Studies on supercritical carbon dioxide as a refrigerant for future detectors

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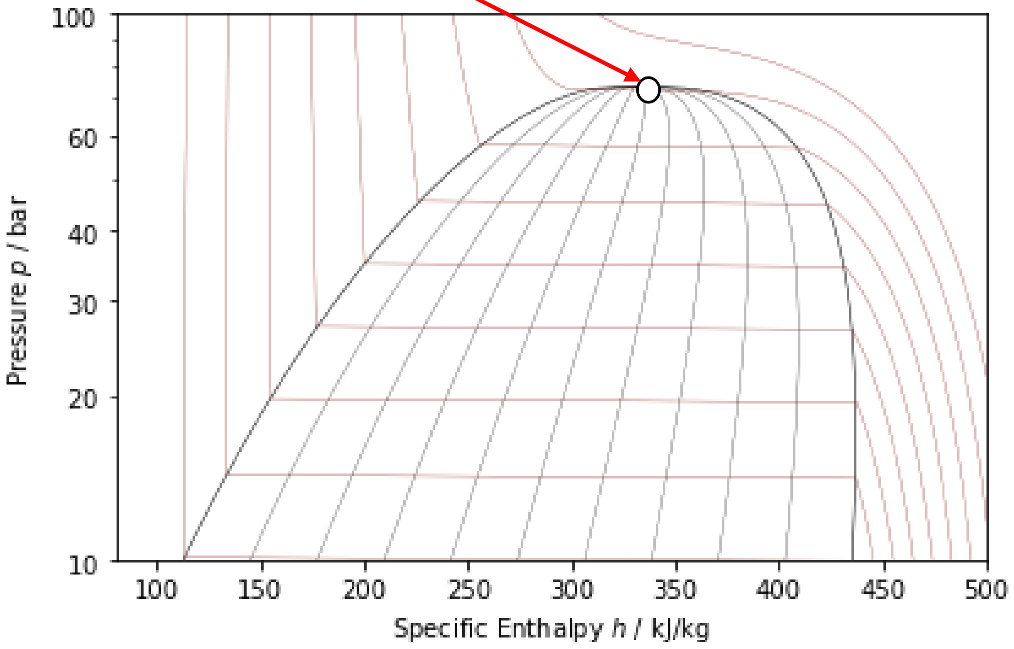
Presentation outline

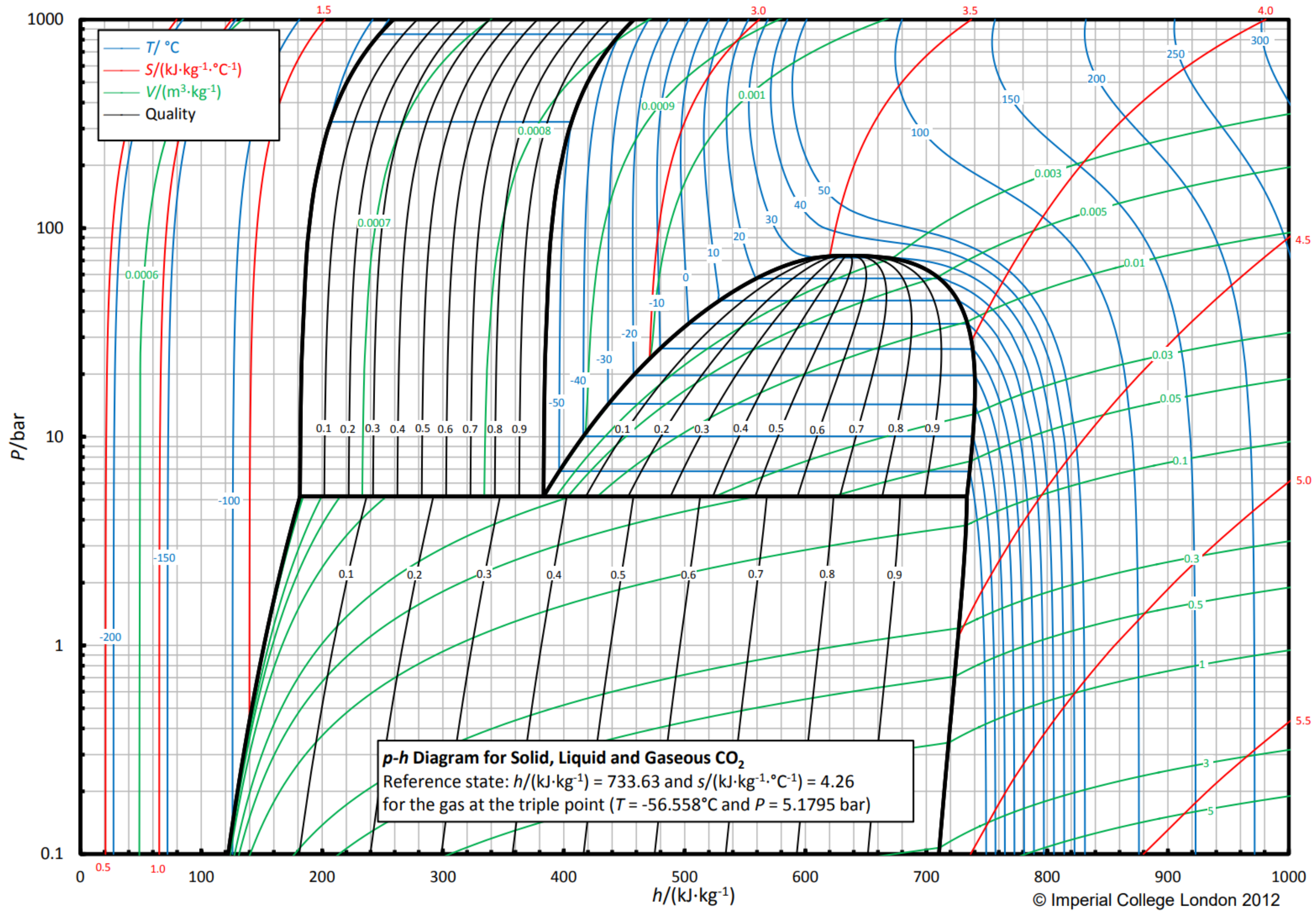
- Introduction: the supercritical condition, why sCO_2
- Objectives
- Fundamentals on the supercritical condition
- Process and Instrumentation Diagram
- Equipment
- Summary

Ok, but what do you mean by supercritical?

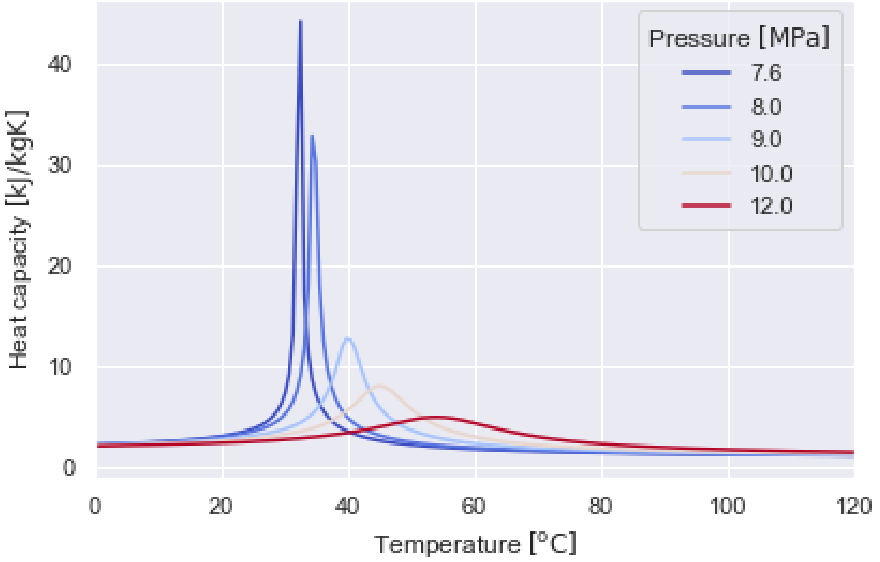
- At subcritical: discontinuities
- Above critical value: change is continuous
  - T<Tc liquid-like fluid
  - T>Tc vapor-like fluid

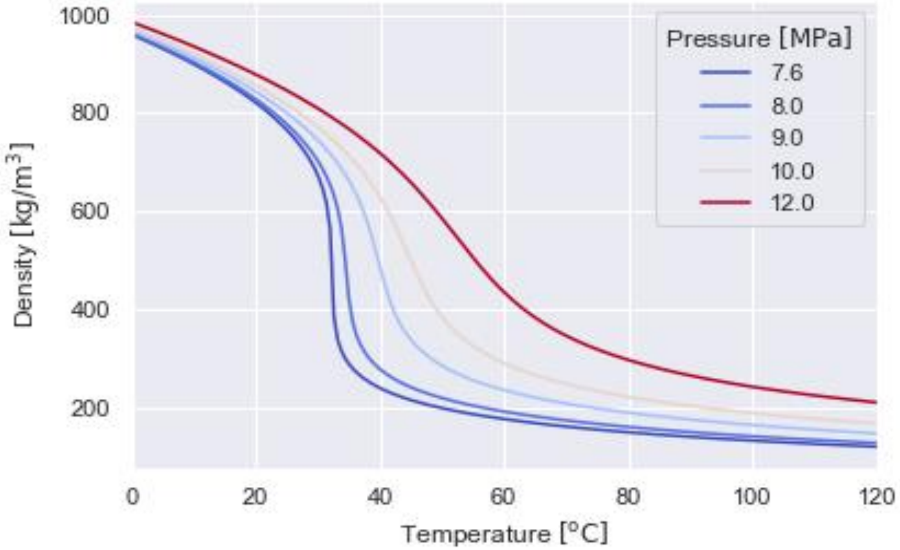
- Critical point of carbon dioxide:
  74 bar, 31 °C

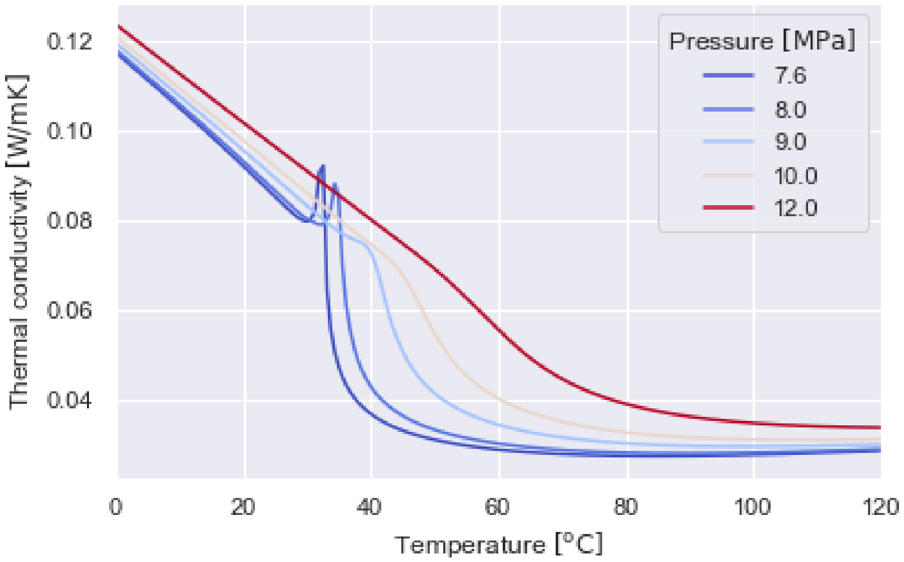


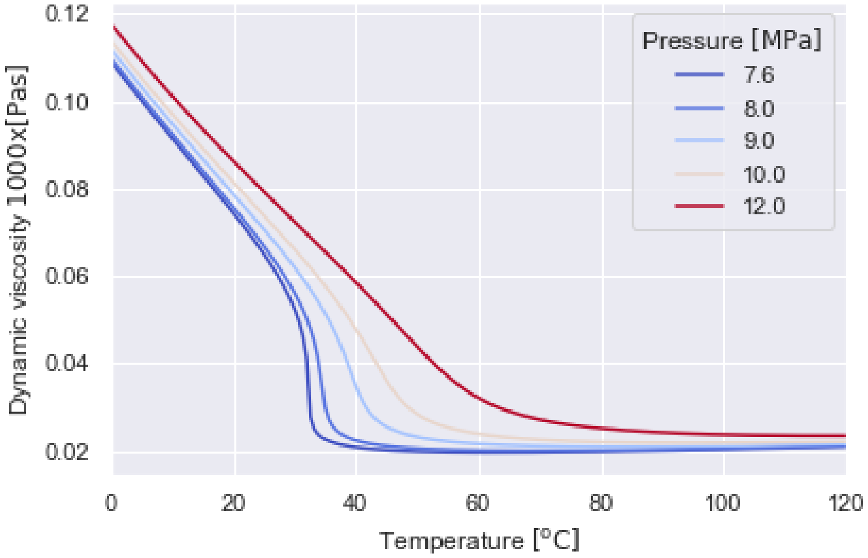


And?


Heat capacity [kJ/kgK]
Temperature [°C]
Pressure [MPa]
7.6
8.0
9.0
10.0
12.0
0
10
20
30
40
0
20
40
60
80
100
120


Density [kg/m^3]
Temperature [°C]
Pressure [MPa]
7.6
8.0
9.0
10.0
12.0
200
400
600
800
1000
0
20
40
60
80
100
120


Thermal conductivity [W/mK]
Temperature [°C]
Pressure [MPa]
7.6
8.0
9.0
10.0
12.0
0.04
0.06
0.08
0.10
0.12
0
20
40
60
80
100
120


Dynamic viscosity 1000x[Pas]
Temperature [°C]
Pressure [MPa]
7.6
8.0
9.0
10.0
12.0
0.02
0.04
0.06
0.08
0.10
0.12
0
20
40
60
80
100
120

Comparison with other refrigerants

Perfluorinated compounds have much higher GWP

A Word to the Novec–649 Issue

Novec line discontinued by 3M end of 2025

- Patent expiration, environmental concerns
  - → Alternative producers?
  - → Cooperation with STS?
  - → **Outcome = unknown!**

Slide credit: Franz Matejcek

EP-DT Detector Technologies

Cooling fluids used at CERN *(with room temperature reference)*

Slide credit: B. Verlaat

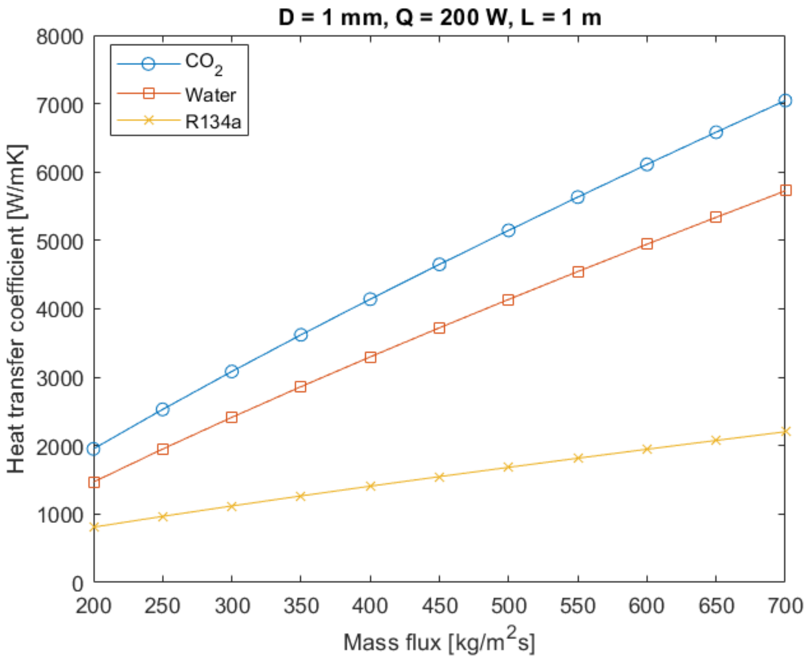
	Normal boiling conditions P=1atm or T=20 °C		2-Phase properties at 20°C	Critical point		Properties at normal conditions T=20 °C, P=1atm or normal boiling pressure in case of liquefied gas			Other properties	
Fluid	Boiling temperature (°C)	Boiling pressure (bar)	Latent heat (kJ/kg)	Critical temperature (°C)	Critical pressure (bar)	Density (kg/m3)	Heat capacity (kJ/kg*K)	Viscosity (µPa*s)	GWP	Prize €/kg
Water	100	0.023	2453	373.9	220.6	998	4.18	1001.6	-	0
Novec 649 [1]	49.1	0.326	96.2	168.7	18.7	1617	1.10	756.6	1	47,-
C6F14	56.9	0.236	94.0	175.9	18.3	1703	1.03		9300	30,-
C5F12	29.8	0.695	95.0	147.4	20.5	1632	1.07	497.6	9160	
C4F10	-2.2	2.29	88.9	113.2	23.2	1516	1.07	230.9	9200	138,-
C3F8	-36.8	7.56	79.1	71.9	26.4	1352	1.15	180.6	8900	38,-
C2F6	-78.1	Super critical		19.88	30.5	Super critical			11100	100,-
CO2	-78.4	57.29	152.0	30.97	73.8	773.4	4.3	66.1	1	0.015

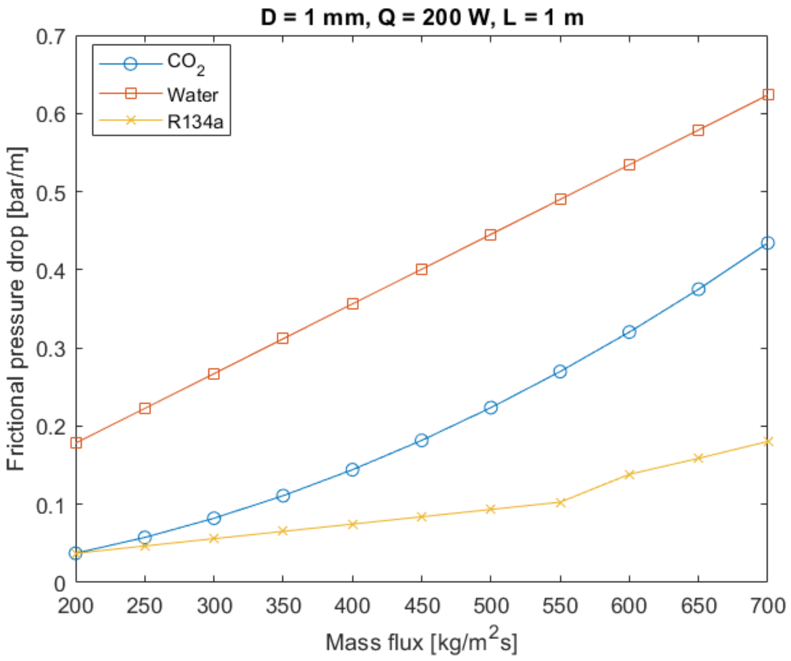
No future (C6F14, C5F12, C4F10, C3F8, C2F6)

[1] Not well understood radiation and material compatibly issues

Ok, but we already have water for single-phase cooling

Yes, but check this out





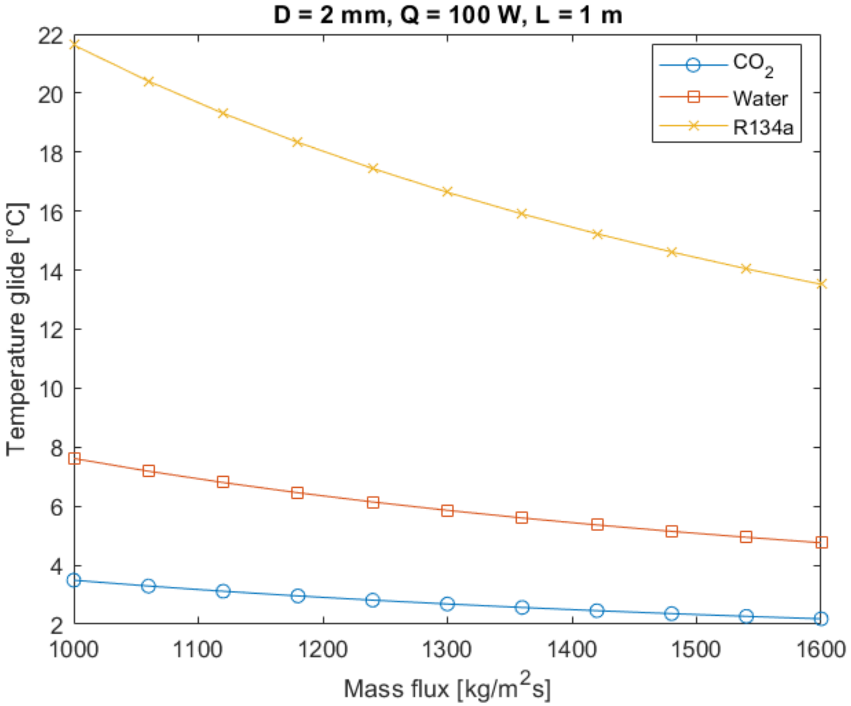
Heat transfer coefficient higher than that of water in the conditions shown

With significantly lower pressure drops

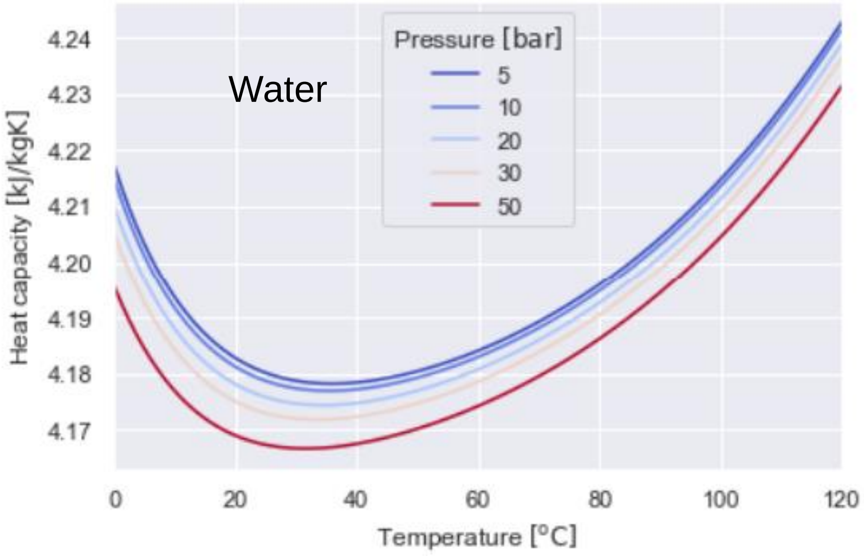
+ CO_2 is not electrically conductive

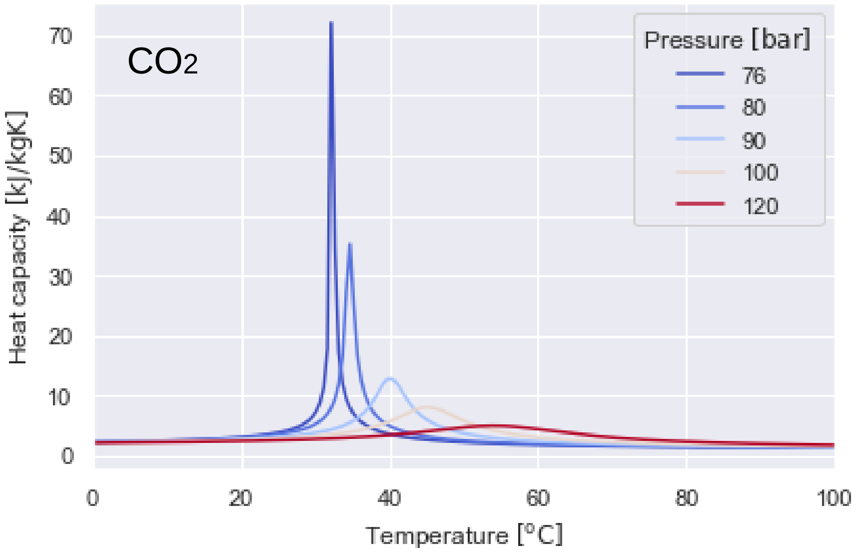
Ok, but we already have water for single-phase cooling

Yes, but check this out



$$d\dot{Q} = \dot{m}CpdT$$





And what about boiling?

Characterized by very high heat transfer coefficients, but also by very significant pressure drops and difficulty in its controllability

Detector environment

Low radiation
Ambient temperature

High radiation
Significantly cold temperature

Aim

Provide precision measurements of thermal-fluidic properties of sCO2 in the range of temperatures of interest for possible ultra-light future detectors operating in environments with low radiation levels.

Design a completely new cycle and provide a precise strategy to move from the warm to the cold area without any thermal shocks on the detector

Fluid

CO_2

Kr

Low radiation
Ambient temperature ← Detector environment

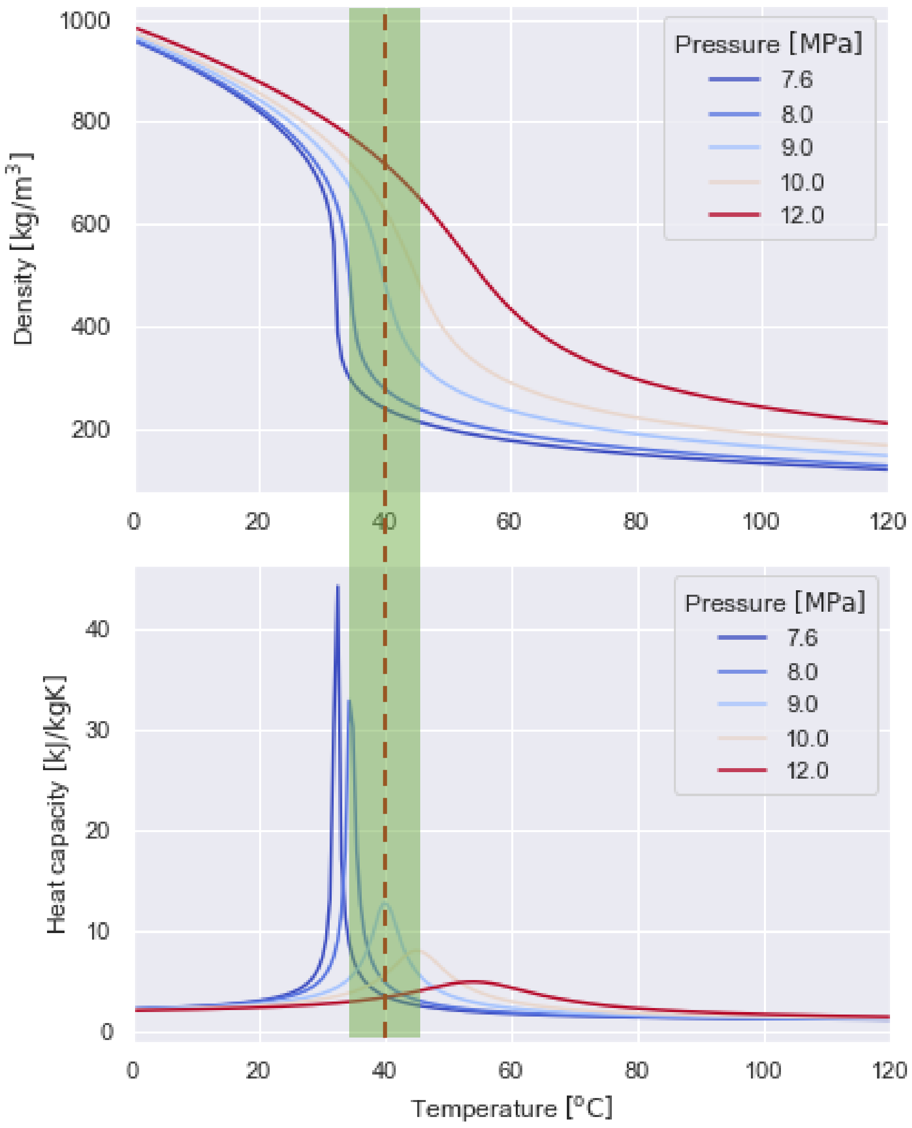
CO_2 ← Fluid

Three fundamental objectives:

1. Theoretical and experimental study of termal and fluidic behavior of carbon dioxide flowing in small pipes passing over its critical conditions
2. Optimization of the use of supercritical carbon dioxide as a refrigerant and characterization on the heat transfer coefficient attainable at conditions between 31 and 45 ºC
3. Study of the design indications for new supercritical heat exchangers for optimal energy recovery in CO2 refrigeration plants

Temperature of interest for room temperature detector cooling (+31 to +45 °C)

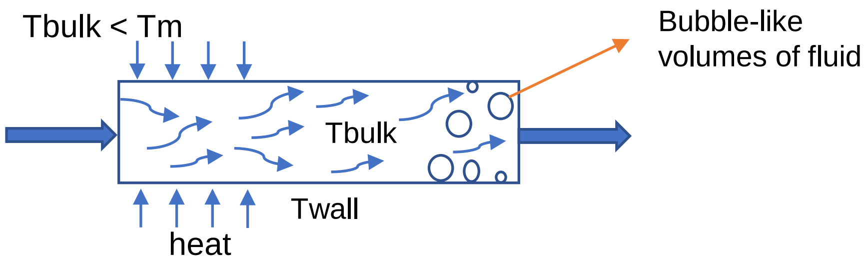
Tm = Pseudo-critical temperature



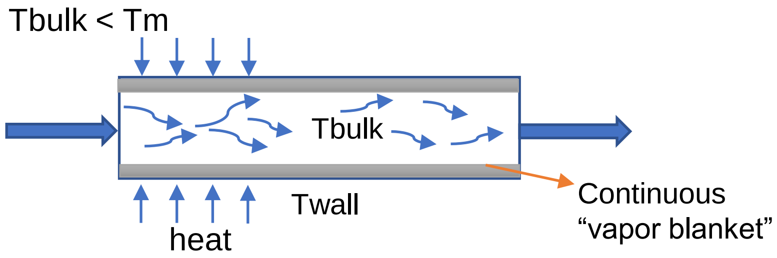
Let's get physical

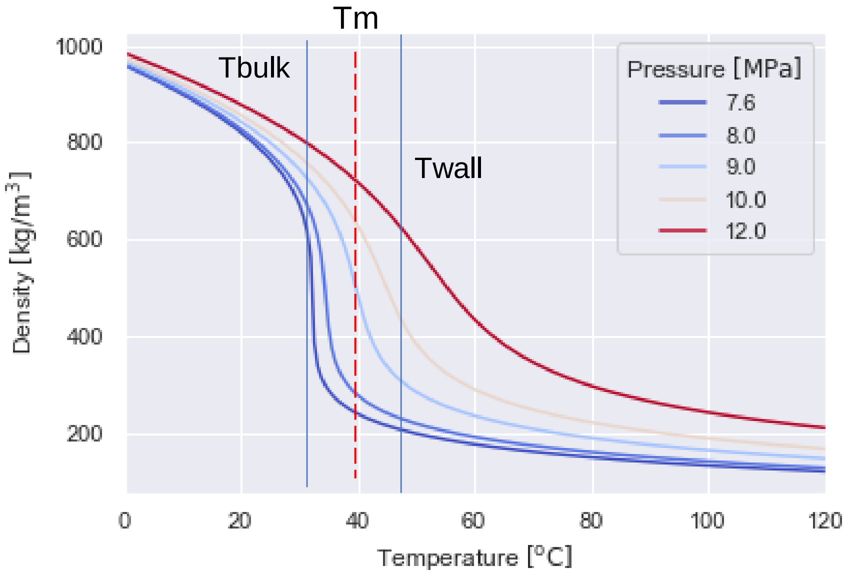
- Mechanisms
  - Normal heat transfer: heat transfer coefficients similar to sub-critical far from critical region when calculated with established correlations (e.g. Dittus Boelter)
  - Enhanced heat transfer: higher than at normal conditions
  - Deteriorated heat transfer: lower than at normal conditions

- One approach (analogy to sub-critical boiling):
  - Pseudo-boiling



  - Pseudo-film boiling





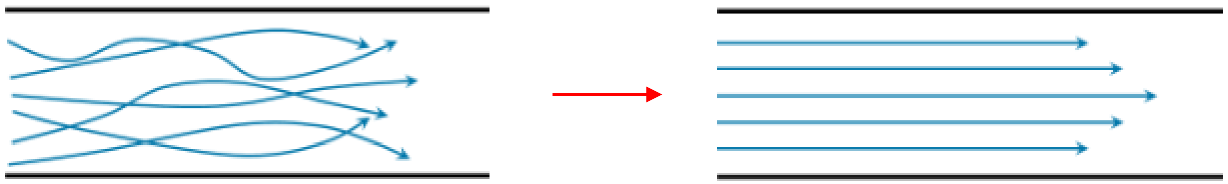
But it is single phase!

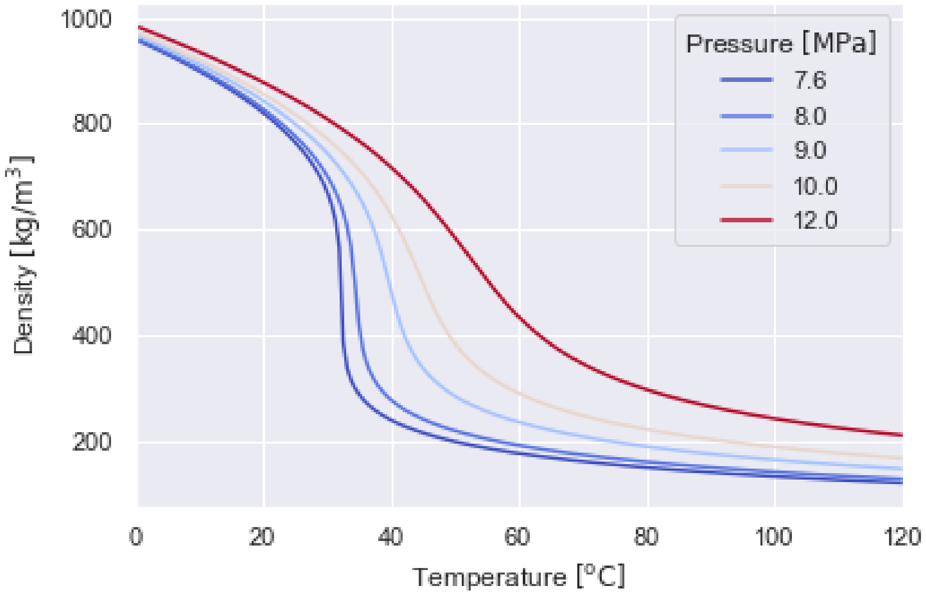
Let's get physical

- Another approach (single-phase):
  - Assumes single phase and homogeneous fluid properties throughout the system
  - Explains heat transfer deterioration as a consequence of laminarization of the fluid flow

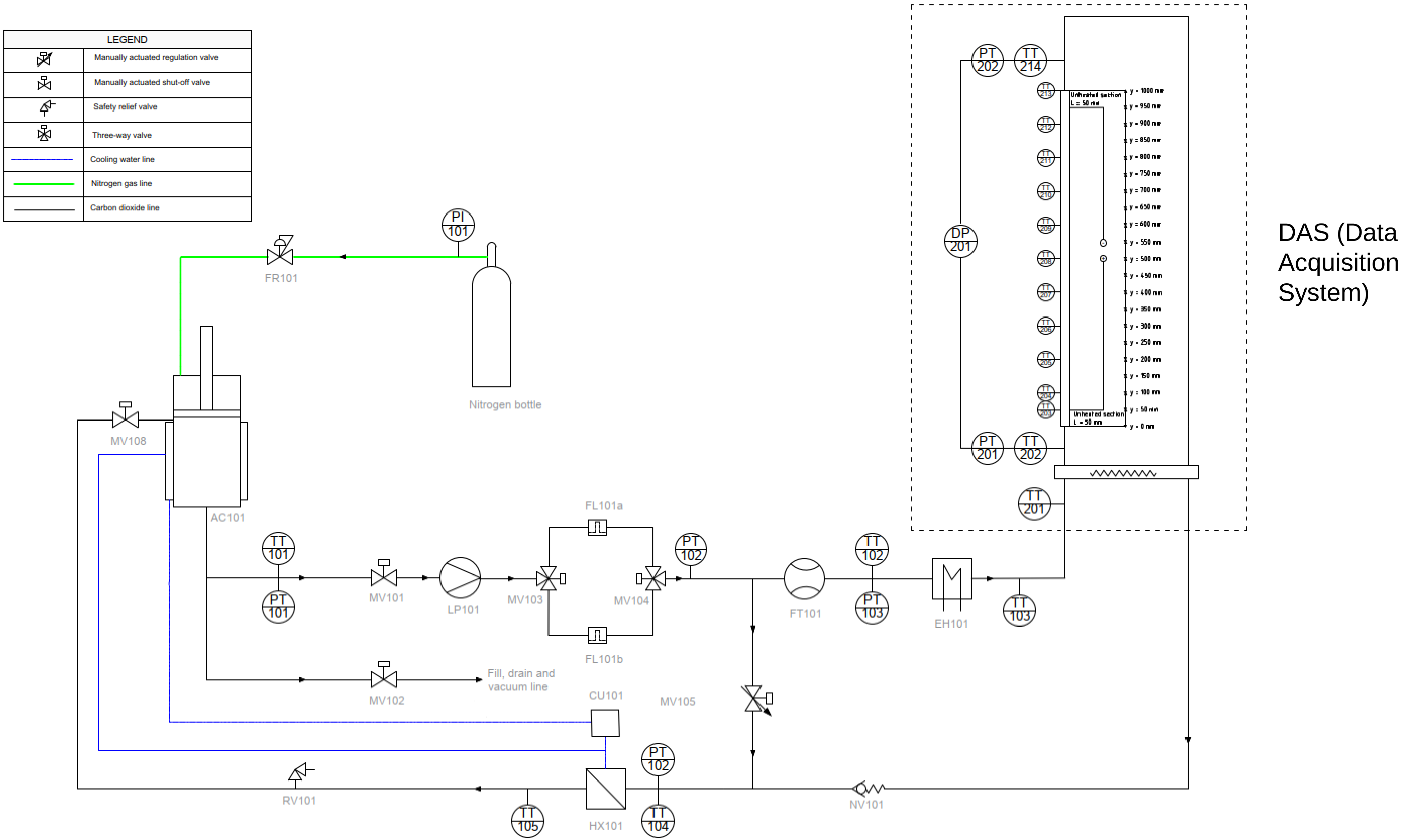
Laminarization: transition of turbulent flow to laminar flow in the boundary layer caused by a decrease in the fluid density near the pseudo-critical point.

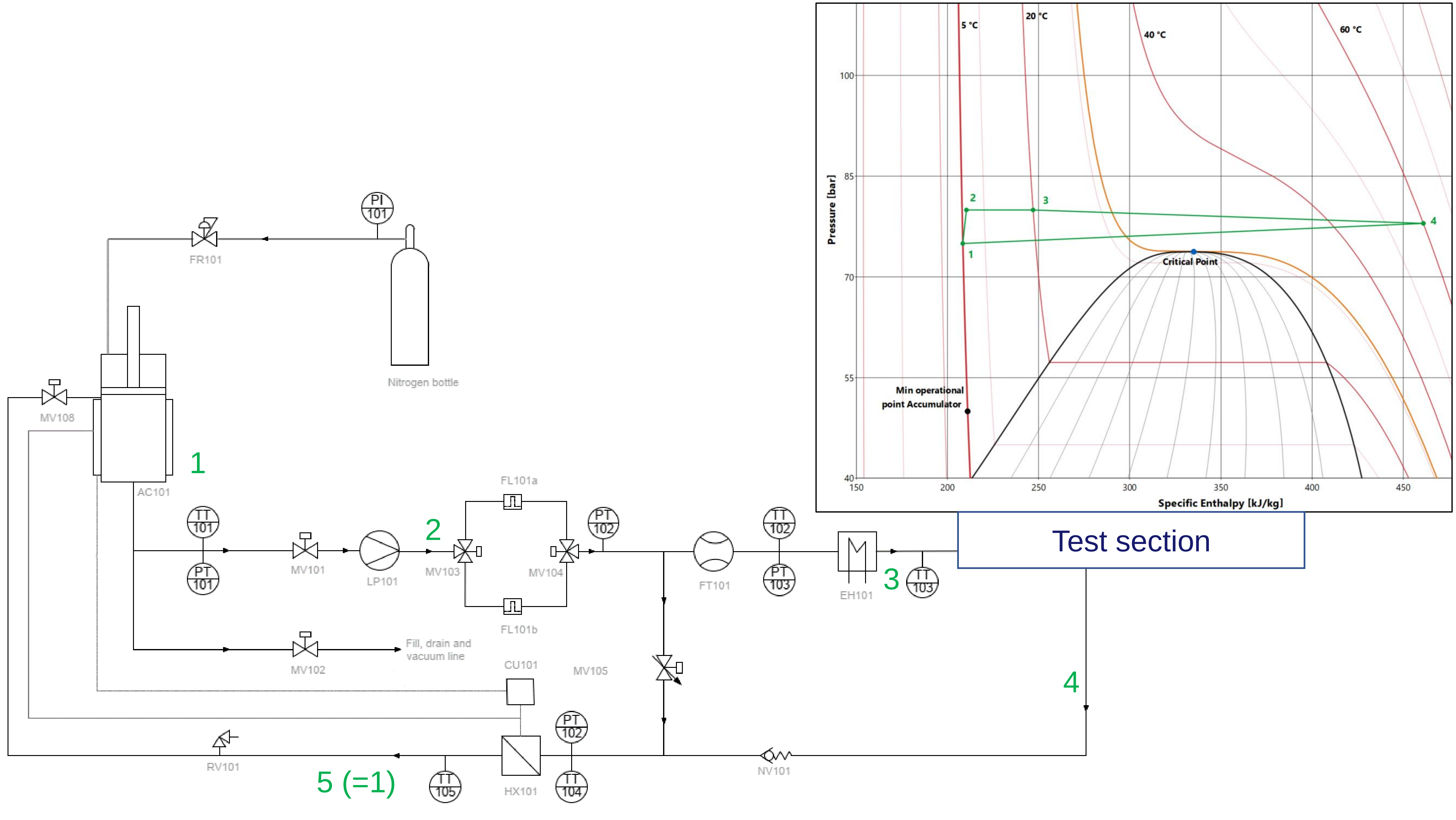
This density reduction affects the fluid's resistance to shear and turbulence generation, promoting the transition to laminar flow





- Important parameters to evaluate:
  - Mass flux: 500 – 1600 kg/m2s
  - Heat flux…
  - Diameter: 1, 2, 3 mm
  - Configuration: vertical upwards, downwards, horizontal
  - Pressure: Pcrit – 120 bar
- Important questions to think about
  - Effect of operating parameters on heat transfer coefficient AND pressure drop?
  - Mechanism of heat transfer deterioration? Onset?
  - Influence of buoyancy on the flow regime… Threshold? Based on what?
  - Are pseudo-boiling and pseudo-film boiling good models? Is the single-phase approach cooler?
  - Correlations?
  - To which extent can knowledge on one fluid be extrapolated to another?

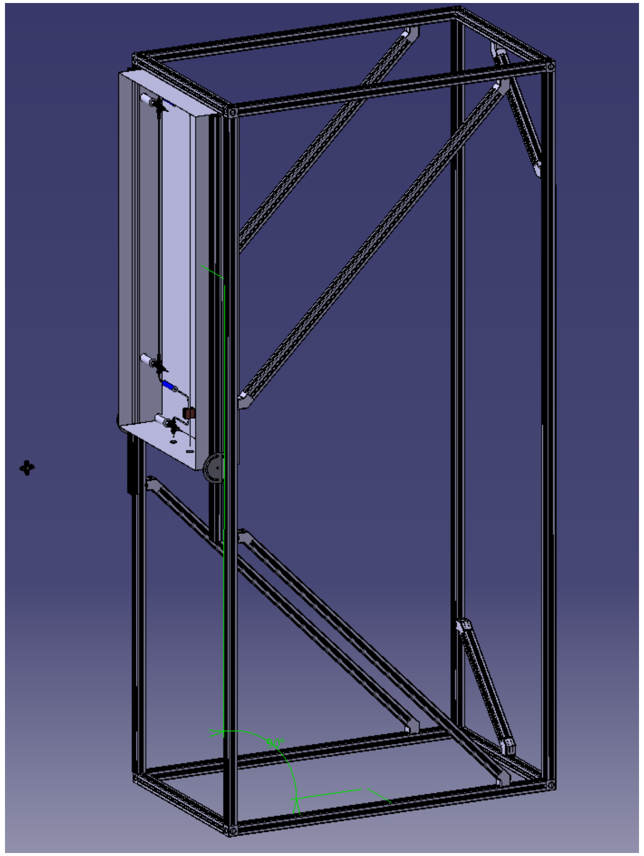

LEGEND
Manually actuated regulation valve
Manually actuated shut-off valve
Safety relief valve
Three-way valve
Cooling water line
Nitrogen gas line
Carbon dioxide line
PI 101
FR101
Nitrogen bottle
MV108
AC101
TT 101
PT 101
MV101
LP101
MV103
MV104
FL101a
FL101b
PT 102
FT101
TT 102
PT 103
EH101
TT 103
MV102
Fill, drain and vacuum line
CU101
MV105
RV101
TT 105
HX101
PT 102
TT 104
NV101
PT 202
TT 214
DP 201
PT 201
TT 202
TT 201
DAS (Data Acquisition System)

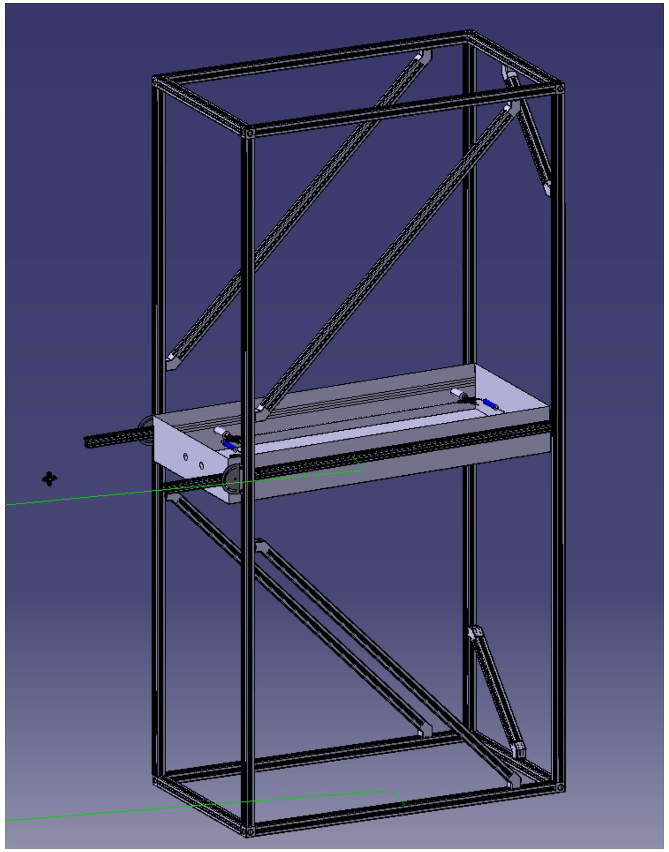


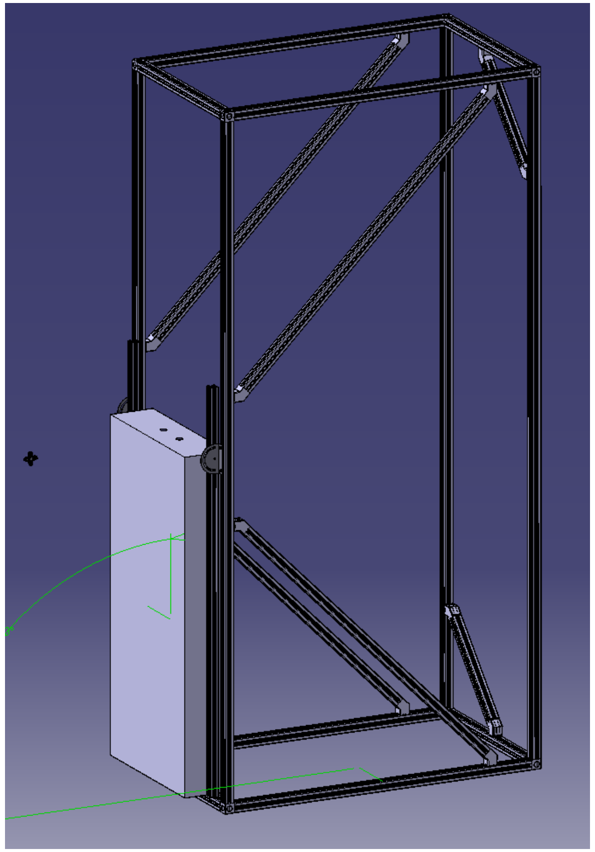
PI 101
FR101
Nitrogen bottle
MV108
AC101
1
TT 101
PT 101
MV101
LP101
2
MV103
FL101a
FL101b
MV104
PT 102
FT101
TT 102
PT 103
EH101
3
TT 103
Test section
4
MV102
Fill, drain and vacuum line
CU101
MV105
RV101
5 (=1)
TT 105
HX101
PT 102
TT 104
NV101
5 °C
20 °C
40 °C
60 °C
Critical Point
Min operational point Accumulator
Pressure [bar]
Specific Enthalpy [kJ/kg]

The main goal is to study three flow configurations: vertical upwards, horizontal and vertical downwards using the same instrumentation.
This means that the test section should tilt.

The design was made in CATIA V5: the frame is built with aluminum extruded profiles.











KELLER

RHEONIK

HYDAC

M PUMPS

SWEP



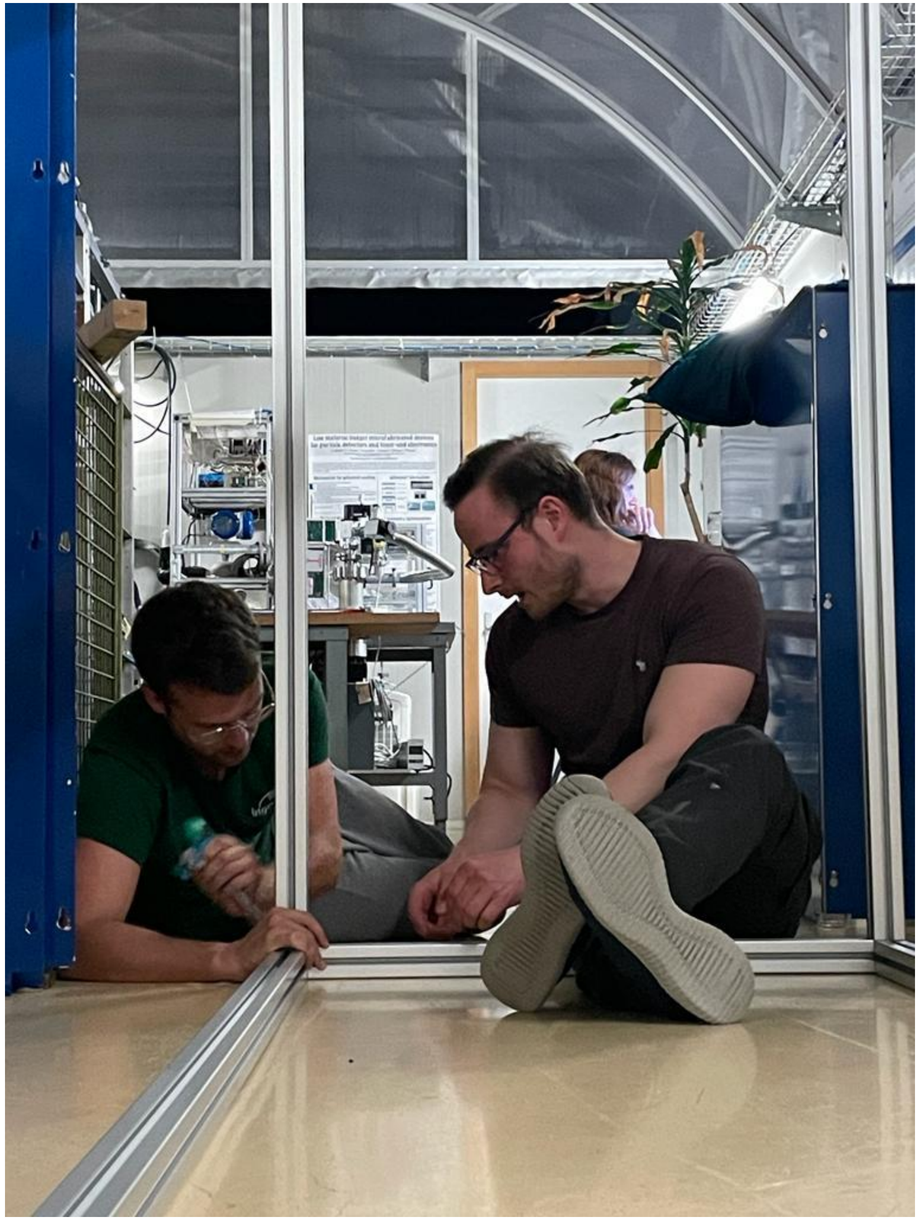

RODAX



huber

VAN DER HEIJDEN Labortechnik GmbH
cool solutions - your advantage

Endress+Hauser




Swagelok
CAMi
Swagelok
sCO2
Swagelok
sc-co2
CAMi
Swagelok
sCO2 - 8way
Swagelok
CAMi
sCO2
CAMi
sCO2
Swagelok


Forum on Tracking Detector
Mechanics 2015
CAMi
sCO2
profiles


Swagelok
Vorsicht!

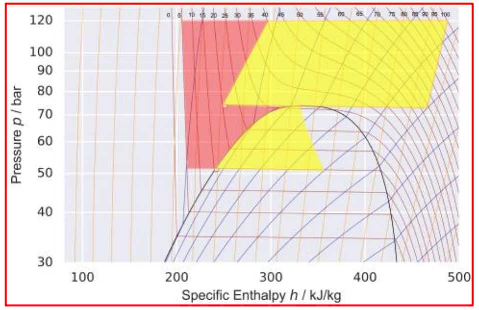
- The supercritical condition
- Comparison with other options:
  - CO_2´s pros with what respects the detector field: radiation-hard and non-electrically conductive
  - CO_2 vs. synthetic refrigerants: much lower ODP and GWP, natural refrigerant, non-toxic
  - Supercritical cooling compared to two-phase cooling: lower heat transfer coefficient, however lower pressure drops and much easier to implement and control
- Mechanisms and fundamentals
- Process conceptualization
- Equipment
- Main conclusion: I have some work to do

Extras – Selection

Equipment selection - Preheater

Requirements for selection: $Q_{max} = 1.04\ kW$

1. Has to be able to supply the maximum heat load needed
2. Must withstand 120 bar
3. Not too expensive



Options:

1. Electric heater: cartridge/cast aluminium heater

   A cartridge could not withstand the pressure

2. Coil inside a heating bath

   Not very precise temperature control, a bit slow

3. Heat exchanger

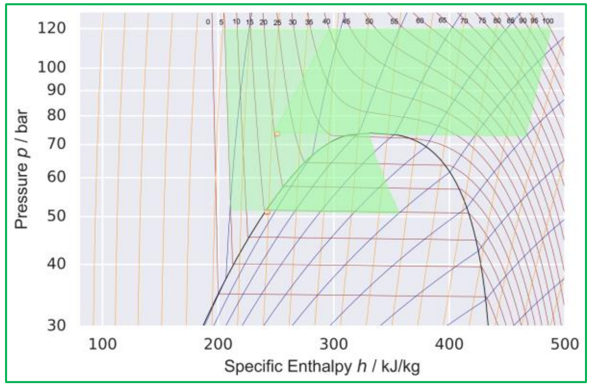
   Requires a second loop, maybe not worth considering the heat load

The final choice was a CAST-X cast aluminium heater with a capacity of 1.1 kW.

Equipment selection – Post-cooling system

Requirements for selection: $Q_{max} = 3\ kW$

1. Has to be able to absorb the maximum heat load needed
2. Must withstand 120 bar
3. Not too expensive



Options:

1. Coil inside a cooling bath
   Cheaper
   Heat load is considerably high and heat transfer occurs slower than in a heat exchanger → more than 30 turns in a coil
2. Heat exchanger
   More efficient heat transfer
   Although heat exchangers are cheap, a chiller unit with such power is expensive

A 20-plate heat exchanger was chos SWEP Model: B4THx20
together with a chiller that can absorb 3.2 kW at 5 °C water temperature

huber VAN DER HEIJDEN Labortechnik GmbH cool solutions - your advantage Model: VDH5000A

Equipment selection – test section

The test section is composed of:

1. 1 meter long SS tube: 1, 2 and 3 mm ID

2. Thermocouples
   Type K
3. Clamps for power supply
   Copper electrodes will be designed soon

   The power supply will be rented from the Electronics Pool at CERN, a load of ~2 kW is needed

A power supply with 30 V and 200 A is available.
Actual voltage and current delivered by the unit will be read by means of the DAS.

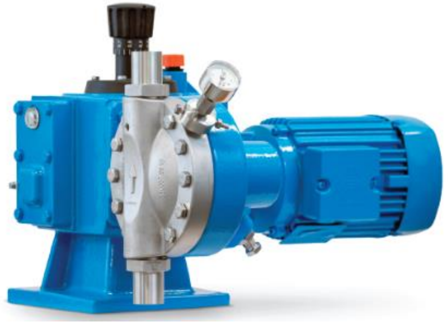
Model: SM30-200

Equipment selection – Pump

The pump's main task is to overcome the pressure drop across the rest of the setup, since the operating pressure of the system is set by the accumulator

The operating conditions set for the pump were:

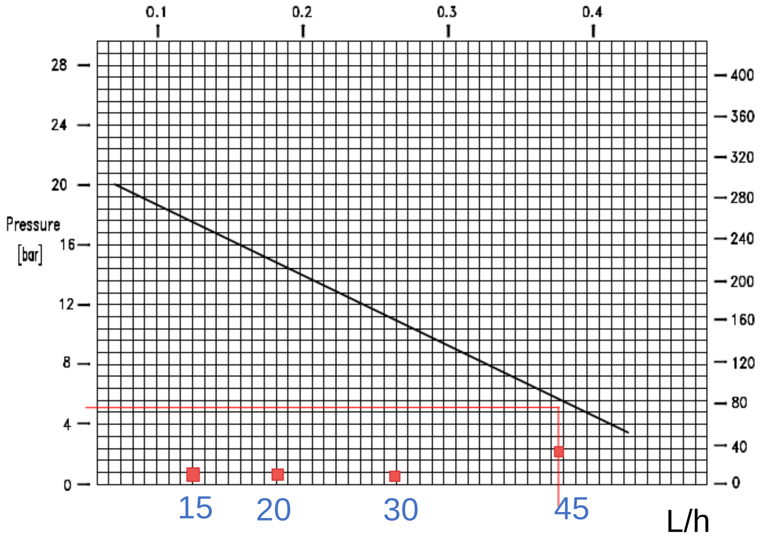
1. Inlet temperature set at 5 °C
2. Suction pressure from 50 to 120 bar
3. Discharge pressure from 55 to 125 bar
4. Fluid: carbon dioxide (liquid)
5. Flow: 0.3 - 43.2 L/h



A magnetic driven pump from M-PUMPS was chosen. It is a rotary vane 2-stage modular pump. Others have experience using it for several years with co2 (INFN)

Seal-less pump, no need for lubricant

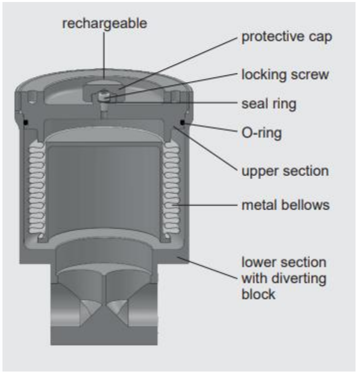
Cheapest option among the ones considered

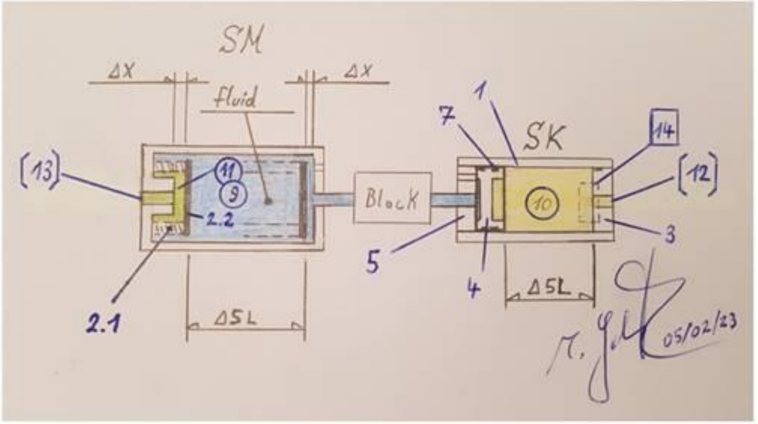


Model: VA MODULAR 005/2S*

Equipment selection – Accumulator

The accumulator is a PCA (Pressure Controlled Accumulator), only subcooled liquid is present in it. The pressure of the liquid can be controlled by means of a gas (N2).





Nitrogen

Hydraulic fluid

Carbon dioxide

The operating conditions are:

1. Pressure from 50 to 120 bar
2. Temperature set at 5 °C
3. Design volume for the carbon dioxide side is 5 L

By means of a coil with cooling water around the unit to compensate for ambient heat losses (around 75 W considering an ambient temperature of 25 °C and without taking insulation into account). The heat load will be taken from the chiller.*

The unit will be designed by HYDAC

The pressure regulator linked to this part of the process is still to be defined and ordered.

Equipment selection – Sensors

The different sensors needed in the test setup are:

1. Mass flow-meter

   RHEONIK

   Once the range of mass flow of interest was defined, the unit was chosen so that it covered the whole range with an acceptable accuracy.

   Model: RHM02

2. Absolute pressure sensors

   These were chosen following the technologies currently used at CERN.

   Model: 23SX KELLER

3. Differential pressure sensors

   The maximum pressure drop expected in the test setup was estimated with the homogeneous model for the most critical case expected. Such case is in subcritical condition at the lowest temperature, 15 °C, the highest mass flux in the smallest diameter in 1 meter length. The dp computed is 0.9 bar. The unit was chosen so that it covered 3 times the obtained value.

   Model: Deltabar PMD75B Endress+Hauser

4. In-flow temperature sensors

   RTD probes inserted in a tee or a cross fitting. Calibration to be done on site.

   RS PRO RODAX

5. Thermocouples (mentioned in test section design) RS PRO

Equipment selection – Valves and fittings

Shut-off valves:

Quarter-turn ball valves with a Cv of 2.4

By-pass valve:

It will only operate with liquid. Since a liquid is an incompressible fluid, the flow rate through a valve depends only on the difference between the inlet and outlet pressures. Flow is always the same whether the system pressure is high or low.

Integral bonnet valve with vee stem with Cv = 0.21

$$q = N_1 C_v \sqrt{\frac{\Delta p}{G_f}}$$

Safety-relief valve:

The cracking pressure is set at the maximum attainable pressure in the pump + 1 bar.

Check-valve:

Chosen considering the chemical compatibility of the sealing with carbon dioxide.

Pipes and fittings:

All the process pipes are either 6 mm or ¼”, SS316L. Pressure lines are 1/8”. Whenever possible, VCR fittings are chosen.

Hoses and flexible lines are used in parts of the setup, dimensions are the same as specified above.

Equipment selection – Data Acquisition System

Data acquisition will be based on CompactDAQ Chassis from National Instruments

Model: cDAQ-9178

Data “sources”:

1. RTDs 8 temperature probes in the setup, 4-wired NI-9219, NI-9216 and NI-9215 fit the application
2. Thermocouples NI-9211, NI-9213, NI-9214 and NI-9217 fit the application
3. Absolute and differential pressure NI-9215, NI-9219 and NI-9203 fit the application
4. Mass flowmeter NI-9217 is a suitable module
5. Preheater
6. Joule heating power supply
7. Peltier element power supply

… ongoing