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DESIGN AND DYNAMIC SIMULATION OF A 200 kW_{th} LABORATORY sCO_2-TEST RIG

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ABSTRACT

The paper describes the development of an sCO_2-test rig, which enables to investigate the behaviour of sCO_2 as a heat transfer medium as well as a working fluid for power cycles. The system can be operated in transcritical and supercritical mode. Maximum operating pressure is 240 bara, max. temperature is 400 °C in phase 1. In a second project phase (phase 2) maximum temperatures of 650 °C are intended to be achieved.

A dynamic simulation of the whole cycle was performed based on the software APROS (Advanced Process Simulator, edited by VTT) in order to evaluate the behaviour of the cycle under transient conditions. The time dependent behaviour of pressure and temperature levels, as well as the trend of the liquid level in the CO_2-tank have been simulated.

INTRODUCTION

Heat recovery from industrial processes is of rising interest due to the Energy Efficiency Directive of the EU and the latest United Nations Framework Convention on Climate Change in Paris (France 2015). Therefore the Institute for Energy Systems and Thermodynamics of TU Wien is currently working on a project that deals with the matter of using supercritical carbon dioxide (sCO_2) as a working fluid for different cycle processes, see [1]. The main aim for the first step of the sCO_2 project is to plan, construct and take into operation an sCO_2 test rig to gain operational expertise of component and process behaviour. In this paper the basic and detail engineering of the test rig and the functionality of the process control system for the different sCO_2 cycles is presented. A dynamic simulation of the test rig was performed to verify the process control system and the general dynamic behaviour of the complete test rig during operation. The current status of the project has the internal title 'phase 1'. In phase 1 of the project no sCO_2 turbo machinery is available, instead a high pressure CO_2 pump and an expansion valve are used. The other main components are a CO_2 heater (tube bundle heat exchanger, thermal oil as heat source), a cooler (tube bundle heat exchanger, water as coolant), a buffer tank and a double pipe heat exchanger (heated with thermal oil). The main scientific objective of phase 1 is to investigate the heat transfer to sCO_2 in the vicinity of the critical point. The test rig can reach pressures and temperatures up to 240 bar and 450 °C at a nominal mass flow of 0.4 kg/s. The maximum thermal heat input is roughly 200 kW. Currently several approaches for a potential 'phase 2' are under evaluation and/or have been/will be submitted for public funding. The extension approaches are:

(a) installation of a gas fired heater in parallel to the thermo-oil heater. Such a heating source will allow to raise the maximum cycle temperature up to 650 °C and to raise nominal sCO2-mass flow from 0.4 into the range of 0.8 kg/s
(b) installation of an sCO_2/sCO_2 recuperator: this will allow to analyse realistic cycle arrangements for high temperature heat sources
(c) installation of turbo-expander and turbo-pump/compressor: this feature will allow to operate the test rig with full range industrial equipment.
(d) Operation of mixtures of CO_2 with other fluids (in the frame of a European research consortium), see [2].
(e) Extension to heat pump operation (flow reversal and

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installation of a high temperature compressor).
The main objective of the phase 1 test rig was to install a flexible tool which allows analysing various questions related to the power cycle, to system operation, to control systems and to heat transfer, see [3], [4] and [5]. Also practical questions such as filling as well as transient operating conditions should be investigated. The test rig is currently (July 2018) in the hot commissioning phase. The next targets are to operate the system under stable conditions for all design cases and to start heat transfer experiments.

TEST RIG DESIGN – PHASE 1:

The set up to be designed should fulfil maximum requirements of flexibility within the financial boundary conditions, see [6]. The basic version of a trans-critical power cycle without expander (using a throttle valve instead) has been realized, in order to analyse heat transfer, start up and shutdown of the cycle and to collect expertise of the transient behaviour of the system. Heat input is performed by a thermal oil/sCO_2 heat exchanger with a maximum temperature level of ϑ_{TO}=380 °C. Heat rejection is realized in a condenser/cooler connected to a refrigeration cycle with cooling temperatures of ϑ_{COOL}=6 °C.
A double pipe heat exchanger allows to investigate heat transfer behaviour under conditions close to the critical point. Besides investigations related to power cycles, the potential of sCO_2 as a heat transfer medium, compared e. g. to pressurized water or thermal oil cycles will be investigated.

Table 1: Phase 1 Design Parameters:

	Supercritical operation			Transcritical operation		
	max.	min.	design	max.	min.	design
p_{High} [bar_a]	240	100	220	240	100	220
P_{Low} [bar_a]	120	75	80	70	50	60
ϑ_{T-V_In} [°C]	400	150	380	400	150	380
ϑ_{Low} [°C]	50	35	40	28.7	14.3	22.0
m_{Dot} [kg/s]	0.7	0.1	0.4	0.7	0.1	0.4

A scheme of the test rig is shown in **Figure 12**, see annex A.
Heater for Phase 1:
The heater for phase 1 is of shell and tube construction (Figure 1).

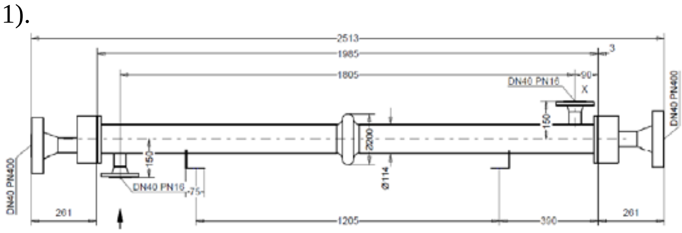

Figure 1: Drawing of Thermo-oil heater.

Pump:
The pump has to fulfil two tasks:

- the pressure increase during supercritical and transcritical operation
- the circulation of CO_2 in the heat displacement mode

The major task of the pump is the high pressure increase during the transcritical mode. Thus the pump design was based on this operation mode. The pump is a TRIPLEX-piston-pump which is able to supply the mass flow over the operating range. The mass flow is measured by using a Coriolis flow meter and controlled via a frequency converter. The inlet temperature for the CO_2 is in the range of 20-25 °C; within this operating range stable operation should be possible.

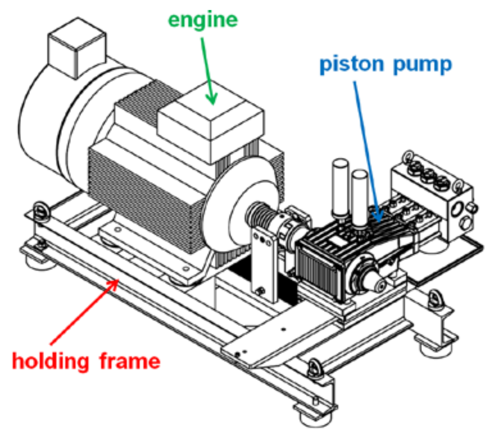

Figure 2: Piston Pump

Table 2: Phase 1 Operating parameters of pump

p_{Out_Max} [bar]	280.0	V_{Dot} [l/min]	50
p_{In_Min} [bar]	11.0	ϑ_{In_Min} [°C]	-40
p_{In_Max} [bar]	220.0	ϑ_{In_Max} [°C]	50
P_{el} [kW]	29.5	f [Hz]	50

Condenser/Cooler:
Whether the tube bundle heat exchanger is working as a cooler or condenser depends on the operational mode. There are two design cases, at the first the heat exchanger works as cooler and condenser at transcritical mode and in the second case as a cooler at supercritical operation mode.

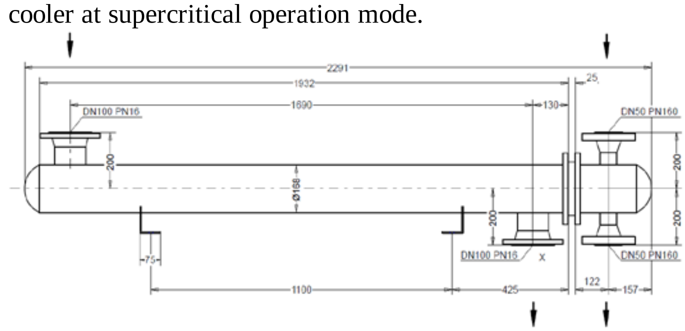

Figure 3: Condenser / Cooler

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Figure 4: Picture of the test rig

OUTLOOK TO PHASE 2

Figure 14 (see annex A) gives a process flow diagram of the intended arrangement for phase 2 (funding is yet pending).

Heater for Phase 2:

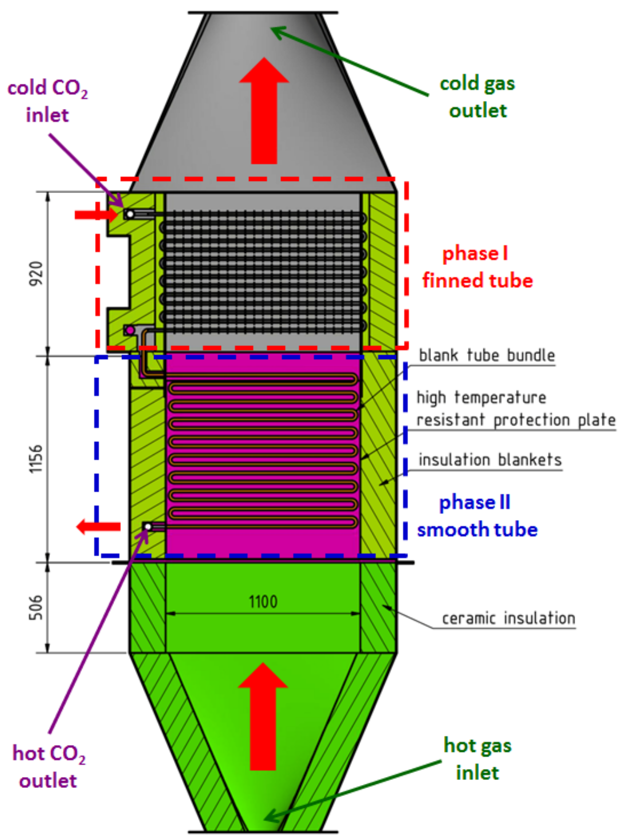

Figure 5: Hot gas heat exchanger

RESULTS AND DISCUSSION

Dynamic simulation of the sCO_2 test rig:

To test the process control system and the general dynamic behavior of the complete test rig during operation of the different CO_2 cycles (transcritical and supercritical), a dynamic simulation by using the process simulation tool APROS (Advanced Process Simulator, VTT) was performed. In **Figure 13** the APROS model of the sCO_2 test rig can be seen.

The basic stationary design of the test rig was done by using IpsePro based on selected and planned operating parameters. The two operating modes power cycle operation and heat transfer mode have been considered. The dynamic simulation is based on data returned from the detail engineering of the test rig. The CO_2-properties were calculated according to Span, R. and Wagner, W.: "A New Equation of State for Carbon Dioxide covering the Fluid Region from Triple Point Temperature to 1100 K at Pressures up to 800 MPa", see [7].

In **Figure 6**, **Figure** 7 and **Figure 8** the results for the transcritical CO_2 cycle are shown.

The simulation starts after filling the test rig at around 6 MPa and 21 °C and switching on the CO_2 pump. The mass flow is constantly held at 0.4 kg/s for the whole test cycle. In case of the TC-cycle the cooler constantly cools down the CO_2 to 21 °C. After 900 seconds the heating is activated and the CO_2 heats up to approximately 360 °C after 3600 seconds (see Fig 8). While heating up, the pressure rises slowly and the tank is completely filled (see Fig 8 and 10). After heating the system up, the high pressure control is activated at 2700 seconds (the expansion valve closes slowly) and the pressure rises up to 22 MPa after 4500 seconds, what is the desired high pressure level for the operation. During the rise of the high CO_2 pressure, the tank level drops a little bit, because more CO_2 mass is kept in the high pressure part of the test rig. In case of the TC cycle the low pressure level is controlled by the cooler. At the desired 21 °C a pressure of around 5.9 MPa is adjusted (see **Figure 7**) between 4500 and 7200 seconds).

To bring the system back to the starting point, first the high pressure level is reduced after 7200 seconds (the expansion valve opens slowly until it is completely open) and then the heating is constantly switched off (from 9000 to 10800 seconds). Finally the system returns to the starting conditions.

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Simulation of the transcritical sCO_2 cycle:

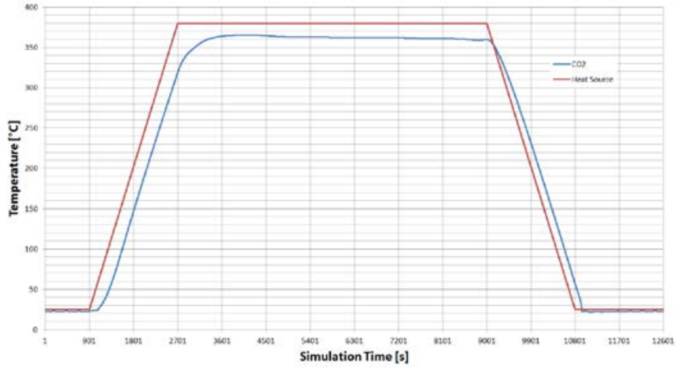

Figure 6: Trend of the temperatures of CO_2 (hot side) and the heat source (TC cycle)

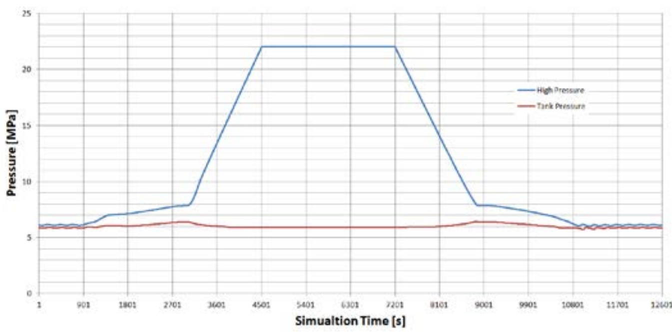

Figure 7: CO_2 pressure trends of the high pressure side and the tank (TC cycle)

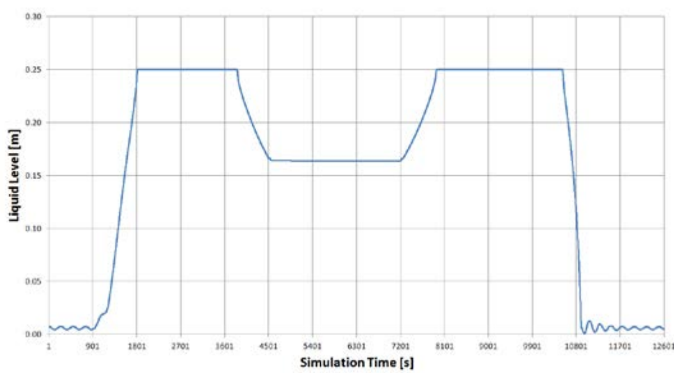

Figure 8: Trend of the liquid CO_2 level in the tank (TC cycle)

Simulation of the supercritical CO_2 cycle (SC cycle):

In **Figure 9, Figure 10** and **Figure 11** the results for the supercritical CO_2 cycle are shown. The simulation starts again after filling the test rig at around 6 MPa and 21 °C and switching on the CO_2 pump. The mass flow is constantly held at 0.4 kg/s for the whole cycle time. Now the starting value of the CO_2 cooling temperature is again 21 °C, but will be changed during the test cycle. This will be described later. In case of the SC cycle, the start up process to reach the supercritical state is a little bit more complex than before. First of all heating is activated after 900 seconds and the CO_2 reaches temperatures of approximately 360 °C after 3600 seconds.

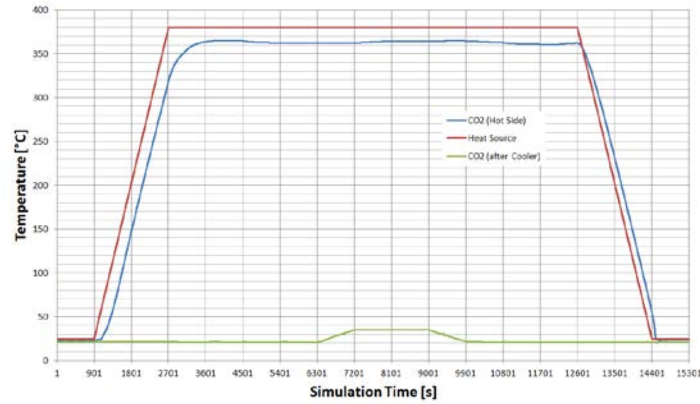

Figure 9: Trend of the temperatures of CO_2 (hot side and after cooler) and the heat source (SC cycle)

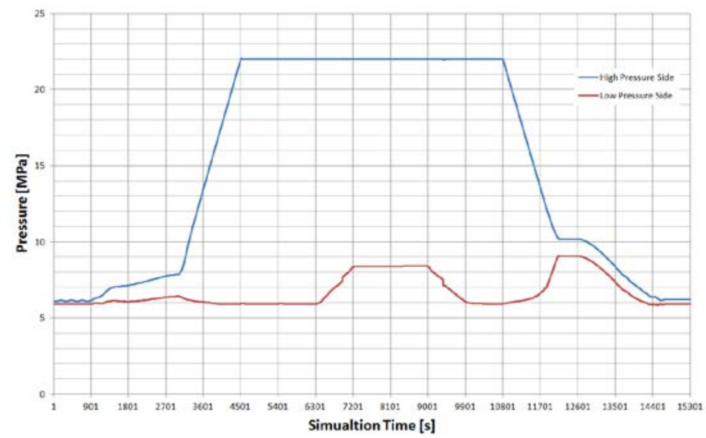

Figure 10: CO_2 pressure trends of the high pressure side and the low pressure (SC cycle)

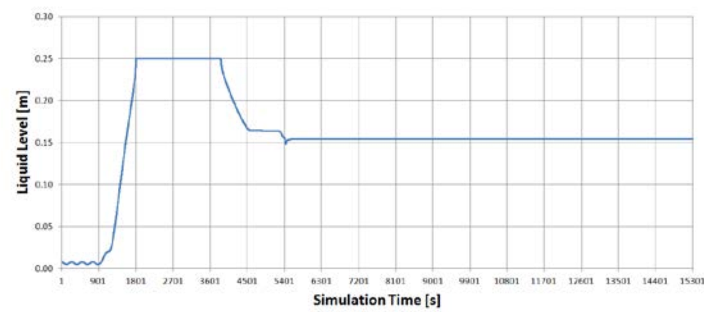

Figure 11: Trend of the liquid CO_2 level in the tank (SC cycle)

While heating up, the pressure rises slowly and the tank is completely filled. After heating the system up, the high pressure control is activated at 2700 seconds (the expansion valve closes slowly) and the pressure rises up to 22 MPa after 4500 seconds, what is again the desired high pressure level for the operation. During the rise of the high CO_2 pressure, the

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tank level drops a little bit (like before for the TC cycle). In the next step, the bypass of the test rig is opened and the tank is decoupled by closing the appropriate valves. Now the total CO_2 flow is directed through the bypass. To reach the supercritical state, the CO_2 cooling temperature is raised to 35 °C to exceed the critical temperature of the CO_2 (T_{crit}=30.98 °C). This is shown in Fig 12 (green curve). Along with the temperature also the pressure rises in the low pressure part of the system. The resulting low pressure level depends now on the total CO_2 mass contained in the system (without the decoupled tank). In this case a pressure of around 8.4 MPa is obtained, what is also above the critical pressure of CO_2 (p_{crit}=7.38 MPa). The system now is completely under supercritical state. In the figures, this state accords to the time span between 7200 and 9000 seconds.

To bring the system back to the starting point, first of all the CO_2 cooling temperature is reduced to 21 °C again (between 9000 and 9900 seconds). The system returns to a TC state. Then the high pressure level is reduced after 10800 seconds (the expansion valve opens slowly until it is completely open) and the heating is constantly switched off (from 12600 to 14400 seconds). Finally the system returns to the starting conditions.
The dynamic simulations showed that the planned control system should work fine with the designed test rig. Nevertheless it will be very interesting to compare these simulation results with experimental data and see how the real system (with all the various components) reacts on dynamic changes.

NOMENCLATURE

f frequency [1/s]
m_{Dot} mass flow (kg/s)
p pressure [bar]
P power [kW]
V_{Dot} volumetric flow (l/min)
ϑ temperature (°C)

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ANNEX A

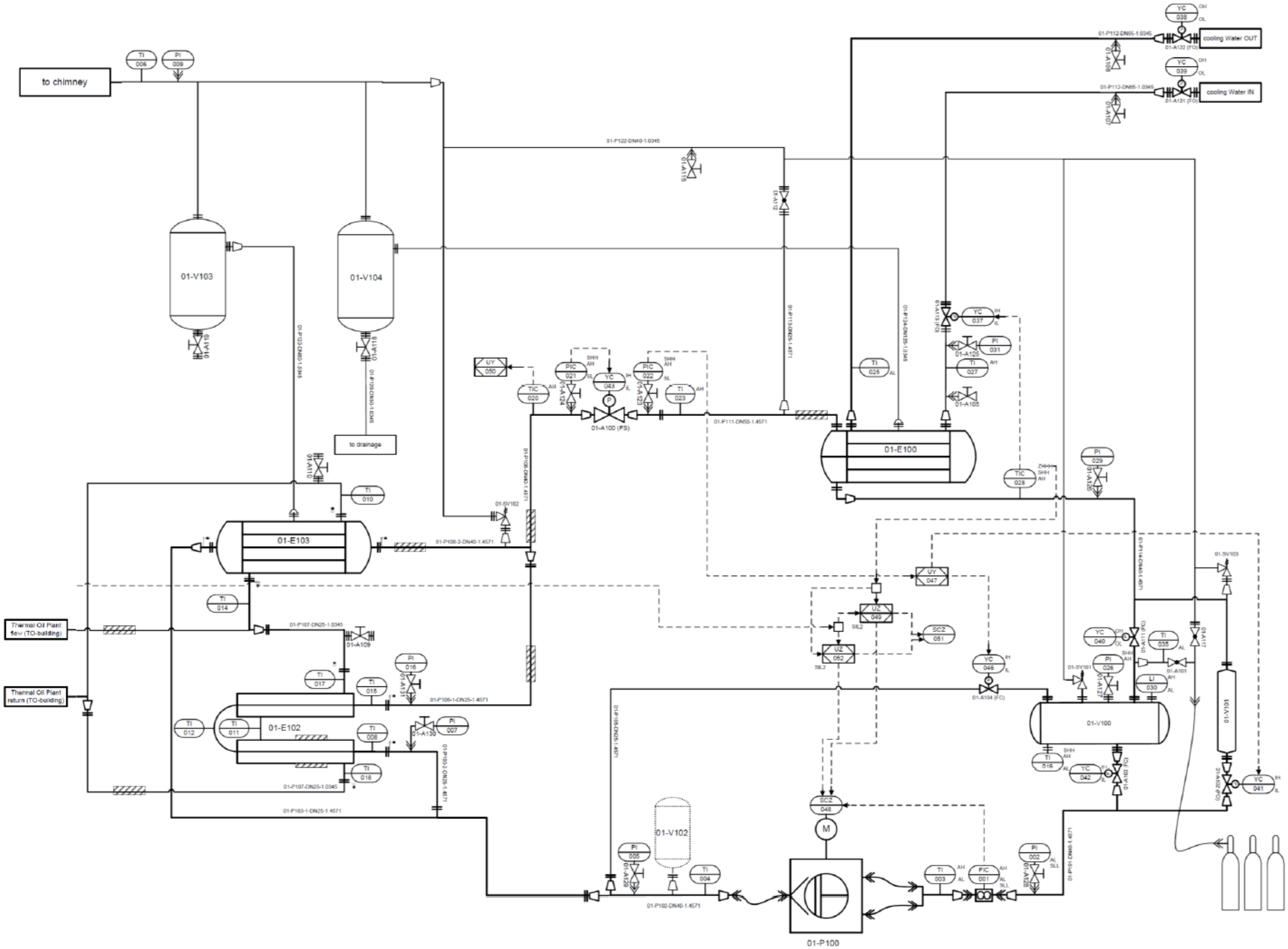

Figure 12: PID of the test rig**-** Phase1

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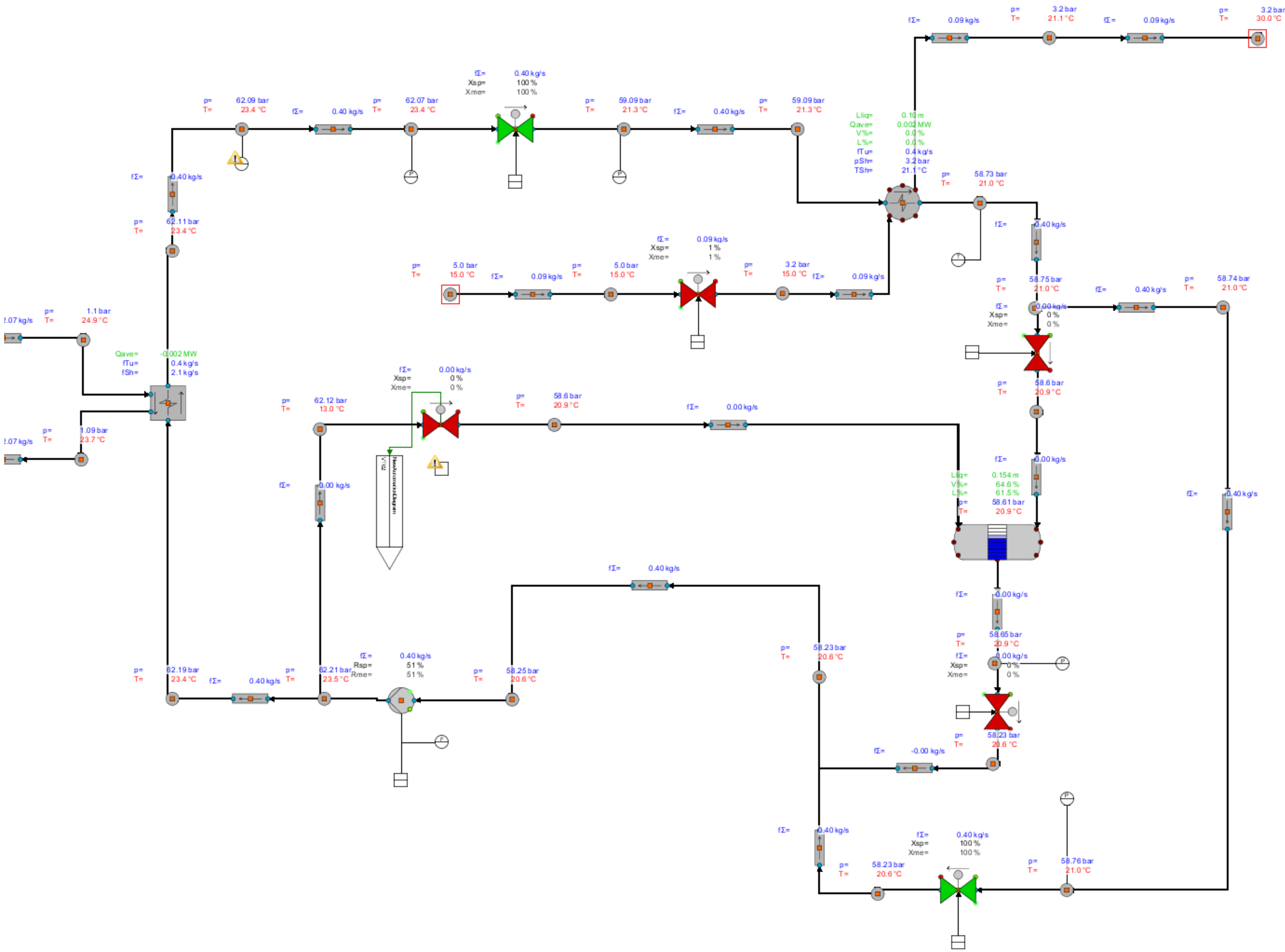

Figure 13: Dynamic model of the sCO_2 test rig in Apros

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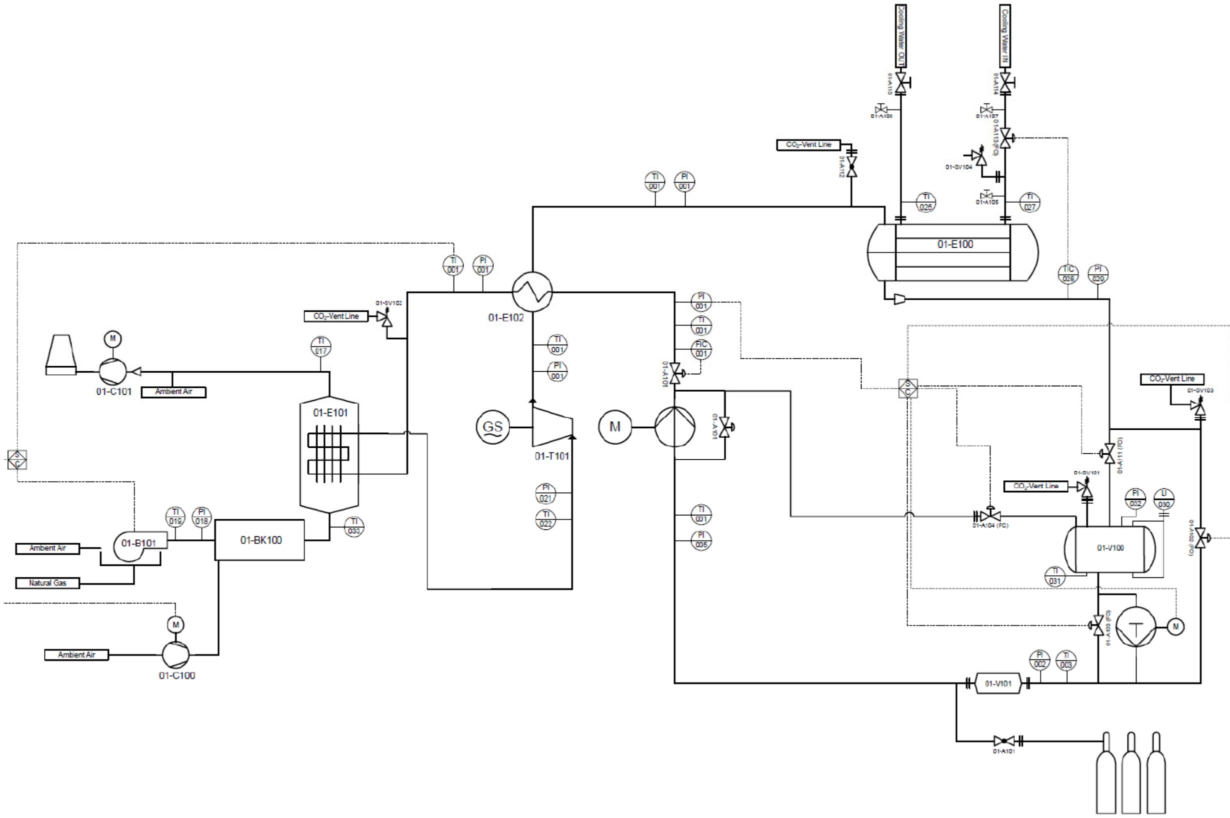

Figure 14: PFD for Phase 2

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