Integrated system & seal rig commissioning at Cranfield University

CCUS Innovation 2.0

Key Knowledge Deliverable 4.2

November 2024

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 carbon dioxide (sCO_2) power cycles are a novel process currently under consideration across the energy sector, including for carbon capture, usage, 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 CO_2 power cycles by using new simulations, material recipes and testing validations. This innovation, expected to work at high temperatures and pressure values, should significantly reduce leakages and potentially even enable the inclusion of an additional turbine expansion stage. Through a supercritical CO_2 cycle efficiency improvement, overall emissions will be significantly reduced, cutting the cost of CCUS and accelerating the adoption of supercritical CO_2 power cycles into existing and future power plants.

This KKD summarises the steps taken to integrate the sCO_2 test loop with the test apparatus produced by John Crane.

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 CO_2 source (subsystem 1)

D3.3 Integrated sub-systems test - shakedown test

D4.1 Commissioning of the 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 200 bar, 600 ºC (CO_2)

D4.3 Test of rig operating at 200 bar, 300 C (CO_2)

D4.4 Testing to 200 bar, 250 ºC

D4.5 Testing to 200 bar, 500 ºC (CO_2)

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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1. Introduction

1.1 Project overview

Supercritical CO_2 (sCO_2) power cycles represent a cutting-edge development in the energy sector, with broad applications that extend to carbon capture, usage, and storage (CCUS). These cycles are gaining increasing attention for their potential to revolutionise power generation and environmental impact. Compared to conventional steam-driven systems, sCO_2 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 (DGS) solution tailored specifically for supercritical CO_2 power cycles. This endeavour involves cutting-edge simulations, advanced material recipes, and rigorous testing validations.

1.2 Project scope

The project scope includes the design, fabrication, and laboratory testing of critical DGS components (balance diameter sealing module) and system prototypes for application in rotating equipment (turbine and compressors) used in sCO_2 power cycles up to typical pressures and temperatures of 200 barg and 500 ºC. The project also includes the design and commissioning of test equipment to verify and demonstrate the innovative DGS concept/ prototype. Modular testing will be conducted at John Crane Slough and Cranfield University (CU) using the University's existing sCO_2 test loop modified to the requirements of this project. The project scope excludes dynamic seal testing of the DGS prototype at sCO_2 conditions but in air at maximum velocity (140 m/s) and pressure rating (200 barg), which is expected to occur following the completion of this project.

This report summarises the steps taken to integrate the sCO_2 test loop, developed by Cranfield University, with the test apparatus produced by John Crane and delivered to Cranfield University. It outlines the process undertaken to ensure that the test apparatus reliably reproduced the results previously obtained by John Crane in Slough. Additionally, it details the actions carried out to ensure the loop's capability to supply CO_2 gas steadily under the required test conditions.

2. Rationale of the commissioning activities

To initiate the test campaigns aimed at evaluating different types of balance diameter seals provided by the University of Edinburgh, it was necessary to repeat previous commissioning activities for the test loop [1] and test apparatus [2], as previously reported in KKD3.3 and KKD4.1. These activities were conducted at Cranfield University from an integrated perspective, which involved operating both components as a unified system. This unified system was expected to safely achieve the test conditions specified in the project's test matrices.

Commissioning the test apparatus at Cranfield aimed to replicate the shakedown test conducted by John Crane, with the additional step of connecting the ventilation system and supplying CO_2 to the apparatus. The commissioning process involved two key steps: first, verifying that the ventilation system effectively maintained the enclosure temperature near set values, and second, demonstrating that CO_2 could be delivered to and removed from the test apparatus in a controlled manner.

During pre-commissioning at Cranfield, it was noted that flowing CO_2 gas into the test cell (balance diameter seal module) would be part of the test campaign itself. Therefore, the CO_2 supply was limited to testing the system's ability to deliver CO_2 at specified flow, pressure, and temperature conditions to the blowdown line, bypassing the test cell.

In contrast to the KKD3.3 test activities, which were designed to evaluate the performance of various components of the CO_2 loop (e.g., preheater, heating tape, finned tube bundle, back pressure control) under theoretical conditions, the KKD4.2 test activities focused on assessing the controlled CO_2 flow supply under different conditions to the fully assembled system. Commissioning placed particular emphasis on evaluating the system's response to control actions designed to achieve steady-state pressures and temperatures. As in KKD3.3, numerical models were refined to determine operating limits for the loop setup and its controls.

Additionally, the integrated commissioning approach included an assessment of potential failure modes in different test scenarios. Using a "what if?" analysis technique, we identified key safety and integrity concerns for the system. This integrated approach also led to the development of a joint emergency stop (E-stop) mechanism, allowing both the loop and apparatus to be stopped simultaneously, in the following referred to collectively as “pilot plant”.

The objectives of this test campaign can be summarised as follows:

1. Verify the test/pass-off criteria of the test apparatus at Cranfield University:

    a. Confirm that the ventilation system maintains actuator temperature near ambient levels.
2. Assess the final layout and control system of the loop, including:
    a. Thermal insulation effectiveness,
    b. Control of resistance heating elements,
    c. Performance of the cooling bundle, and
    d. Performance of automated metering valves as flow regulator
3. Diagnose potential failure scenarios resulting from the integration of the test apparatus and test loop (now as a pilot plant):
    a. Develop and test a joint emergency stop for the pilot plant.
4. Evaluate the system's capability to achieve steady-state pressures and temperatures consistent with the test matrices under discussion

3. Test apparatus commissioning

After the delivery, installation, and pre-commissioning of the test apparatus at Cranfield University, a second shakedown test was performed using the test cell specifically designed for this project. As previously [2], this shakedown test was conducted to verify the correct functioning of the rig's mechanical parts, electrical components, and control systems.

The test/pass-off campaign conducted for this deliverable was a simplified version of the actual test designed to assess the polymer test cell against a hot gas supply of 200 bar and 500 °C. The three main elements considered were:

- Actuator: Capable of moving the shaft inside the testing cell by ± 3 mm, detected by a laser encoder.
- Ceramic heater: Capable of heating the centre core of the testing cell up to 200 °C, where the sealing polymer is located.
- Load cell: Measuring and reporting friction forces up to -100 Newtons as the shaft moves and the cell is pressurised.

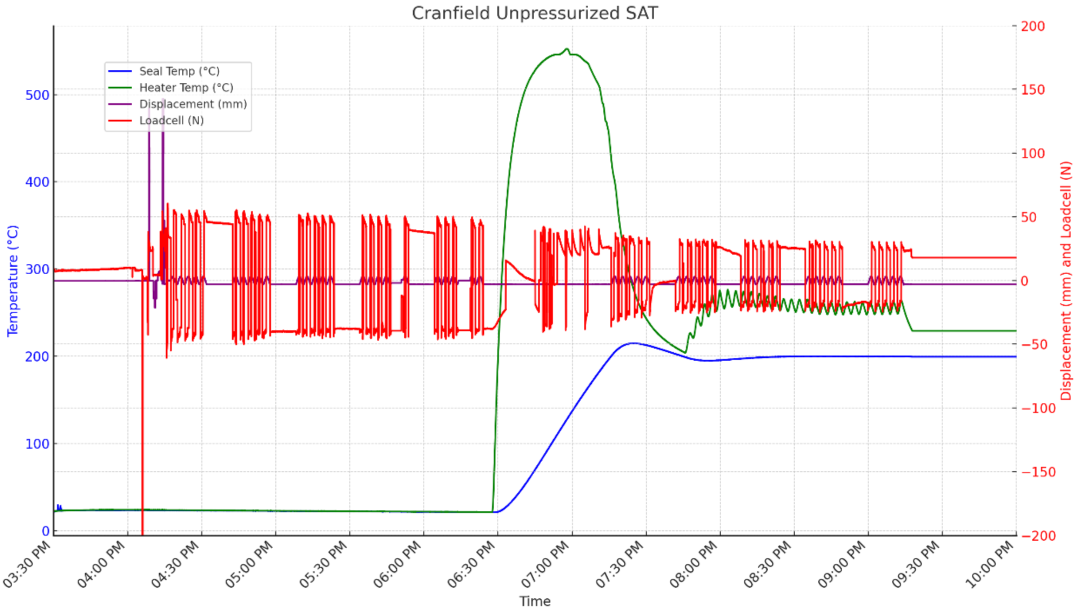
Additionally, the test apparatus was also provided with key measurements from the test loop, namely:

- Pressure at the inlet of the test apparatus (PT60)
- Temperature at the inlet of the test apparatus (TT61)
- Pressure at the inlet of the leakage flowmeter (PT83)
- Temperature at the inlet of the leakage flowmeter (TT83)
- Volumetric flow at the leakage line of the test apparatus (FCO96)

3.1 Commissioning results

Figure 2 shows the records of temperature (seal and heater), friction force and displacement of the shaft during the shake-down test.

Figure 1: Shake-down test.



Similarly to the experience reported in KKD4.1, this confirms that the ceramic heater is functioning and capable of providing the desired temperature of 200 °C at the centre core of the test cell. It also demonstrates that the heater can reach up to 500 °C in approximately 15 minutes. The recorded load cell values ranged from 50 to -50 N, while the laser encoder reported a shaft displacement within ±3 mm as expected. Figure 3 shows the local exhaust ventilation (LEV) system installed to the test apparatus to collect air and potential CO_2 leakages.

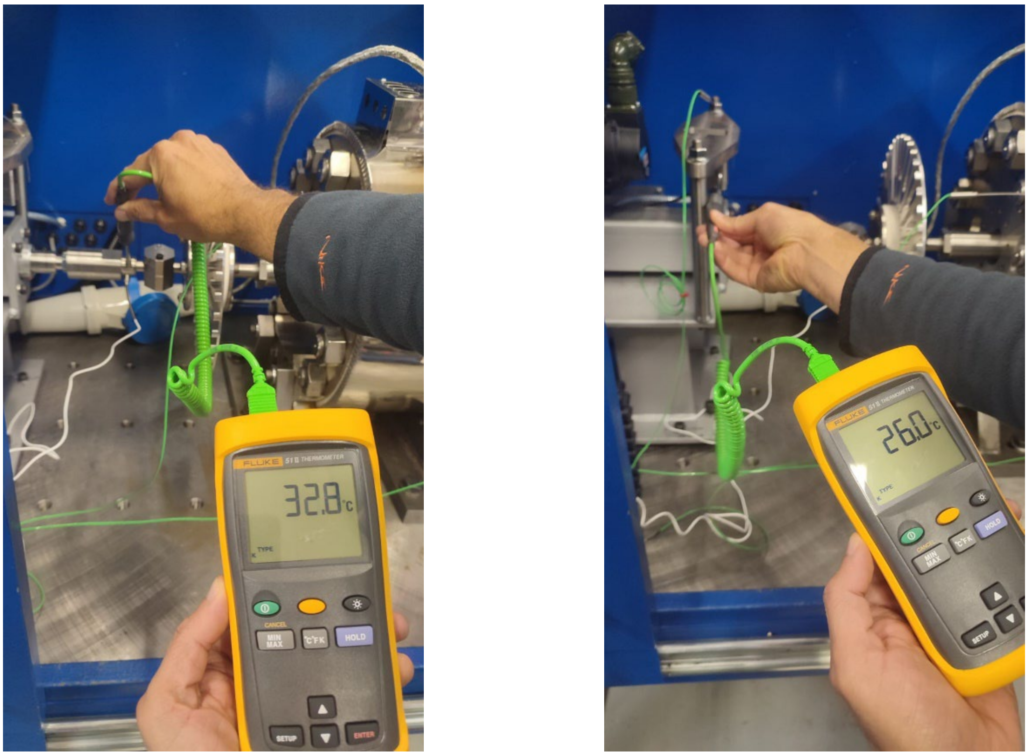
Figure 2: LEV for test apparatus.

During the commissioning activities of the test apparatus, it was confirmed that the ventilation system maintains actuator temperature near ambient level when the ceramic heater operates within the range of 200 - 250 °C. A surface temperature measurement was performed across the main inner components of the test apparatus, with results shown in the sequence of pictures in Figure 4. These measurements were taken once the shakedown test had concluded, and the safety interlock was temporarily disabled to verify the actual temperature conditions of each section of the test apparatus. At an ambient room temperature of 21 °C, the ventilation of the enclosure was sufficient to allow the doors to be opened without experiencing any thermal shock. The ventilation system kept surface enclosure temperatures just above room temperature, enabling surface measurements to be taken carefully with bare hands and without a face shield.

Figure 3: Temperature distribution inside the test apparatus

a) Temperature at cell non-drive end face (179.2 °C)

b) Temperature at shaft end (92.2 °C)



c) Temperature at load cell (32.8 °C)

d) Temperature at actuator (26.0 °C)

4. Test loop commissioning

The commissioning activities for KKD 4.2 were designed to evaluate the final layout and control system of the loop when integrated with the test apparatus. For this purpose, the supercritical CO_2 (sCO_2) loop was operated under conditions to the test apparatus via the installed blowdown line. This allowed for the assessment of the thermal insulation’s effectiveness, the control of the resistance heating tape over the tubing delivering CO_2 flow to the test apparatus, as well as the performance evaluation of the finned tube bundle for cooling and the motorised metering valves used as flow regulators downstream of the test apparatus.

4.1 Safety requirements specifications

The integrated commissioning of the pilot plant involved an analysis of how potential process failures in either the test loop or test apparatus could impact the overall system. To identify and address possible issues, a 'What if' analysis technique was employed, in which critical scenarios were discussed and their potential consequences evaluated. The main scenarios assessed included:

- Unintentional core temperature
- No signals in one/two DAQ system(s)
- Over/under pressurised
- Over/under temperature
- High/Low supply of CO_2
- No/intermittent flow supply
- Over leakage flow
- No ventilation
- Actuator no moving
- Actuator over/under range
- Key measurements failure
    - Load cell
    - Flowmeters
    - Test cell pressure and temperature

The most relevant scenarios for plant failure are presented in Table 1. The analysis took into account the safety measures in place and the adequate design of both the test loop and test apparatus. It also involved assigning a likelihood of occurrence to each scenario based on the team's experience.

Table 1: Most relevant findings of “What if?” technique

Scenario	**Functional consequences**	**Likelihood**	**Observations**
Deliver CO_2 temperature > setpoint	Seal flow extrude, increased the friction, leakage increased	Unknown, depends on polymer limit	Know limits of i.e. PTFE = 300 ◦C PEEK = 343 ◦C
Deliver CO_2 pressure > setpoint	Seal flow extrude, increased the friction, leakage increased	Medium, depends on operation of metering valves	There are pressure relief valves/burst discs to protect overpressure, but once activated the test needs to stop
Deliver CO_2 pressure < setpoint	No effect on the polymer, impact on ice formation during expansion	Medium, depends on operation of metering valves, heating tapes and cooling bundle	Observe ±5% deviation, close monitoring of the loop operation
Unintentional core temperature	Damage of seal	Medium, depends on operation ceramic heater	Thermocouple in cell for monitoring, system will shut down, but polymer lost, close monitoring of ceramic heaters required
Deliver CO_2 flow > setpoint	No effect on the polymer, the parameter to monitor is leakage flow.	Medium, depends on operation of metering valves	No impact on testing, but influence CO_2 consumption
Deliver CO_2 flow < setpoint	No effect on the polymer, the parameter to monitor leakage flow. Impact on loop performance.	Medium, depends on operation of metering valves	Changes operational envelop of the loop, calculations required if deviation continues
Temperature of enclosure > setpoint	Damage of electronics	Low, given the number of fans provided (3) + extraction system	Alarms based on thermocouple above encoder 48 ◦C / 70 ◦C
Leakage flow stream pressure > setpoint	Damage of laminar flowmeter	Low, given a pressure relief valve is set to protect the equipment	Verify pressure relief valve set below 6 bar(g)
Unintentional release of CO_2 to test room	Asphyxiation	Low, given the local exhaust ventilation and gas detection system in place	More relevant is exposure to high temperature streams, clear safe operational procedures required

Two points of concern were identified:

- The commissioning of the plant should avoid flushing gases into the polymer seal already installed in the test cell, as this could compromise the mechanical integrity of the seal itself and should be addressed as part of the test campaign.

- The integration of the emergency stop should cut off all energy sources from the equipment, but this must be done in a controlled manner to prevent creating additional hazards, in accordance with PUWER [3].

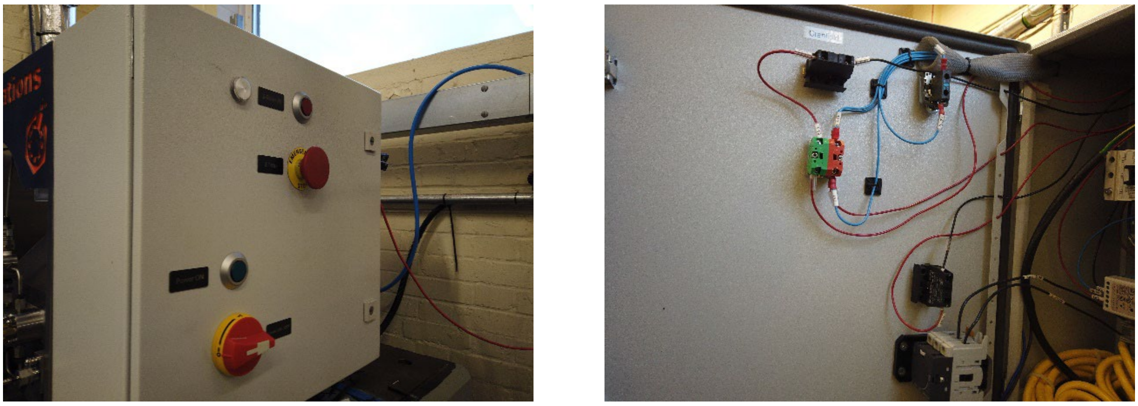
For the purposes of the first element, it was agreed to bypass the test cell during plant commissioning. For the second element, the integrated emergency stop included the following sub-systems:

- Subsystem 1 (as reported in KKD3.2)
- Test apparatus (as reported in KKD4.1)
- Subsystem 2: Control system for the interface between subsystem 1 and the test apparatus

Effectively, this final subsystem, Subsystem 2, represents the implementation of the components previously described in KKD3.3: heating tapes, metering and needle valves, instrumentation, and the cooling bundle. Of these components, only the heating tapes and motorised valves should be evaluated in the emergency stop scenario. It was concluded that there was no requirement to de-energise the motorised metering valves, as the system should favour depressurisation of the tubes and cell. Heating tapes, on the other hand, need to be disconnected from electrical power. The 'What if' assessment also concluded that the fan of the local exhaust ventilation should not be stopped.

Figure 4 shows the modification to the control panel of Subsystem 1 to enable integration with the pilot plant. An additional safety assessment will be conducted for future deliverables.

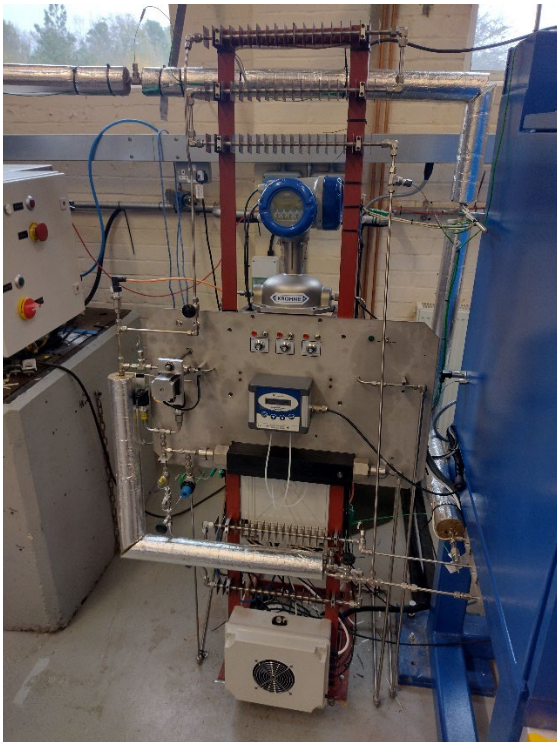
Figure 4: Integrated emergency stop at control panel subsystem 1



4.2 Features of the test loop commissioned

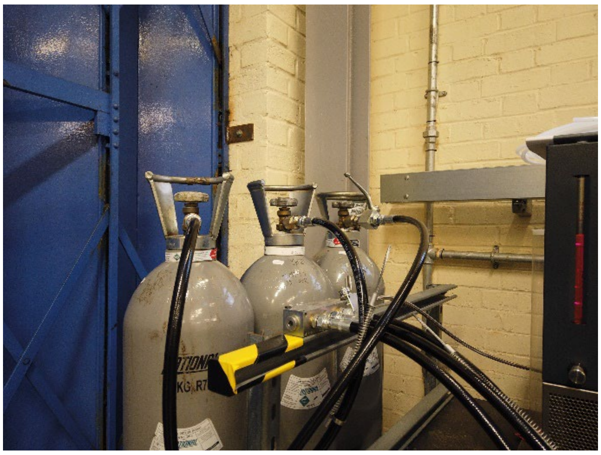
Figure 5 shows a picture of the test rig layout, highlighting differences from the layout used in KKD3.3. These differences include the removal of three bundle units originally planned upstream of the Coriolis flowmeter, as well as the addition of a bypass to the same bundle (which will be explained later in this document).

Figure 5: Picture of the test loop used for the commissioning of the pilot plant.



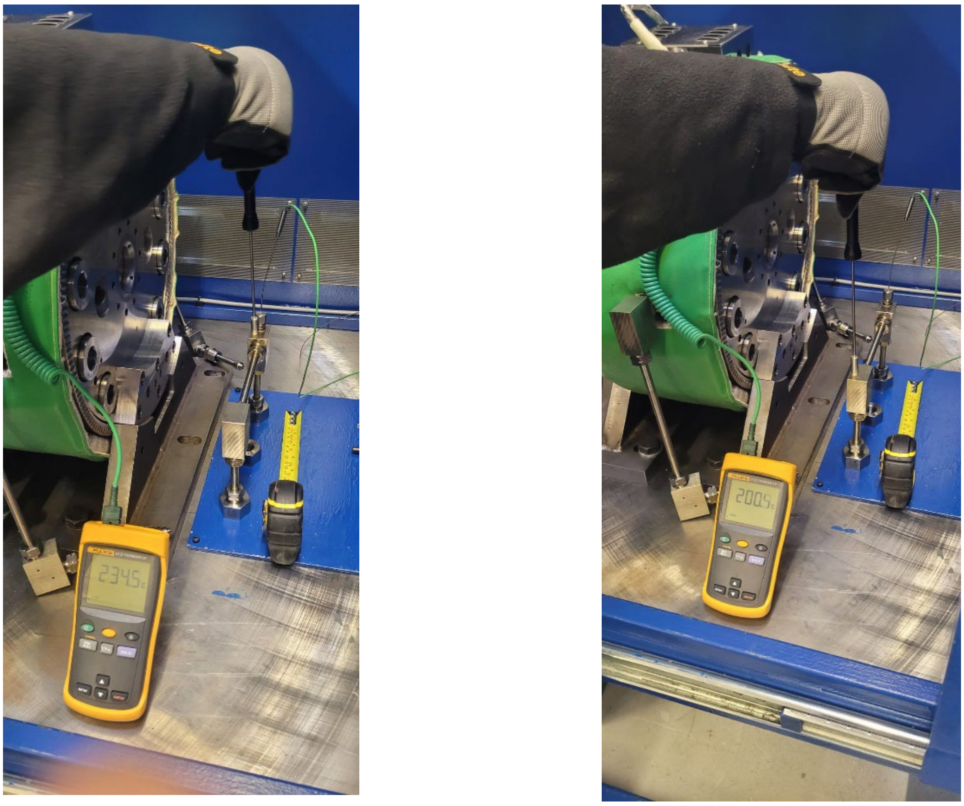
During the commissioning of the pilot plant, three bottles of liquid R744, of 35 kg of CO_2 each, were used to supply the gas to the test loop (Figure 7).

Figure 6: Picture of the manifold implemented for multiple supply of CO_2 bottles.



As described in the previous section, to avoid compromising the mechanical integrity of the polymer seal installed in the test cell, a bypass of the test cell was manufactured. Figure 8 shows the arrangement used, demonstrating the delivery of a 200 °C CO_2 stream. A significant temperature loss of approximately 30 °C was observed over a 20 cm length of non-insulated tubing.

Figure 7: Picture of the bypass of the test cell used for the commissioning of the test loop



To control and monitor the operation of the of the test loop, a comprehensive data acquisition and control system was developed. This system comprises a group of six graphical user interfaces, allowing real-time monitoring of the main components of the rig. The system was developed in-house on a LabView platform.

The two major challenges for the test loop control system were developing a temperature control system for the heating tapes, which could ensure the delivery of hot gas to the test apparatus, and developing a flow regulator using automated metering valves, which could guarantee the stable delivery of CO_2 to the test apparatus in conjunction with the liquid CO_2 pump. As shown in Figure 9, the challenge of the temperature control system was overcome by using solid-state relays with a zero-cross trigger control method. Whereas the challenge of controlling the metering valve required a good understanding of setting the motor drives (not disclosed in this report), see Figure 10 as general reference.

It should be noted that, based on the lessons learned from KKD3.3, the flow control of the plant is achieved by using the pressure control setting of Subsystem 1, combined with the flow control PID developed for KKD4.2, which is based on the motorised metering valve in the blowdown line.

Figure 8: AC control circuit for the heating tapes of the blowdown line.

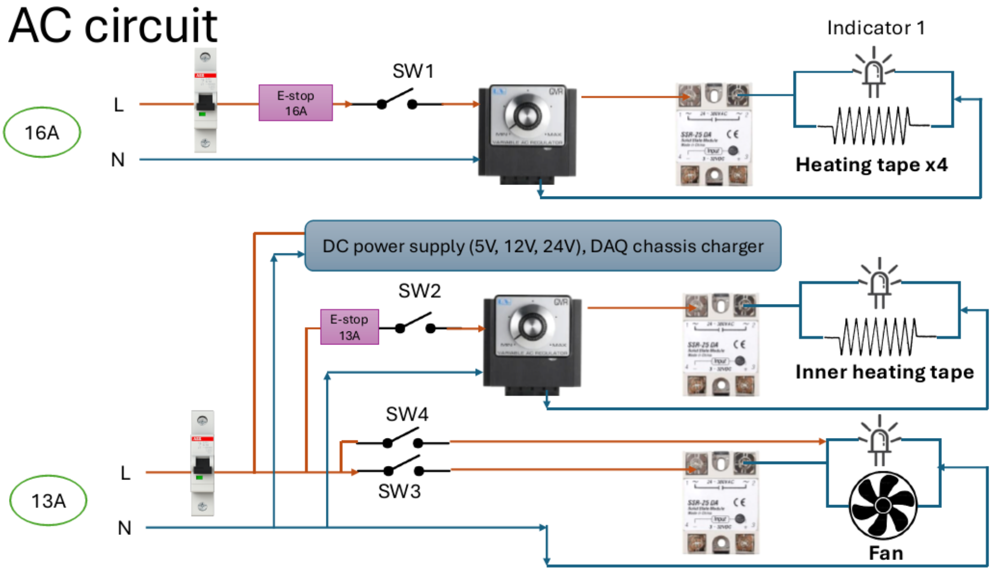
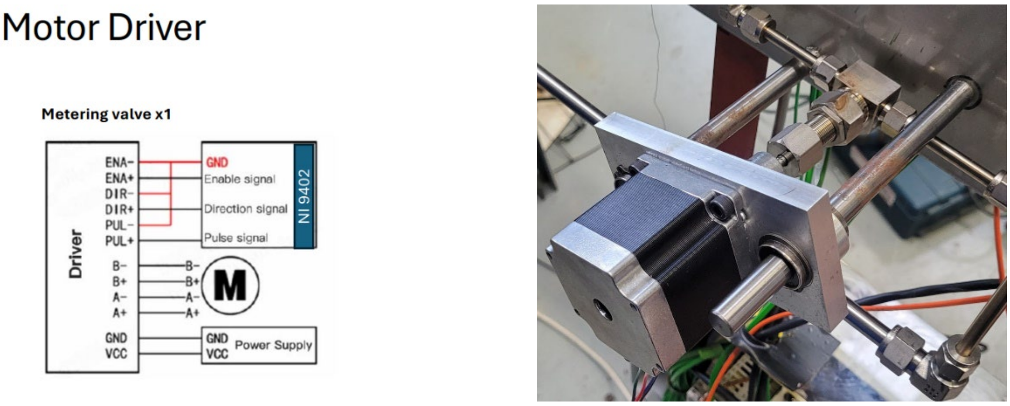


Figure 9: General reference of automated metering valve



4.3 Commissioning plan

Evaluating the pilot plant's capability to achieve steady-state pressures and temperatures consistent with the test matrices under discussion is one of the main objectives of the present commissioning activity. For this purpose, a numerical model has been developed to estimate steady-state pressures and temperatures throughout the pilot plant when CO_2 is supplied by the blowdown line (with no leakage considered).

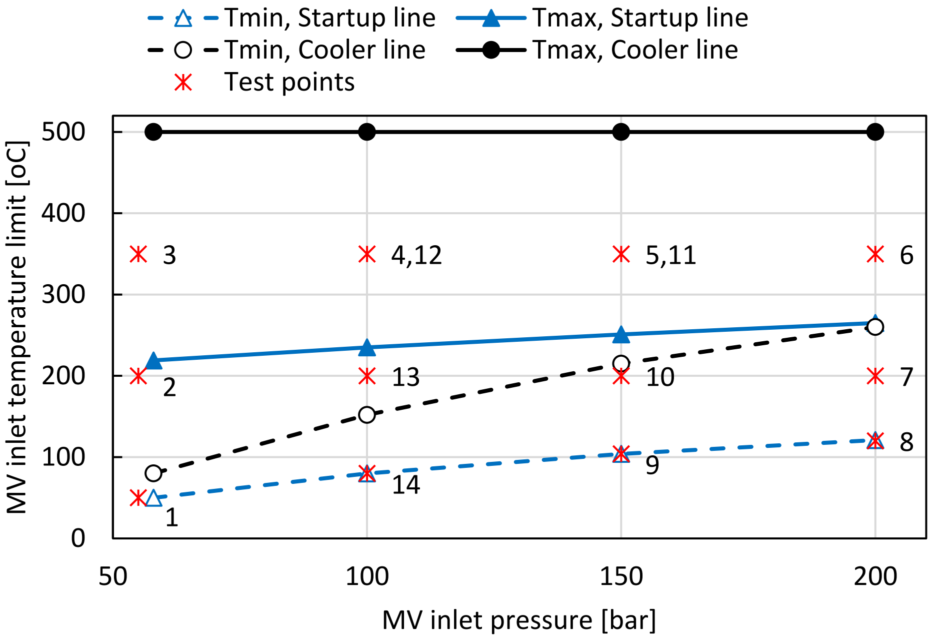
This model is used to determine the operating limits, considering various constraints, including:

- The maximum flow meter temperature is 150 °C.

- The minimum flow meter temperature is -30 °C.
- The minimum temperature of the expanded gas across the test seal is -15 °C.
- The minimum temperature of the expanded gas across the metering valve is -10 °C.
- The global maximum temperature limit of the test rig components is 500 °C.

The pressure is varied between the saturation pressure of CO_2 at room temperature, approximately 55 bar (the bottle pressure), and the maximum design pressure of the test rig, which is 200 bar. The resulting minimum and maximum applicable temperatures that satisfy the above constraints are identified at each operating pressure and represented by the pressure-temperature envelope in Figure 11.

Figure 10: Allowable operating pressure and temperature ranges of the test rig along with the tested points



In Figure 11, the two operating modes are presented, operation via start-up line and cooler line, routing the gas via a heated bypass section or the cooling bundle section. The heated bypass section is designed to facilitate the startup process by heating the gas just before the expansion process occurs across the metering valve. This line can also be used for operating points designed at low temperatures to avoid ice formation during the expansion process or to ensure the minimum temperature limit of the flow meter is met. In contrast, the cooling bundle is designed to handle high operating temperatures to prevent exceeding the upper flow meter temperature limit.

Several operating points are designed within the developed pressure-temperature envelope to pre-test the rig without the test cell by bypassing the gas between the supply and the continuous flow line. The test points selected, shown in Table 2, help to verify the test range capability with regards to pressure and temperature limits. The maximum tested temperature in this test campaign is 350 °C, which is slightly above the project milestone target of 300 °C.

Table 2: Test matrix.

Point	P_{test} [bar]	T_{test} [°C]
1	55	50
2	55	200
3	55	350
4	100	350
5	150	350
6	200	350
7	200	200
8	200	120
9	150	104
10	150	200
11	150	350
12	100	350
13	100	200
14	100	80

4.4 Commissioning procedure

The following procedure reflects the steps taken for the characterisation of the pilot plant.

4.4.1 Preparation

1. Turn on the water chiller and set the temperature to 3°C.
2. Turn on the pump control system and ensure that the E-stop light is not active.
3. Turn on the CU control system and connect the DAQ/control software.
4. Close the continuous flow line needle valves.
5. Open the bottles valve manifold to pressurise the system.
6. Ensure the pump suction and discharge valves are open.

4.4.2 Starting up

1. Turn on the external heaters to preheat the packing and tubes to 200 °C.
2. Turn on the startup heater to preheat the packing and tubes to 100 °C.
3. Turn on the metering valve to 1 turn and monitor the temperature of the Coriolis flow meter. The normal operating range of the flow meter is -30 °C to 150 °C.

4. Wait until TT71 reaches 200 °C.
5. Turn off the startup heater and monitor TT73. The lower limit is defined as a function of the test pressure using the equation

$$T_{MV,in} = aP^2 + bP + c$$

6. Achieve a steady flow of 10kg/h at the bottle pressure (~55 bar) with a test temperature of 50 °C, 80 °C, 120 °C, 200 °C and 350 °C

4.4.3 Liquid pump operation

1. Turn on the pump with a set point of 100 bar.
2. Turn on the preheater and set the temperature to 80 °C.
3. Readjust the heater/flow meter controls to reach a steady state flow of 10 kg/h with a test temperature of 80 °C.
4. Try to achieve a steady flow of 10 kg/h at 100 bar with a test temperature of 80 °C, 120 °C, 200 °C and 350 °C.
5. Change the pump set points to 150 bar and 200 bar and repeat the temperature ramp within the predefined limits in Figure 11. Switch between the cooling/startup lines as needed

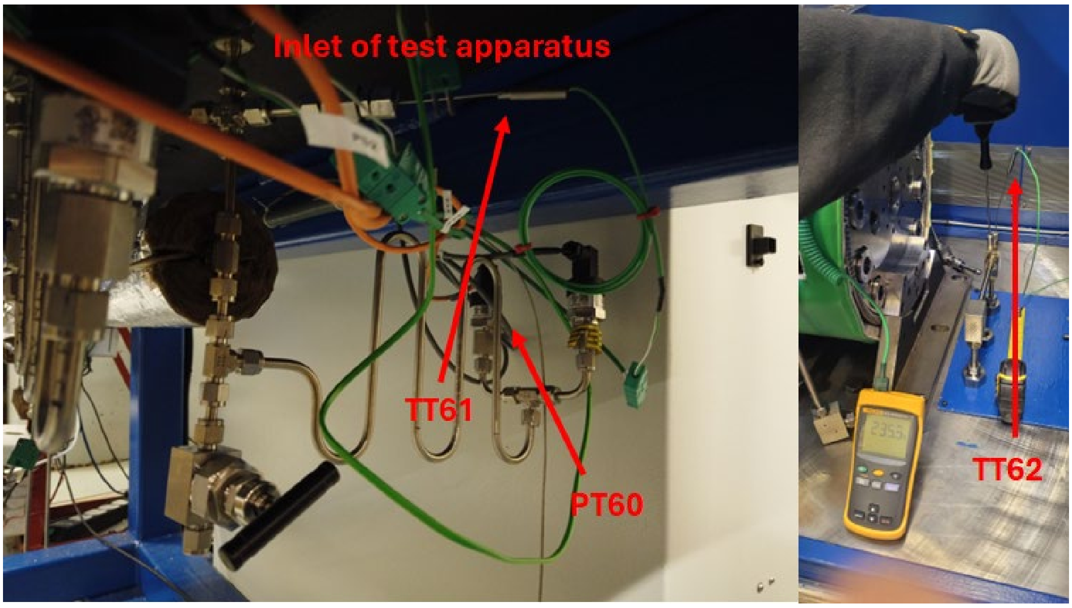
4.4.4 Shutting down

1. Turn off the preheater and all the heating tape elements.
2. Switch off the pump.
3. Keep the flow running using the bottle pressure for a few minutes to cool down the components.
4. Close the metering valve and the needle valves on the continuous blowdown line.
5. Close the CO_2 bottles supply manifold valve.
6. Reopen the metering valve and the needle valves on the continuous blowdown line to depressurise the system.

4.5 Results and discussion

This section presents the experimental results obtained after performing the commissioning procedure for the characterisation of the pilot plant, specifying various combinations of pressure and temperature for each test condition (as per Figure 11). The target CO_2 flow was set at 10 kg/h, with the pressure and temperature not exceeding 200 bar and 350 °C, respectively. Figure 12 reflect the location of sensors PT60, TT61 and TT62.

Figure 11: Physical location of sensors PT60, TT61 and TT62

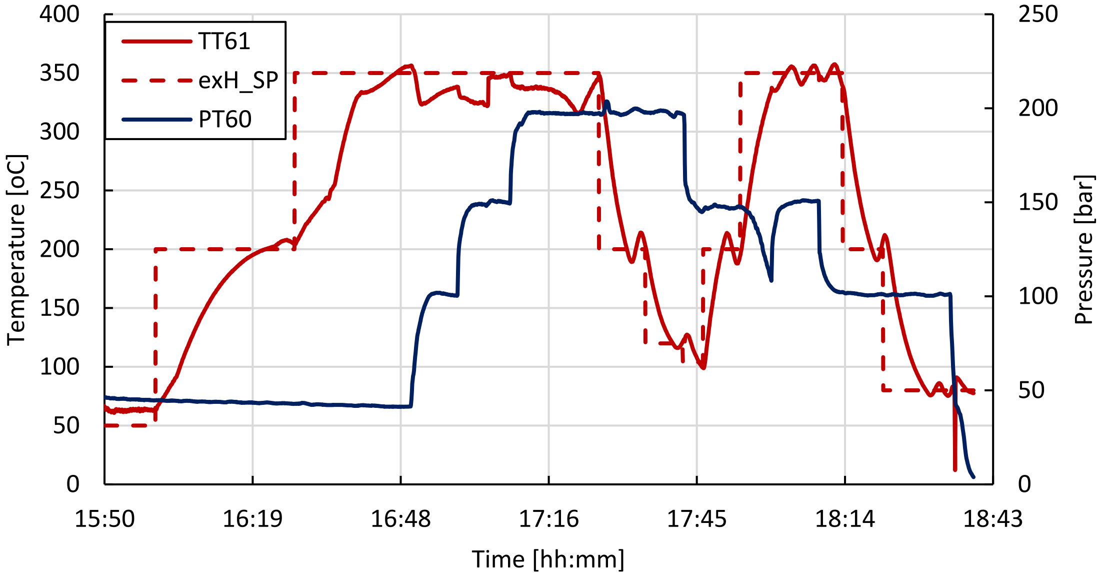


The measured supply gas pressure and temperature over time are shown in Figure 13, along with the external heater temperature set point. The pressure and temperature combinations defined in Table 2 are achieved by operating, at CO_2 bottle pressure, and progressively increasing the temperature set point from 50 °C to 350 °C, covering points 1 to 3. The maximum temperature is then held constant until approximately 17:25 (Figure 13), while the pressure is stepped up to 200 bar, covering test points 4 to 6. The pressure is maintained at 200 bar until approximately 17:41 (Figure 13), while the test temperature is reduced to 120 °C, covering points 7 and 8. It is worth noting that the minimum applicable temperatures at the bottle pressure and 200 bar are 50 °C and 120 °C, respectively. This is due to the higher pressure drop across the metering valve at elevated test pressures, which increases the required valve inlet temperature for solid-free expansion.

The test pressure is then changed to 150 bar, with the temperature varying between 104 °C and 350 °C, achieving points 9, 10, and 11. A drop in test pressure is observed around 18:00 (Figure 13) due to CO_2 bottle depletion, which is resolved by switching to the second bottle in the supply gas system. Similarly, the pressure is reduced to

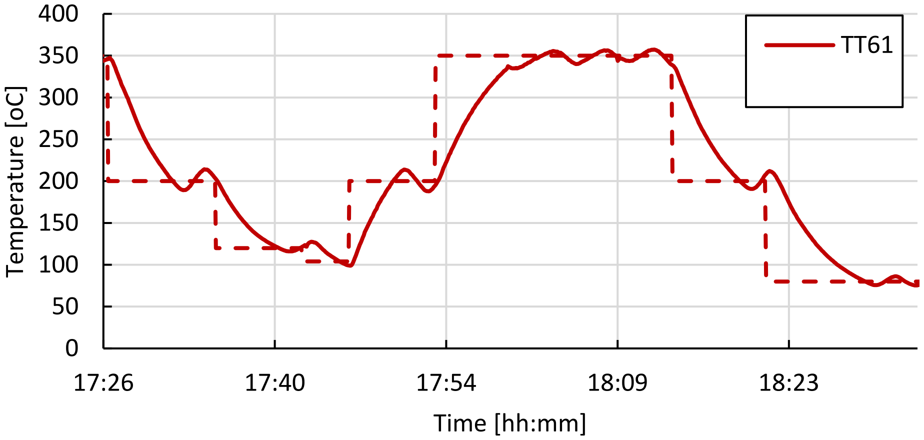
100 bar, with three temperature levels of 350 °C, 200 °C, and 80 °C, achieving points 12, 13, and 14, respectively.

Figure 12: Data for supplying gas pressure and temperature



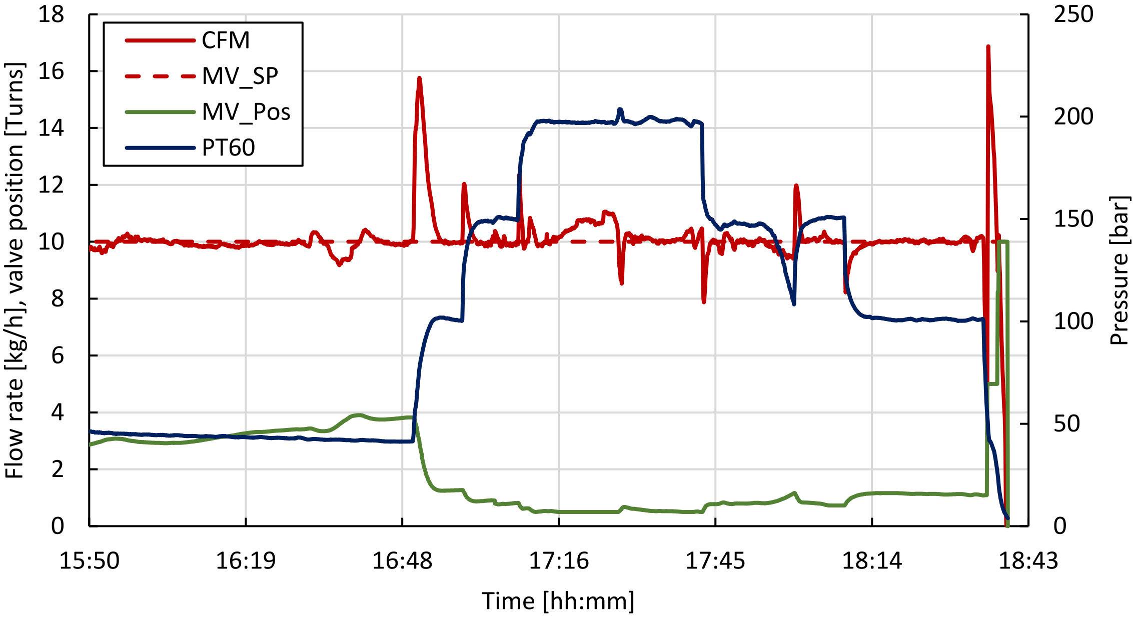
It can be seen from Figure 13 that the control system response has significantly improved in the second part of the test due to continuous adjustments to the PID control gains throughout the test. The improved PID gains have enhanced the response speed, resulting in minimal temperature overshooting, approximately after 17:26, as shown in Figure 14. The time taken to change the supply gas temperature (TT61) from 350 °C to 200 °C is approximately 8 minutes, resulting in an undershoot of about 10 °C. The time taken to increase the supply gas temperature from 200 °C to 350 °C is also approximately 8 minutes, resulting in an overshoot of 7 °C.

Figure 13: Resistance heating tape PID control response



The flow rate is recorded over time and plotted against the test pressure and valve opening position in Figure 15 (flow is labelled as CFM in this figure). The flow rate set point remains constant throughout the test, designed to maintain a continuous flow of 10 kg/h through the test cell, regardless of seal leakage. The flow rate is controlled using a stepper motor installed on the metering valve (previously shown in Figure 10). It can be seen from Figure 15 that the controller maintains the flow rate within the specified range most of the time. However, changes in the flow rate are observed with changes in the test pressure when moving from one set point to another. At 16:50 (Figure 15), an increase in the test pressure from 45 bar to 100 bar resulted in an instantaneous increase in the flow rate to 15.5 kg/h, which is subsequently brought back down to 10 kg/h in under three minutes.

Figure 14: Flow rate control against test pressure and metering valve opening



To maintain a continuous flow rate, an inverse proportional relationship has been observed between the valve opening and the test pressure. The rationale behind this is that increasing the test pressure raises the gas density and decreases the specific volume, resulting in a smaller cross-sectional area required by the valve to pass the same amount of gas per unit time.

The temperature drop between the supplied gas at the bulkhead (TT61) and the internal supply (TT62) is shown in Figure 16. A significant temperature drops of approximately 50 °C is observed when operating near 300 °C over a short tube section. This necessitates the need for an internal heating tape to be wrapped around the tube section connecting the supply bulkhead to the cell inlet connection. This measure is required to compensate for heat loss and ensure that the required test temperature is supplied to the cell inlet.

Figure 15: Data of supply gas temperature (TT61, TT62) against the cooling line temperature (TT72) and metering valve inlet temperature (TT73)

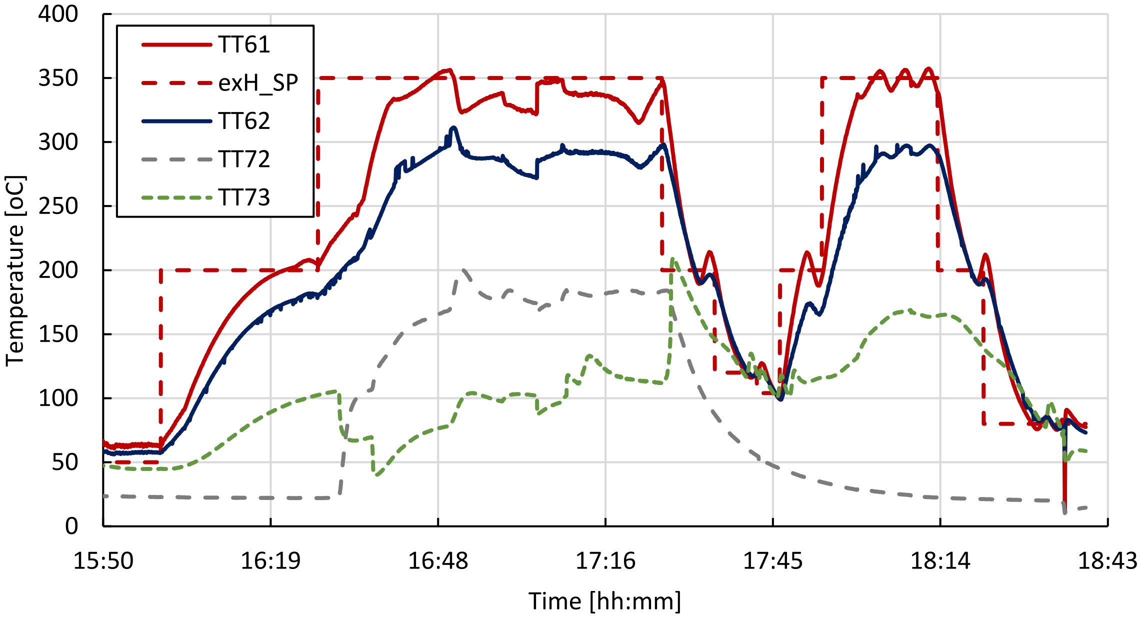
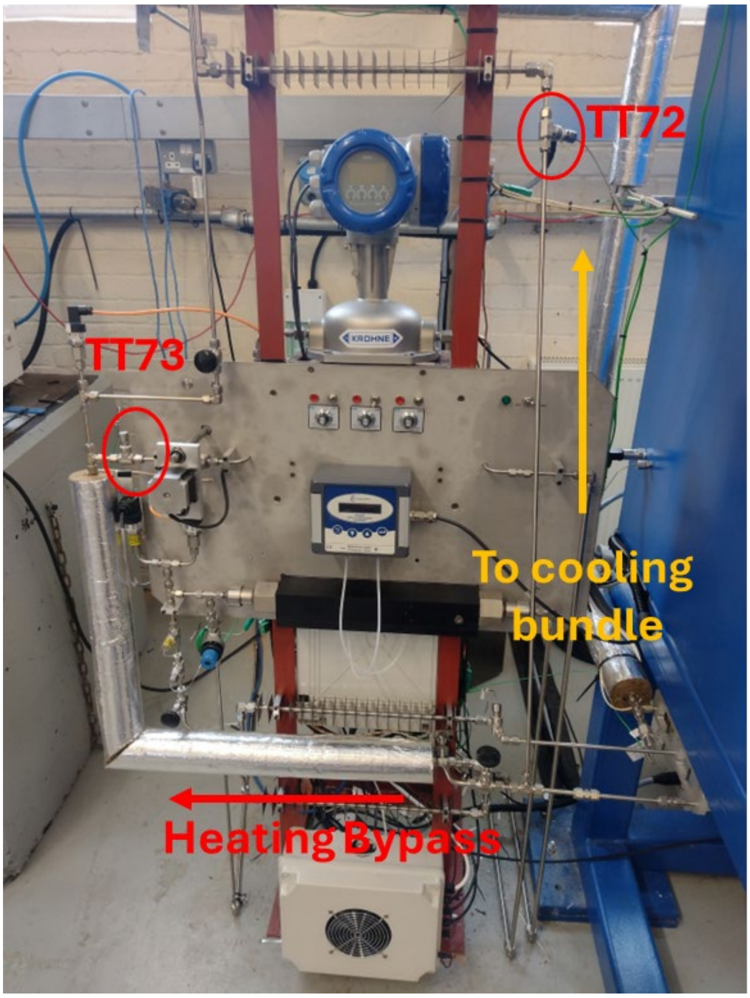


Figure 17 illustrates this layout arrangement for internal heating. During cold startup operations or low-temperature test points, the heating line is used to provide a sufficiently high temperature to the metering valve inlet and ensure ice-free expansion. This is evident in the figure between the start of the test and 16:32 (Figure 16) , as well as after the reduction of the test temperature around 17:29. Depending on the test temperature and the duration for which this temperature is held, a decision should be made to switch between the heating and cooling lines to protect the flow meter placed downstream of the metering valve from excessive temperatures. The cooling bundle effect is shown in Figure 16 between 16:32 and 17:29, where the inlet temperature to the cooling bundle line (TT72) is higher than the metering valve inlet temperature (TT73).

Figure 16: Start up arrangement for blowdown line and position of TT72 and TT73



The pressure and temperature measured across the metering valve are shown in Figure 18. The inlet pressure (PT73) is nearly the same as the test pressure due to minimal pressure losses in the tubes and fittings between the test cell and the valve inlet, relative to the operating pressures. The outlet pressure is close to ambient pressure; however, a slight increase can be observed for short periods due to temporarily increased flow rates at the test pressure, which contributes to the pressure drop between the valve outlet and the CO_2 vent.

It can be seen from the figure that the temperature drop is directly proportional to the pressure drop across the valve. When the test pressure is high and the inlet temperature is insufficiently raised, as observed around 17:15 (Figure 18), negative gas temperatures can occur at the valve outlet. This may lead to ice formation and potential line blockage if the expanded gas temperature falls below the CO_2 triple point temperature of -56 °C. In such cases, the bypass heater can be used to instantly heat the valve inlet and protect the flow meter from excessively low temperatures. Figure 19 illustrates this scenario.

Figure 17: Data of supply gas temperature (TT61, TT62) against the cooling line temperature (TT72) and metering valve inlet temperature (TT73)

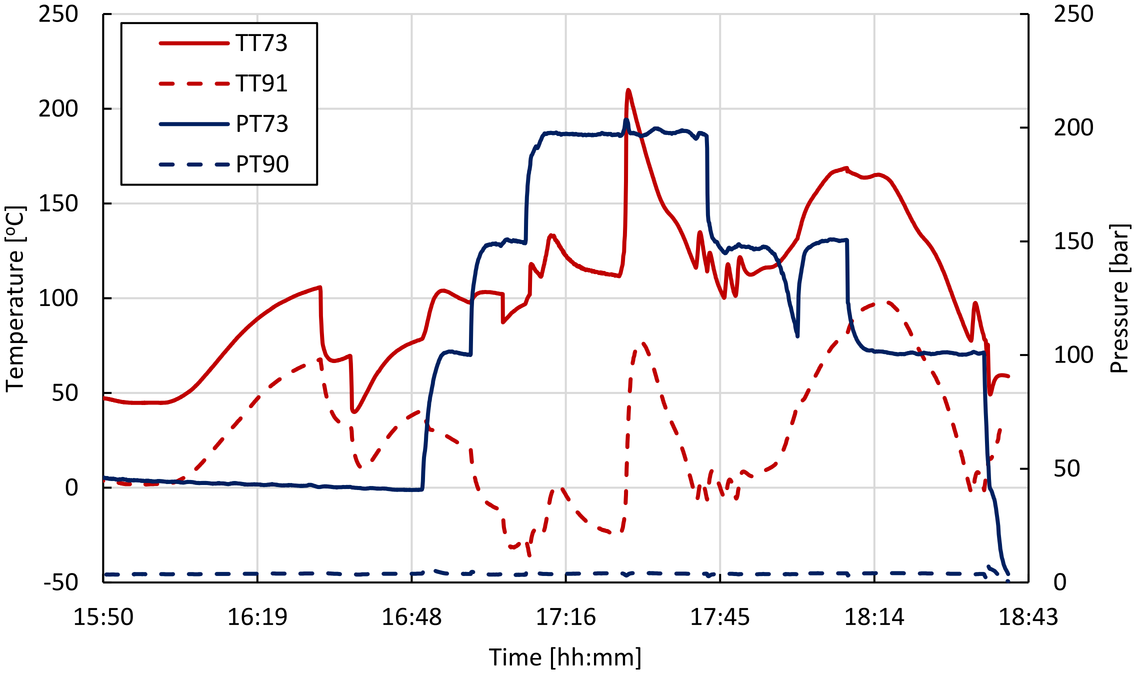
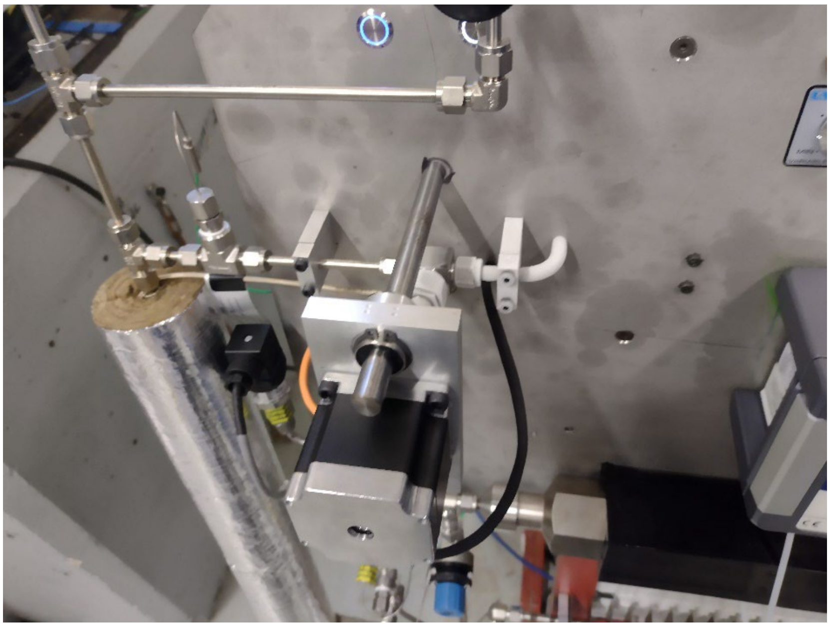


Figure 18: Example of low temperature at the outlet of metering valve



5. Conclusions

The commissioning activities have resulted in a pilot plant that is ready for operation. Both the test apparatus and test loop have been operated to satisfactory levels, confirming that they meet their design objectives.

Several conclusions can be drawn regarding the commissioning and operation of the pilot plant, particularly in relation to the flow and temperature management of CO_2 gas:

1. Temperature Management is critical for “safe expansion of the gas”: Significant temperature drops in the system, especially across the metering valve and in the connecting tubes favour ice formation, which can lead to blockages and operational failures.
2. Adjustments based on test matrix specifications: The test matrix with the individual pressure and temperature points requires adjustments in the operation of the test loop. The use of heating tapes and a bypass around the cooling bundle are proactive measures designed to manage various pressure and temperature profiles while accounting for the constraints of the test loop.
3. System response and adjustments: The control system’s response has improved over time due to adjustments made to the PID control gains of the heating tapes and motorised metering valve. This demonstrates that real-time monitoring and tuning of the system are essential for optimising performance and achieving the desired flow rates and temperatures in the pilot plant. Similar monitoring is expected for the ceramic heater of the test cell.
4. Continuous monitoring: Key parameters must be continuously monitored to avoid exceeding specified limits that could lead to operational hazards.
    a. In the test apparatus: Core temperature of the cell, friction force and shaft displacement, temperature of the enclosure, and the actuator.
    b. In the test loop: Pressure and temperature at the test apparatus inlet, flow delivered to the blowdown line, pressure and temperature at the metering valve inlet, and leakage line pressure.

The forthcoming test campaign at Cranfield University will identify procedures and best practices for testing balance diameter polymer seals at high pressure and temperature in carbon dioxide media.

6. Key knowledge deliverable

To operate the sCO_2 test loop and test apparatus for future testing of DGS technologies related to CCUS applications, the following considerations are recommended:

1. Installation of final heating tape: A final internal heating tape should be wrapped around the tube section connecting the supply bulkhead and the cell inlet to compensate for heat loss and ensure that the required test temperature is maintained at the cell inlet.
2. Flow control for multistream apparatus: Due to the multistream nature of the test apparatus, a flow control valve should be used in conjunction with the CO_2 liquid pump operating in pressure control mode to deliver specific flow rates from the test loop.
3. Rig loop modifications for a wide testing envelope: The expected wide testing range of the loop necessitates modifications to the original P&ID layout, specifically:
    a. Addition of a bypass around the cooling bundle
    b. Installation of heating tape in this bypass to ensure temperature control before metering valve expansion
    c. Controlled distribution of gas around this bypass (through a set of valves)

With the integrated commissioning activities completed, tuning the gains of various PID controllers has been identified as the upcoming focus for KKD 4.3

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References

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