A test rig to study heat transfer of sCO_2 at CERN

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Abstract

In high-energy physics (HEP) detectors and modern electronics, thermal management is critical to ensure reliable, long-term operation. Increasing power densities, compact geometries, and stricter environmental regulations are driving the need for efficient, low-GWP cooling solutions. At CERN, boiling carbon dioxide is already well-established for low-temperature detector cooling. However, above its critical temperature (31°C), sCO_2 becomes a highly attractive option for electronics operating in the warm regime.

Introduction

Several factors make of supercritical carbon dioxide a perfect candidate for warm/room temperature cooling:

- High specific heat capacity: change in temperature due to energy absorption *lowers* in certain temperature ranges.
- Low viscosity: lower pumping power, allows using *smaller pipes* or higher flows due to less frictional pressure drop.
- Single-phase-like behaviour: *crucial* factor, considering the difficulty in flow distribution when dealing with multi-line two-phase flow.

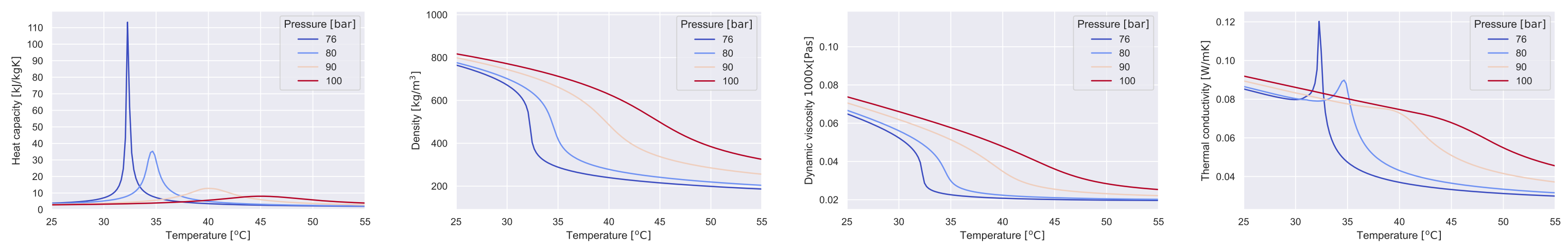

Figure 1: *Physical properties of carbon dioxide in the potential conditions of interest for electronics cooling.*

Despite these advantages, available data in the open literature remains scarce, and a consistent parametrization of the heat transfer coefficient (h) of sCO_2 as a function of process variables has yet to be established.

Knowledge gaps

Effect of hydraulic diameter Existing studies have reported contradictory trends in heat transfer performance with tube diameter. *Figure 2* shows the heat transfer coefficient profile measured by Liao and Zhao [1] and Wang et al. [2] showcasing the different values obtained at similar conditions. The large difference in values suggest measurement inconsistencies or differing experimental conditions.

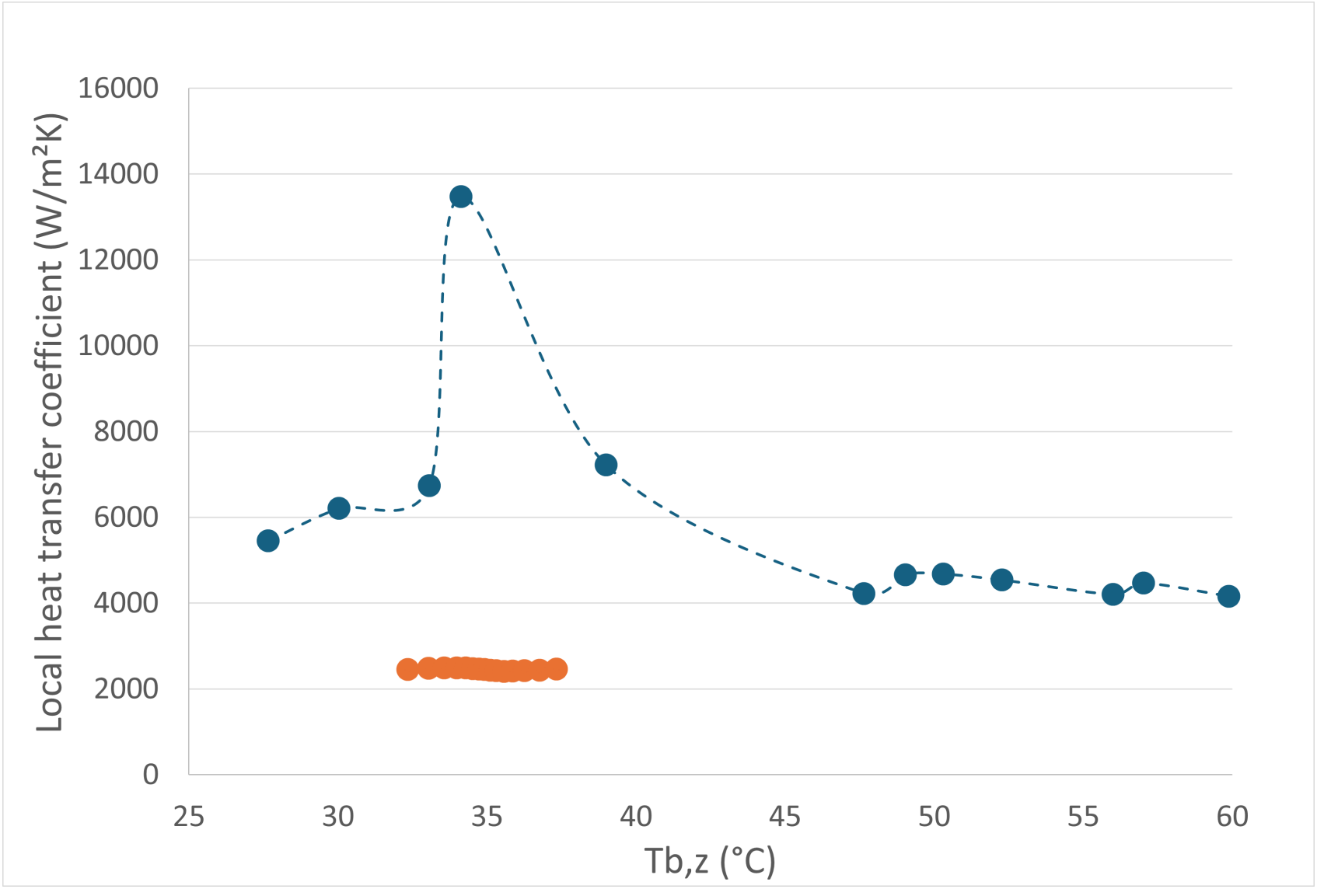

Figure 1: *Local heat transfer coefficient of $sCO2$ from different research articles [1-2].*

Table 1: *Operation parameters in Figure 1.*

Variable	Value	Value
Mass flow (g/s)	1.7	1.1
Hydraulic diameter (mm)	1.4	1.0
Inlet pressure (bar)	80	80.7
Inlet temperature (°C)	27	32.5
Heat flow (W)	315	80

Effect of mass flux A threshold value has been defined at which the trend of the heat transfer coefficient with respect to the flow velocity showed a reversal in vertical upward configurations. References [3-5] show increasing h when inclеasing the mass flow (m); [6] reports the opposite. This suggests that both forced and natural convection contribute to the heat transfer process. *Figure 3* shows the qualitative trend of the heat transfer coefficient with the mass flow.

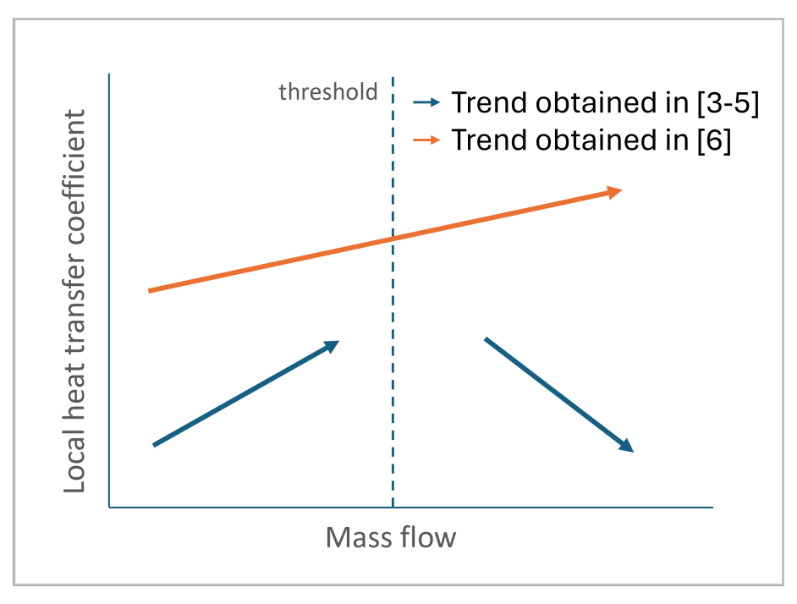

Figure 3: *Qualitative trends reported of the heat transfer coefficient changing with the mass flow.*

Onset of Heat Transfer Deterioration (HTD) Defining the onset of HTD has been the most studied aspect, yet a general trend of the effect of important variables on the appearance of this have not been fully established. For many years, authors have correlated this onset as a function of the heat-to-mass ratio (q/G) and not reached a uniform correlation. Nowadays it is believed that the history of the process (inlet conditions) plays a *significant* role.

Subcritical/supercritical transition Direct comparisons of the heat transfer coefficient obtained in subcritical and supercritical near-critical regimes under similar flow conditions are scarce in literature.

Experimental setup

Motivation Obtention of heat transfer coefficients and pressure drop during the *heating process* of carbon dioxide in supercritical state as well as in the near-critical subcritical region. Figure 4 shows the P&ID of the facility. The test rig operation can be followed with Figure 5, which shows the p-h diagram containing an illustration of the cycle in the two available operation modes: red - subcritical, blue - supercritical. The different sections of the system are described below.

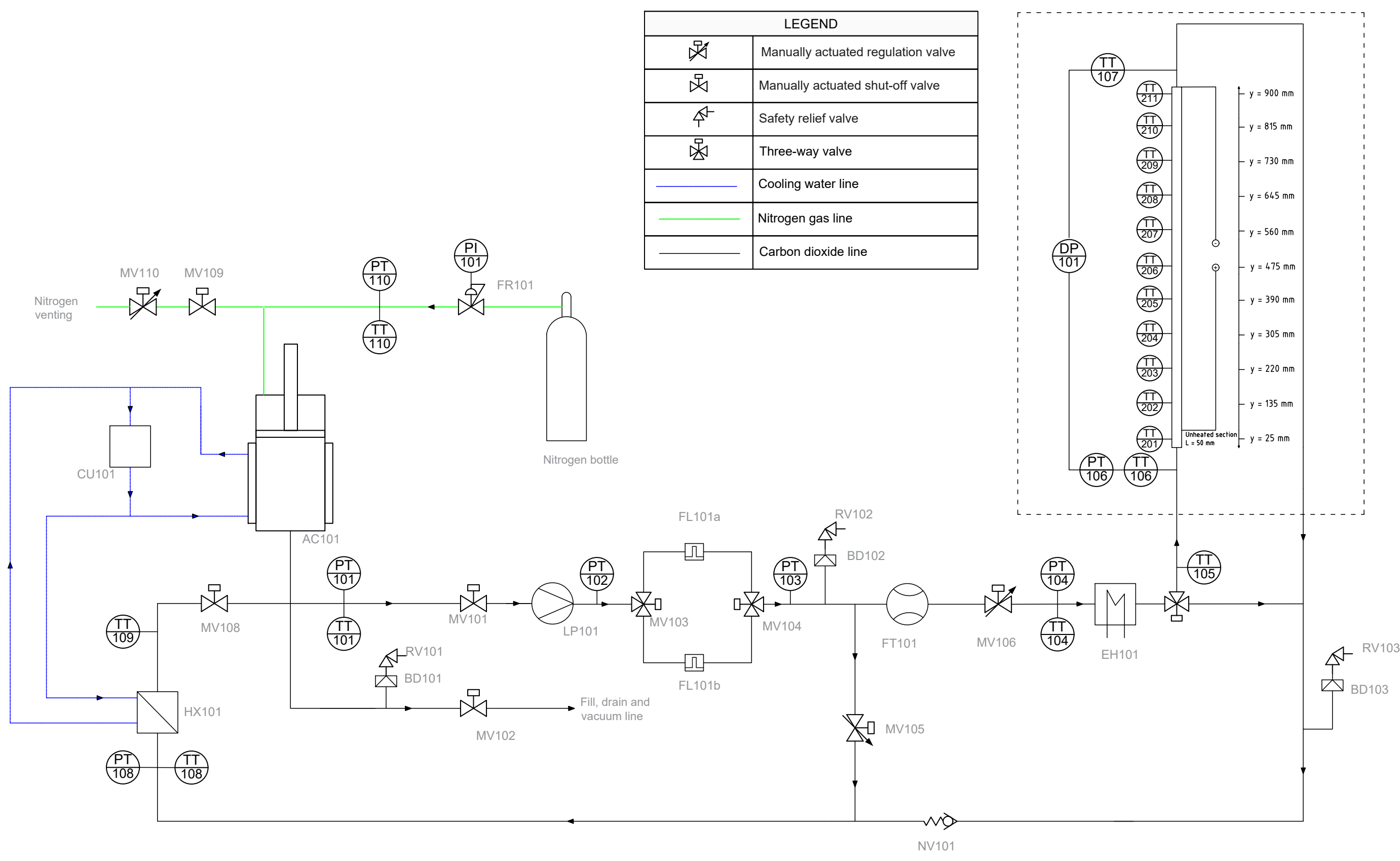

Figure 4: *P&ID of the test facility.*

Pressurization (Point 1) The fluid is pressurized in a range 50-120 bar by means of a hydraulic accumulator (AC-101).
Flow (1-2) A rotary vane pump flows the fluid through the test rig (LP-101).
Conditioning (2-3) The flow to the test section is regulated with two needle valves (MV-105, MV-106). An electric heater sets the inlet temperature value (EH-101).
Measurement (3-4) Absolute pressures are monitored in the test section, as well as differential pressures, in-flow temperatures and wall temperatures. The test section is installed in a rotatable frame, allowing operation with the flow in vertical, horizontal, or intermediate orientations.
Return line (4-1) The fluid is cooled back to the start of the process in a heat exchanger (HX-101 with CU-101).
The process variables are measured with the accuracies reported in *Table 2*. Besides the illustrative process cycles, *Figure 5* also shows the possible operating temperature and pressure conditions.

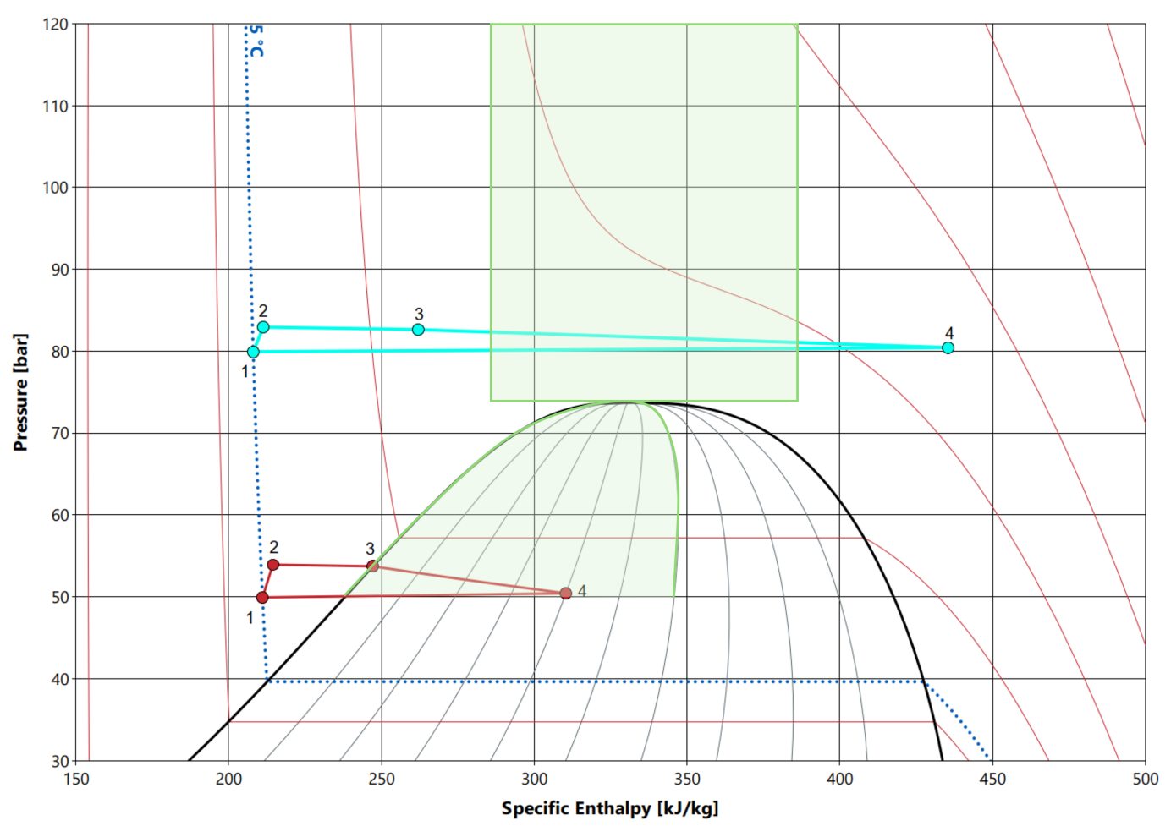

Figure 5: *p-h diagram of carbon dioxide and the possible operation modes (red, blue). In green, the pressure and temperature conditions the test setup can operate in.*

Table 2: *Accuracy of key measurements in the test section.*

Measurement	Accuracy
Mass flow	0.10%
Absolute pressure	0.16%
Differential pressure	0.05%
In-fluid temperature	0.07°C
Wall temperature	0.10°C

Scan the QR code to see images of the rig.

The test rig is now commissioned and ready to start operation. The first tests will evaluate the *diameter effects* in pipe diameters between 1-2.15 mm.

References

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