Conceptual design of the rig

CCUS Innovation 2.0

Key Knowledge Deliverable 3.1

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Key Knowledge Deliverable Cover Sheet

This Key Knowledge Deliverable (KKD) has been produced by Cranfield University as part of the Department for Energy Security and Net Zero £1bn Net Zero Innovation Portfolio (NZIP) - CCUS Innovation 2.0 programme. The document is reflective of the status of the project at the time of writing. The material presented could have been subject to change as the project matured. These documents should not be considered a full representation of the final project.

Supercritical CO2 power cycles are a novel process currently under consideration across the energy sector, including for carbon capture, utilization, and storage (CCUS). Compared with conventional steam-driven systems, they boast higher cycle efficiencies, reduced emissions, and compact turbomachinery, resulting in reduced fuel and water consumption and lower capital expenditures. Through this project, John Crane—in collaboration with Cranfield University and the University of Edinburgh—aims to develop an innovative, uncooled high-temperature dry gas seal solution for supercritical CO2 power cycles by using new simulations, material recipes and testing validations. This innovative dry gas seal, expected to work at high temperature and pressure values, will significantly reduce leakages and potentially enable the inclusion of an additional turbine expansion stage resulting to a higher efficiency CO2 cycle. Through a supercritical CO2 cycle efficiency improvement, overall emissions will be significantly reduced, cutting the cost of CCUS and accelerating the adoption of supercritical CO2 power cycles into existing and future power plants.

KKD 3.1 focuses on the conceptual design of the supercritical CO2 (sCO2) loop. This loop will be integrated into the test apparatus provided by John Crane. The primary objective of this stage is to ensure that the sCO2 loop will function effectively and efficiently within the provided test apparatus.

KKDs to be released in full:

D2.2 Performance of 3D printed discontinuous fibre reinforced polymer composites.

D3.1 Conceptual design of the rig

D3.2 Component commissioning of CO2 source (subsystem 1)

D3.3 Integrated sub-systems test - Shakedown test

D4.1 Commissioning of rig at John Crane

D4.2 Integrated system + seal rig commissioning at Cranfield University

KKDs to be released after being modified with critical information removed:

D3.4 Design and build of static/ dynamic test cell for 300 bar, 250 ºC

D3.5 Design and build of static/ dynamic test cell for 200bar, 600 ºC (CO2)

D4.3 Test of rig operating at 200 bar, 300 ºC (CO2)

D4.4 Testing to 200 bar, 250 ºC

D4.5 Testing to 200 bar, 500 ºC (CO2)

D5.1 Design/ build test seal with new seal head module/ bd-module

D5.2 Dynamic seal testing/ Benchmark testing, 140 m/s, to 200 bar, to 200 ºC

D5.3 Dynamic Seal Testing, 140 m/s, to 200 bar, to 200 ºC

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Introduction

Project Overview

Supercritical CO2 (sCO2) power cycles represent a cutting-edge development in the energy sector, with broad applications that extend to carbon capture, utilization, and storage (CCUS). These cycles are gaining increasing attention for their potential to revolutionize power generation and reduce its environmental impact. Compared to conventional steam-driven systems, sCO2 power cycles offer a range of compelling advantages, including high cycle efficiency, reduced emissions, compact turbomachinery, and reduced fuel and water consumption. In pursuit of these benefits and to overcome critical challenges, John Crane, in collaboration with Cranfield University and the University of Edinburgh, has embarked on a visionary project. The project's objective is the development of an innovative, uncooled high-temperature dry gas seal solution tailored specifically for supercritical CO2 power cycles. This endeavour involves cutting-edge simulations, advanced material recipes, and rigorous testing validations.

Purpose

The purpose of this report is to provide details on the status of the Project after the conceptual design of sCO2 rig.

Vision of the experimental activities

Testing of the new balance diameter sealing module will be occurred into two stages:

1. In air to 250 °C– John Crane UK.
2. In CO2 to 500 °C – Cranfield University.

The objective of the test campaign is to produce performance maps that can verify and validate the results of Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) studies. The sealing capability of the entire balance diameter sealing arrangement will be tested under representative conditions of CO2 at Cranfield University. Temperature measurements will be taken at various locations to map the temperature profile throughout the sealing module. The test campaign will be successfully concluded if the extrusion resistance of the balance-diameter sealing module is within the design specifications for a Dry Gas Seal (DGS).

Experimental facilities at Cranfield University

The experimental activities of the project are going to be developed around an existing industrial scale facility currently operating in Building 205A of the Gas Turbine Laboratories in Cranfield University.

The supercritical CO2 breadboard was developed during the years 2015 - 18 as part of the Innovate UK project 101982 “Supercritical CO2 Waste Heat Recovery for Marine Applications”. The project was joint research between Rolls-Royce plc, Heatric (Division of Meggitt plc) and Cranfield University. The design of the breadboard adopted a modular approach [1]. 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. Figure 1 shows the modular and staged development followed. Presently, the rig comprises three stages or loops: Gas triangle, Stage 1A and Stage 1B. Stages are interconnected through a manifold (not shown), which allows the deviation of the CO2 stream at supercritical state to the stage under testing while bypassing the remaining stages. The basic principle for testing is to maintain a transcritical circulation loop, using different expansion devices to adjust the intermediate/low pressure level and mass flow in each branch. The circulation loop is a modification of a transcritical CO2 refrigeration system (shown in Figure 2), which can be adjusted to provide a reliable source of carbon dioxide in a supercritical state for testing heat exchangers. The rig is currently used in Innovate UK / Aerospace Technology Institute UK project led by Rolls- Royce plc and has been used in several other industrial contracts.

Figure 1: sCO2 Breadboard concept at Cranfield University

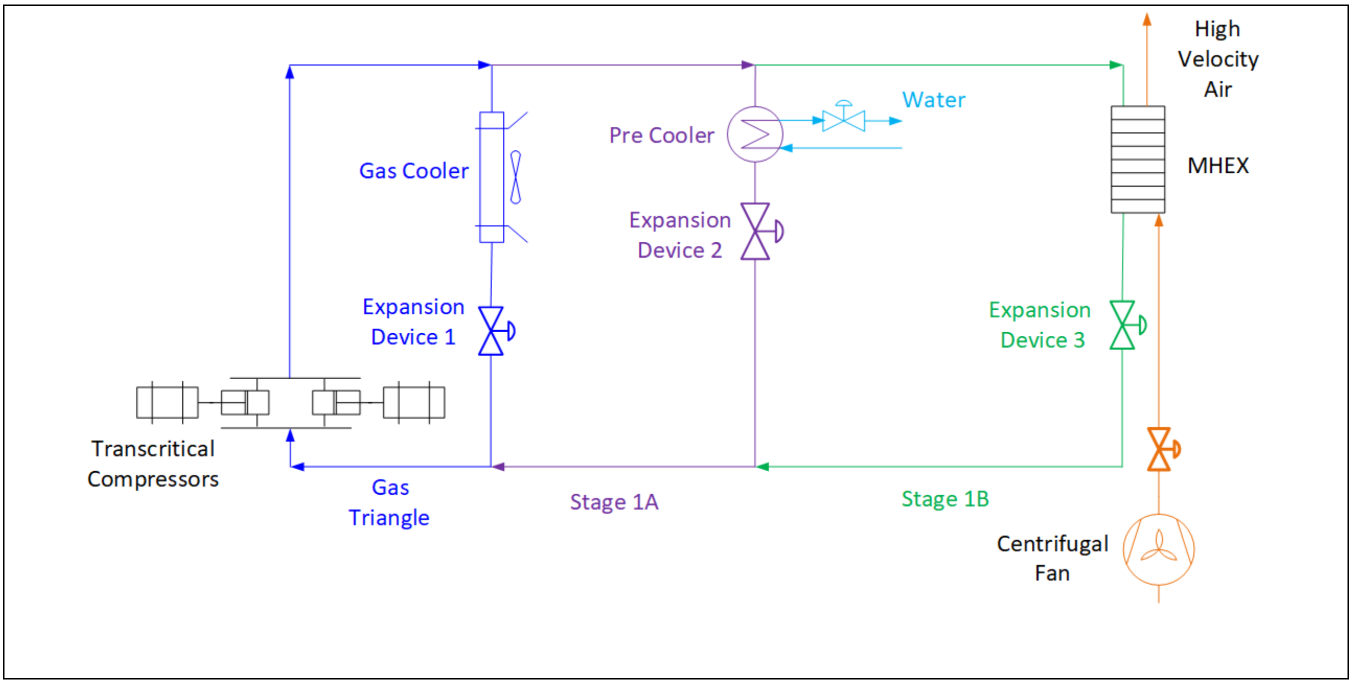
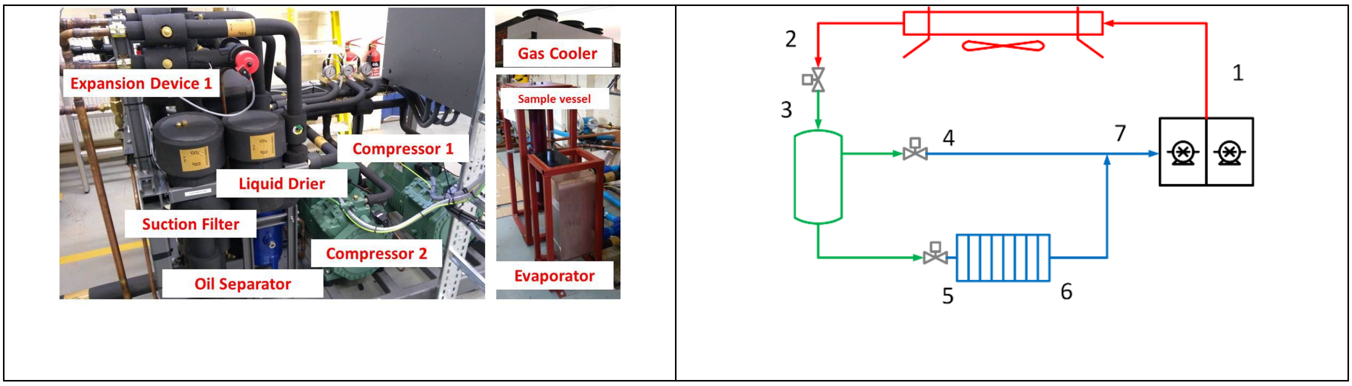


Figure 2: Transcritical CO2 circulation loop at Cranfield University



The existing sCO2 test loop requires modification to satisfy the testing requirements of this DESNZ project. On one hand, new equipment should be acquired to guarantee the delivery of CO2 to the balance diameter sealing module at specific conditions of flow, pressure, and temperature. On the other hand, equipment from the current supercritical CO2 breadboard will be reconfigured or relocated, diverting the CO2 stream accordingly to requirements of cooling or heating.

There are technical challenges that need to be addressed in the development of the test campaigns of this project, among them:

- sCO2's target temperature to be delivered at the sealing module requires a free oil stream of CO2.
- sCO2's target temperature to be delivered at the sealing module requires a controlled profile of temperature increase.
- sCO2's target mass flow to be delivered at the sealing module requires circulation units that favour steady state performance at low flows.

- sCO2’s target pressure to be delivered at the sealing module requires an increasing pressure device that is rated to reach those levels with minimal power consumption.
- Due to the high temperatures and pressures added to the CO2 stream delivered to the John Crane test apparatus:
    - There is no certainty that the composite seals to be used in the test apparatus, will not degrade into the sCO2 stream, contaminating it.
    - Returning the sCO2 stream to the rig (in a closed loop) will require filtration, and temperature conditioning equivalent to the heat load applied.
- Operation of valve system should avoid “water hammer” effects or sudden depressurisation of the test apparatus (sealing module).
- Delta pressures across components imply the risk of sealing failures and pipe whip.
- Temperature levels of the rig vessels (and test apparatus) should be controlled across the whole range of operations.
- Continuous and timely supply of CO2 to the test apparatus during operations of filling/depleting should be guaranteed.
- Noise during operations of the modified test loop should be in accordance with HSE regulations.

Methodology

For the conceptual design of the test rig, a simple approach was followed:

1. Problem definition.
2. Determining experimental approach.

The conceptual design of the test rig was based on fundamental principles. The output was the size of the equipment for a test rig that can satisfy the required functionalities. From the sizing exercise the cost and the development timescales are evaluated.

Problem definition

As pointed out in the previous section of “Vision of the experimental activities”; the overall objective of the experimental program at Cranfield University is to produce performance maps of novel DGS components that can verify and validate the results of FEA and CFD studies performed by John Crane. From the development point of view, the challenge for Cranfield University is to develop a test loop able to provide carbon dioxide (CO2) in representative conditions to the test apparatus containing the sealing module. Stream process conditions requested (in design point) are shown in Table 1:

Table 1: Carbon dioxide representative conditions requested.

Process Variable	**Value [Unit]**
Pressure	≤ 200 bar(g).
Temperature	≤ 500 ºC
Purity	As per R744 refrigerant – (purity of 99.995%)

Following these fluid properties requirements, complementary key requirements were collected:

- Carbon dioxide flow, temperature and pressure should be delivered/retrieved in ø1/2” BSP ports.
- Supply and venting of CO2 under control of the test loop.
- Ramps for supply and venting CO2 are still under assessment, however heat of the rig will be achieved by other means than the CO2 supply.
- Estimated time for testing each sealing module is around 30 to 45 minutes, seals will be visually inspected after the test is concluded and the unit accessible.
- Number of tests per day: max (2) two (considering warming up and cooling down of the John Crane test apparatus).

- Preliminary dimensions of the test apparatus footprint are around 2 square meters.

The requirements reflect the necessity of a test loop that operates intermittently supplying supercritical CO2 on demand. Therefore, the problem definition of the test loop can be summarized as: How to provide a stream of CO2 at specific supercritical conditions, into a test apparatus, in a controlled and safe manner, for short periods?

Determining experimental approach

Several experimental approaches were conceived at the outset, analysing the capabilities of the current equipment of Cranfield's sCO2 rig and its future integration with the test apparatus to be provided by John Crane. Attention to the properties of the rig's working fluid, CO2 as a refrigerant R744 [2] was also given:

- R744 is non-corrosive, non-toxic and non-flammable.
- R744 has no Ozone Depletion Potential (ODP=0) and minimum Global Warming Potential (GWP=1).
- R744 is a quota-free product, there are not restrictions on production, import or use in the F-Gas Regulation.
- R744 does not have a specific release quota to the atmosphere, but it has workplace inhalation exposure limit threshold limit value for 8 hours period of 5,000 ppm, and for 15 minutes, 15,000 ppm [3].

Following the challenges and requirements already mentioned, and taking into consideration R744 properties, the proposed approach of the experimental approach is:

- The test loop is aimed firstly to de-risk the operation of the test apparatus and, secondly to enable the execution of test matrices which will allow the collection of data of the sealing module.
- The test loop will be an open loop, controlling the supply and release of CO2 to the atmosphere (no specific need to include the John Crane test apparatus in a closed test loop).
- The test loop will be a scaled mini plant, located in the same facility (Bd205a) of the current rig, to take advantage of the gas detection system, data acquisition systems, and proximity to sources of heat, electricity, and water.
- Operation of the test loop will aim to exert control over the temperature of the CO2 stream, with the capability of providing ramps in pressure, flow and temperature, and keeping steady targets of the same parameters.
    - The current sCO2 rig does not have mean to increase temperature independently.
- The pressure-increasing device will be different from the current compressors used in the sCO2 test rig due to the following:

    - Bitzer Compressors 4FTC-30K are not oil-free, they use oil BSE 85K which has a flash point of 246 ºC (ISO 2592). This is less than the temperature requirements of the test.
    - Compressors can deliver up to 130 bar(g) of pressure which is less than the pressure requirements of the test.
    - Compressors can deliver a minimum mass flow which is 180 times bigger than the mass flow requirements of the test.
- Controlled expansion of the CO2 should be aimed, to avoid uncontrolled release of CO2 into the atmosphere.
- Final release of the CO2 (when required) should be performed outside of the building in a well-defined no-access perimeter to avoid any workplace exposure.

The general experimental approach can be summarised as: Development of an open loop mini plant that can provide CO2 at a supercritical state, on-demand and following pre-determined temperature profiles (pressure, mass flow and purity (%) can be assumed constant for the purpose of the test campaigns). Currently, future test matrices seem to be set around testing different materials and geometries of the sealing module. Therefore, the conceptual design of the mini plant is focused on the delivery of CO2 streams to the test apparatus in its different operational scenarios: commissioning, operational test, and component inspections.

Calculations reference

All calculations of the mini plant (test loop) were performed using NIST REFPROP [4] as a database for the thermophysical properties of the fluids into consideration. Calculations were performed following chemical process engineering principles for design point steady state. A preliminary model of the mini plant was also created in SIEMENS AMESIM to provide input about off-design trends in performance.

Calculations were aimed to produce a first Process Flow Diagram (PFD) of the test loop, to show expected stream CO2 values of pressure, temperature, and flow during normal operation. These tabulated design values showed the connectivity and relationships between the test loop and external units such as the hot air source required to elevate the temperature of the CO2 up to 500 ºC.

Selection of materials

The initial assumption is that equipment and tubing operating with CO2 (R744 grade) will use stainless steel 316/316L as the material of construction. This material is well known for its superior corrosion and oxidation resistance (compared with SS 304). Even for stainless steel with a low concentration of chromium (less than 18%), the recommended maximum service temperature (oxidising conditions) for intermittent service lies around 819 ºC [5], which is sufficient for a short-time-span pilot plant of CO2.

Test rig (mini plant) process description

The test rig is an open loop system that will provide the required carbon dioxide stream to a John Crane test apparatus. The test rig or mini plant will consist of the following elements:

- CO2 storage.
- CO2 conditioning
- CO2 pump
- CO2 pre-heater
- CO2-heater
- CO2 expansion
- Control of the test rig

A general process flow diagram of the mini plant, which includes information about tubing, measurement, control, and materials; it is shown in the diagram CCUS2108-CU-P&ID-001 version A. Therefore, this drawing is an early version of a piping and instrumentation diagram (P&ID) to guide conversations with providers about tubing diameters, materials of construction, and insulation properties, controller architecture and instrumentation to be required. The drawing **CCUS2108-CU-P&ID-001 version A** constitutes the main outcome of the deliverable D3.1 and it is provided separately as an attachment.

CO2 storage

The supply of R744 (CO2) will be achieved by using high-pressure cylinders containing R744 in liquid form. These cylinders are equipped with a manifold that allows swapping the active cylinder (being depleted) with a spare cylinder (fully charged). The active cylinder is going to be safely sitting on a refrigeration weight scale to monitor the depletion process. Downstream of the manifold a pressure regulator might be set to maintain the CO2 at the desired conditions of 20°C temperature and 58 bar(a) pressure. Additionally, a pressure gauge can report the pressure of the system towards the condenser. Alternatively, the flow of refrigerant from these cylinders can be also conveyed to the subsequent component using a liquid connector hose with a manual isolation valve.

CO2 conditioning

This subsystem will guarantee that sub-cooling conditions at the inlet of the liquid pump are satisfactory, preventing any vaporisation of the CO2 from its source. It is comprised of a condenser linked with a chiller. The chiller will be dimensioned to keep temperatures of the CO2 stream down to -20 ºC if required. Temperature, mass flow rate and density will be monitored by a Coriolis flowmeter, which is strategically placed between the condenser and the next component, which is a liquid pump. The conditioning system should be rated up to 80 bar(g), capable of handling R744 from the source without a pressure regulator.

CO2 pump

As a mechanism for circulating and increasing the CO2 pressure, a liquid CO2 pump was chosen. The operative range of the pump was selected to overcome unknown pressure losses in the system and unexpected leakages in the test apparatus. The required flow of CO2 will be achieved using variable speed drive of the electric motor (preferable) or control valve downstream of the pump. Performance control of the liquid pump is required (head vs flow rate). Pressure and temperature measurements will be monitoring the controlled discharge of the pump unit toward the pre-heater. It is expected that the setting of pressure discharge (above 200 bar(a)) will be adjusted after the commissioning of the mini plant.

CO2 pre-heater

Given the energetic requirements to increase the temperature of the CO2 up to 525 ºC, a staged approach was decided. At first, a pre-heater (preferably electrical rather than oil-supported) will increase the temperature of the stream up to 300 ºC. A temperature signal at its discharge will control the rate of heat input towards the CO2 stream. The pre-heater unit will deliver hot CO2 to a high-temperature manifold which can divert the fluid either to a commissioning line or to the heater. It is envisaged that the pre-heater can be operated linked to the pump, to avoid scenarios of low or no flow to the pre-heater.

CO2 heater

The heater is the most critical component of the system as deals with both high pressure (211 bar(a)) and high temperature (from 300 to 525 ºC) of the CO2 stream. The current conceptual design of the mini plant operates under the assumption that the heating media will be coming from a nearby facility called “pebbled bed” (located at 35 m from the mini plant). This facility can provide non-vitiated air up to 1,500 ºC, at 15 bar(a). However, for this concept, only a fraction of the hot air at reduced pressure (3 bar(a)) and temperature (540 ºC) will be used. The heater will operate as one-step temperature-increasing device for the CO2 stream. Delivering the final target temperature to the test apparatus, monitored via a temperature measurement.

CO2 expansion

The supercritical CO2 gases coming from the John Crane test apparatus will be collected and expanded before being released to the atmosphere in an outdoors-elevated stack. Due to the nature of the process, the expansion will occur in a staged manner using two orifices (diameter relationship (beta) of 0.75 and 0.5) located in the inlet and outlet of a damping vessel (high pressure rated). Conditions of pressure and temperature of the expansion vessel will be monitored to adjust the size and number of chokes (to avoid critical pressure ratios). A manual valve, downstream orifice 2, will isolate the system. Alternatively, a printed circuit heat exchanger (such as the one used in Stage 1B of the original sCO2 rig) could be used to reduce the temperature of the stream and enable the coupling of a control valve for the final segment of the mini plant.

Control of the test rig

The control philosophy for the test rig (mini plant) is described with the signal and corresponding equipment controlled.

- Flow, density, and temperature measurements of the CO2 upstream to liquid pump, will be monitored via a Coriolis flowmeter (FM350). Pressure (PT20) and temperature (TT21) at the pump's discharge will be also monitored. Performance of the liquid pump, will be controlled by adjustment of the electric motors speed using variable speed drives.
    - Low flow or low pressure at the suction of the liquid pump will be reported through the same controller.
    - High or low temperatures at the suction of the liquid pump will be monitored and reported via the chiller's internal thermocouple.
    - Visual monitoring of CO2 cylinder depletion will be possible through by: weighting CO2 content of the active cylinder, and pressure indication in the pressure gauge (PG10).
- Low or high temperature at the discharge of the preheater will be reported by temperature measurements (TT31). The performance of the pre-heater will be controlled by adjustment of current to the electrical heater.
    - Visual monitoring of CO2 temperature towards the heater will be possible through a temperature gauge (TG40)
    - High or low pressure at the suction of the heater will be monitored and reported via pressure transmitter (PT30)
- Low or high temperature at the discharge of the heater will be reported by temperature measurements (TT41). The performance of the heater will be externally controlled by adjustment of airflow through the pebble bed.
    - External control is already in place for the pebble bed, communication protocol is required to couple the interaction of both systems.
- Pressure and temperature at the discharge of the expansion vessel, will be monitored and reported via pressure transmitter (PT50) and temperature transmitter (TT51).
- Emergency stop via centralized safety relay, which once activated will cut off electrical supply to liquid pump and pre-heater.

- Supply of R744 will be isolated at the pump inlet.
- Supply of hot air to the heater will be requested to the external controller of the pebble bed.

Pipe dimensions

High-pressure tubing of running lengths below 5 meters will be used in the current design. The pressure losses across the running tubes are expected to be less than 10% of the entry pressure of each tube. Most pre-selected equipment uses connections of ø1/4”, ø1/2” and ø5/8” for the CO2 stream. Preliminary tube selection is presented in Table 2, reflecting allowable working pressures based on equations from ASME B31.3 for a stress value of 138 MPa at -28 to 37 ºC, and then corrected at elevated temperatures [6].

Table 2: Suggested allowable working pressure for stainless steel tubing.

Tube OD (in)	Tube wall thickness (in)	Working pressure (bar(g))	Allowable* working pressure (bar(g)	Fittings and accessories available
¼	0.035	352	268	Yes
¼	0.065	703	534	Yes
½	0.065	352	266	Yes
5/8	0.095	414	315	Yes

*Pressure rating corrected at 537 ºC for SS316/316L (factor of 0.76)

All equipment named or represented in the diagram CCUS2108-CU-P&ID-001 version A, corresponds to the actual equipment price quoted thanks to the development of this P&ID. More details will be disclosed as the project evolves.

Recommendations

The conceptual design has identified opportunities for improvement in the selection of the heating source for the sCO2 heater. Mechanisms to integrate the control of the pebble bed with the control of the sCO2 rig will require additional resources not contemplated initially.

The control strategy shall be developed further when more detailed information is available for equipment such as sCO2 heater and its integration with the JC test apparatus.

Additionally, complementary documentation such as a cause & effect matrix shall be developed, and a systematic process hazard analysis shall be performed, e.g., hazard and operability analysis (HAZOP), with the participation of the test apparatus owner, technology, and engineering consulting providers, and experimentalist personnel.

The development of numerical models of the mini plant will contribute to estimating the off-design performance of the rig, and identifying additional resources required for the commissioning, operation, and maintenance of the mini plant. The same models can be upgraded as transient models, as input of the control logic of the rig.

Key Knowledge Deliverable

In order to develop a sustainable and permanent test rig for future testing of DGS technologies associated with CCUS applications, the following conditions should be addressed:

1. The test apparatus and test loop should be designed and integrated in a closed loop, which allows filtering and temperature conditioning of the carbon dioxide stream for continuous re-utilization.
2. The design and manufacture of the sCO2 heater should be defined well in advance (more than 12 months), in order to identify providers that can manufacture bespoke equipment for continuous service above 900 ºC and 300 bar(a).
3. Ideally, the operation of the test loop should have provision for component inspection of the sealing module without compromising continuous operation of the mini plant or time-consuming re-setting of the loop.

The current conceptual design has been successful in addressing two requirements for future applications:

4. Modularity of the mini plant, which allows easy reconfiguration/re-location of it.
5. Capability of addressing temperature profile in the CO2 stream using heating stages.

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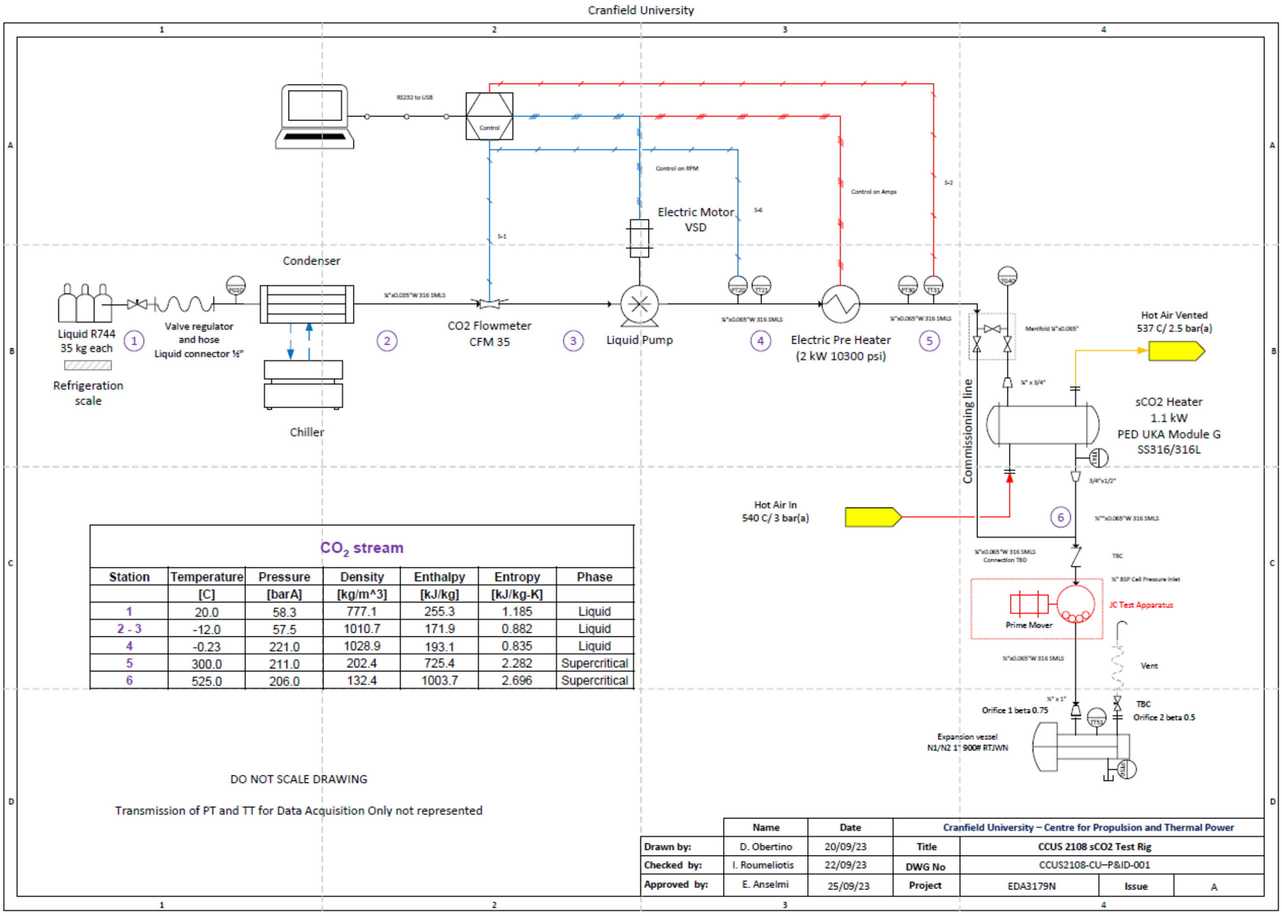
Appendix



CO_2 stream

Station	Temperature [C]	Pressure [barA]	Density [kg/m^3]	Enthalpy [kJ/kg]	Entropy [kJ/kg-K]	Phase
1	20.0	58.3	777.1	255.3	1.185	Liquid
2 - 3	-12.0	57.5	1010.7	171.9	0.882	Liquid
4	-0.23	221.0	1028.9	193.1	0.835	Liquid
5	300.0	211.0	202.4	725.4	2.282	Supercritical
6	525.0	206.0	132.4	1003.7	2.696	Supercritical

	Name	Date	Cranfield University – Centre for Propulsion and Thermal Power			
Drawn by:	D. Obertino	20/09/23	Title	CCUS 2108 sCO2 Test Rig		
Checked by:	I. Roumeliotis	22/09/23	DWG No	CCUS2108-CU–P&ID-001		
Approved by:	E. Anselmi	25/09/23	Project	EDA3179N	Issue	A

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