introduction

Waste heat recovery is the process of using residual exhaust heat to generate additional power from a primary (topping) power cycle. This approach has notable benefits in terms of combined cycle efficiency enhancements without additional fuel burn. However, it comes with the pitfall of increased footprint and weight of the retrofitted topping power plant. This drawback can be addressed by a S-CO_2 plant, which offers the possibility of substantially high power-to-size/weight ratios [1].

The rig design described herein is a pilot research project, aiming to de-risk the development of key components for a future prototype demonstrator of a bottoming S-CO_2 power cycle. During the preliminary stages of this work, the focus is on testing the compressor and the main heat cycle exchanger (MHEX). In order to de-risk each component individually, the envisaged closed loop S-CO_2 system allows de-coupled testing of the main heat exchanger and the compression system by means of the sub-loops that are separately controlled.
The project incorporates some of the lessons learned from existing test facilities of this type [2-11].

2. Rig design considerations

The aim of this project is to design, build and commission a closed loop S-CO_2 system to enable critical component testing and whole cycle demonstration of a representative waste heat recovery system. As starting point, a simple recuperated Brayton cycle has been selected as a baseline reference system. This design choice will allow interfaces with data acquisition and control systems and a gradual development and implementation of more sophisticated layouts such as simple recuperated split shafts or nested expansion configurations.

The development of the facility comprises the following stages (see also Table 1):

1. Development of the baseline SCO_2 closed loop facility and specification of required components and opeating processes.
2. Development of a high-pressure air-to-CO_2 compact heat exchanger.
3. Design and development of an S-CO_2 compression system. This includes the design definition of the main flow path as well as the mechanical design of the system.
4. Development and implementation of data acquisition and rig control systems for operating the test loop:
    - Compressor speed / recirculation valves
    - Start-up/shut-down procedures
    - CO_2 inventory control

Table 1- Roadmap of the test rig development

Stage	Components	Outcomes
I	Circulation compressor, expansion valve, post cooler	- De-risk S-CO_2 loop. - Demonstrate component/rig robustness and proof of concept. - Demonstrate pressure and temperature acquisition data at supercritical state.
I + MHEX	MHEX, combustor, pre and post cooler, circulation compressor, expansion valve	- Test MHEX performance. - Demonstrate pressure and temperature control cooling system.
II	Stage 1 + centrifugal compressor, expansion valve	- De-risk compressor installation. - Demonstrate pressure and temperature control at supercritical state. - Demonstrate compressor performance at representative PR. - Demonstrate representative uncoupled rig control.
III	Stage 1 + centrifugal compressor, turbine - uncoupled	- De-risk turbine installation. - Demonstrate uncoupled design point performance and control. - Demonstrate part load/transient
IV	Stage 1 + centrifugal compressor, turbine - coupled	- Demonstrate coupled design point performance and control. - Demonstrate start-up & shut-down process of representative cycle.

3 . Description of the experimental loop

The combined conceptual schematic diagram of stages I, I + MHEX and II is shown in Figure 1. The loop at stages I and I + MHEX comprises of a main heat exchanger, an expansion valve, pre- and post-cooler heat exchangers and a transcritical compressor. A combustor will provide the required heat input to the system while the heat sink will be an evaporative cooling system. Stage II features the centrifugal compressor and the recirculation anti-surge valve. Ultimately, a fully coupled operation of the compression – expansion systems is envisaged. Table 2 summarises the main operating parameters of the envisaged S-CO_2 facility.

Table 2- Design parameters for the S-CO_2 rig test facility.

Parameter	Stages: I / I + MHEX	Stage II
Overall Pressure Ratio	2.66	1.95
Top pressure [MPa]	12	15
Top temperature [K]	450 / 820	820
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	

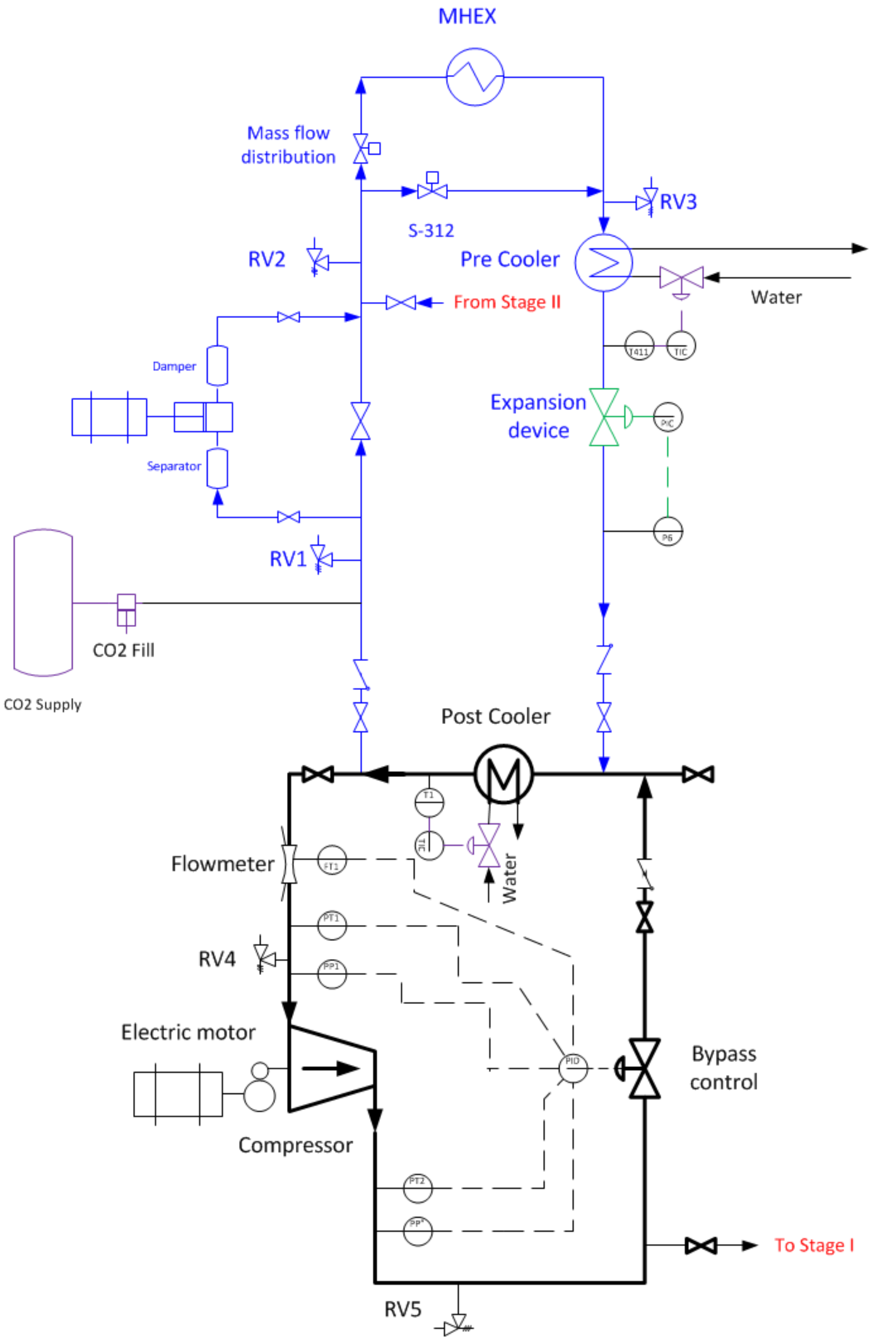

Figure 1 – Schematic of the envisaged S-CO_2 test rig. Blue: Stage I loop, Black: Stage II loop.

4. Loop design considerations

The initial phases of the rig commissioning process will address closed loop system robustness, monitoring and controllability of gas properties across the system, CO_2 inventory management and health and safety considerations.

Heat exchanger testing will be the objective of rig Sage I and Stage I + MHEX. The design will feature a "hybrid" printed circuit (PCHE) and formed plate heat exchanger (FPHE) technology (see Southall *et al.* [11]). The former has been used in recuperation applications, including S-CO_2 rig test at high pressure (SANDIA [7,12], Bechtel [8]). The latter is more applicable to low pressure cases as its mechanical integrity at high-pressure is questionable. Combination of these two technologies will extend the applicability at high pressures.

A set of transcritical compressors from the refrigeration industry will be used to deliver the specified flow rate of 1 kg/s for Stage I. For the expansion process, a control valve will temporarily replace the turbine required in these cycles. A series of flow mixing and splitting points shown in Figure 1, will be used for temperature control across the system.

A bespoke, supercritical centrifugal compression system will be commissioned and tested during Stage II of the facility development. Lessons learnt from previous stages will allow a progressive implementation of more sophisticated measurement techniques. At stage II, pressure and temperature measurements will be introduced at key loop stations such as compressor inlet, compressor outlet and post cooler inlet. Additionally, 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, platinum resistance temperature detectors of class A will be used (± 0.2 K envisaged accuracy). Finally, for mass flow and density measurements, Coriolis mass flow meters (±0.1% envisaged accuracy), will be installed at the inlet of the compressor.

5. Summary and future plans

This abstract 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. This loop is designed to satisfy testing requirements of each major component in a flexible environment. Commissioning of the loop is currently planned for early 2017 with initial tests planned for later that year.

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8. List of Symbols

FHPE	Formed plate heat exchangers
MHEX	Main heat exchanger
PCHE	Printed circuit heat exchangers

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