Grant Agreement No: 101004761

AIDAinnova

Advancement and Innovation for Detectors at Accelerators

Horizon 2020 Research Infrastructures project AIDAINNOVA

MILESTONE REPORT

MID-TIME REPORT DETAILING THE NEW EXPERIMENTAL FACILITY AND RESULTS FROM THE THEORETICAL STUDIES

MILESTONE: MS43

Document identifier:	AIDAinnova-MS43
Due date of milestone:	End of Month 22 (January 2023)
Report release date:	31/01/2023
Work package:	WP10: Advanced Mechanics for Tracking and Vertex Detectors
Lead beneficiary:	NTNU
Document status:	Final

Abstract:

This report describes the activities performed so far according to the plan for task 10.4:" Supercritical fluids as refrigerants". The project aims at defining the feasibility of future detector cooling systems based on refrigerant in supercritical state. The present document summarises the main achievements at this stage:

- Review of the literature available regarding thermal efficiency studies with carbon dioxide at supercritical state.
- Selection of the best suited supercritical refrigerant candidate for low temperature applications.
- Final designs of two dedicated test stands and description of the processes.

The Advancement and Innovation for Detectors at Accelerators (AIDAinnova) project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 101004761. AIDAinnova began in April 2021 and will run for 4 years.

Delivery Slip

	Name	Partner	Date
Authored by	C. Pedano L. Contiero	CERN NTNU	18/01/2023
Edited by	P. Petagna	CERN	25/01/2023
Reviewed by	A. Hafner [Task coordinator] P. Petagna [WP coordinator] G.Calderini [Deputy Scientific coordinator]	NTNU CERN CNRS	25/01/2023
Approved by	G.Calderini [Deputy Scientific coordinator]		31/01/2023

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Executive summary

Task 10.4 in AIDAinnova is led towards the study and conceptualization of processes to evaluate the feasibility of detector cooling using supercritical fluids. Theoretical background and a literature overview of the research performed in this field are briefly provided, as well as a description of the conceptual studies carried out until now. Process and Instrumentation Diagrams are presented, including the frozen design of the facilities to be built. Finally, a detailed workplan is also included.

1. INTRODUCTION

Supercritical fluids are characterized by low values of density and viscosity while exhibiting high thermal capacity without phase change. This makes them interesting candidates as refrigerants for the thermal management of future High Energy Physics detectors. However, in compliancy with the recently updated European Strategy, general interest developments for future detectors should ideally target both ultra-light detectors operated at temperatures above 0 °C and detectors operating in extreme radiation environments requiring very low temperatures, below those attained for the forthcoming LHC detector upgrades.

In this context, thanks to synergies with the CERN-funded EP-RDET programme and leveraging on the recently signed collaboration frame agreement between CERN and the Norwegian Institute of Technology (NTNU), it has been possible to launch two parallel programmes targeting both directions of investigation.

The first one aims at providing precision measurements of thermal-fluidic properties of supercritical carbon dioxide (sCO_2) in the range of temperatures of interest for possible ultra-light future detectors operating in environments characterized by low radiation levels. By starting the exploration from the region just below the critical point and then moving at higher pressures and temperatures, the activity will provide fundamental information also for other fluids of potential interest for their properties in the supercritical region, including fluids that are supercritical at low temperature.

The second programme targets specifically the use of supercritical fluids at lower temperatures than the ones presently attainable with subcritical carbon dioxide. Different from the previous case, this approach first requires the development of an innovative thermodynamic cycle capable of bringing the selected fluid in its supercritical region starting from standard conditions (20 °C) while connected to a detector without causing thermal shocks. The definition and verification of such a process are in this case the main objectives.

2. THEORETICAL BACKGROUND

2.1. SUB- AND SUPER-CRITICAL CONDITIONS

At temperatures below the critical point, the variation of pressure with volume along an isotherm exhibits discontinuities where it intersects with the saturation line, where phase change takes place (Figure 1). Two distinct phases coexist under these conditions. However, above the critical point, such discontinuities as well as the coexistence of two phases do not take place. Macroscopically, there is a continuous variation from a liquid-like fluid to a less dense, vapour-like one. This transition is delimited by the critical temperature: where for temperatures below the critical temperature liquid fluid is found, while for temperatures above gas is found. For instance, the critical values for CO_2 are 31.1 °C and 73.8 bar, respectively. This continuous change is of particular interest, but the extreme dependency of fluid properties on temperature can trigger important effects on the mean flow and turbulence fields as well as on the heat transfer effectiveness [1].

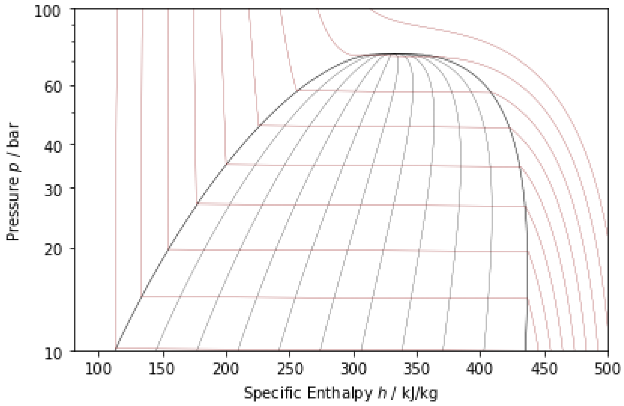
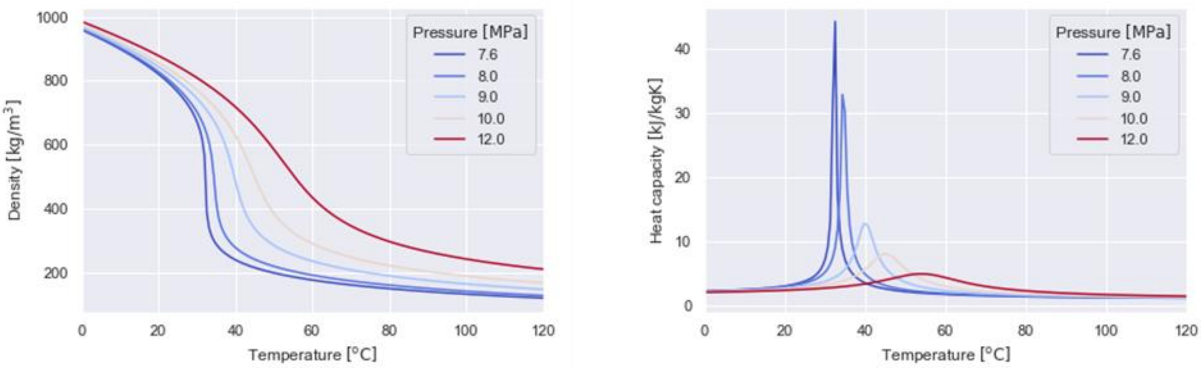


Fig 1. Pressure-enthalpy diagram of carbon dioxide (red lines are isotherms).

This strong variation of physical properties is depicted in Figure 2, where a clear sudden reduction of the density (a) is observed in the vicinity of the critical point for the pressure values shown in the plot. Meanwhile, for those values, the heat capacity (b) has a sudden peak and is reduced afterwards. The point at which this peak is reached is called the pseudo-critical temperature and is commonly denoted as T_m. This, in combination with the strong variation in other parameters that affect heat transfer (heat conductivity and dynamic viscosity, among others), may have important consequences on the heat transfer effectiveness *[2]*.



(a) Density *(b) Heat capacity*

Fig. 2 Variation of density (a) and heat capacity (b) with temperature at different system pressures.

2.2. MECHANISMS AND PHENOMENA OBSERVED IN SUPERCRITICAL CONDITIONS

A considerable number of studies have been carried out to investigate flow and heat transfer characteristics of fluids at supercritical conditions, in particular for water and carbon dioxide. Overall, two main approaches have been adopted by the authors in this field to explain the observations made on supercritical fluids: one that considers only single-phase phenomena as the cause of variations in the Heat Transfer Coefficient (HTC) and another one that assumes that a liquid-like and a vapour-like phase coexist in a tube and lead to boiling-like phenomena.

Regarding the first approach, experimental measurements using water as the working fluid [3] confirmed the existence of three different regimes of heat transfer at supercritical pressures:

- **Normal Heat Transfer (NHT):** characterized by heat transfer coefficients similar to those of sub-critical convective heat transfer when far from the critical region, when calculated with a single phase Dittus-Boelter-type correlation. The standard Dittus-Boelter equation is:

$$Nu = 0.023Re^{0.8}Pr^{0.4}$$

- **Deteriorated Heat Transfer (DHT):** defined as a situation where the HTC is lower than that expected with normal heat transfer. Higher values of wall temperature within some parts of the test section are found, when compared to normal heat transfer mechanisms, and large difference between the wall and the bulk fluid are observed [2]. Some authors have explained DHT to be caused by the variation of the thermo-physical properties as well as due to buoyancy and flow acceleration effects [4].

- **Improved Heat Transfer (IHT):** characterized by higher values of HTC compared to those obtained at NHT conditions, hence lower values of wall temperature within a part of the test section. In addition, the difference between the film temperature and the bulk fluid is very small [2].

On the other hand, the authors following the "two-phase-like" approach provide the following explanation for the observed phenomena:

- **Pseudo-boiling** is related to the nucleate boiling phenomenon in sub-critical conditions. When a fluid with bulk temperature $T_b<T_m$ flows inside a heated pipe, some layers near the heated surface achieve temperatures above T_m. This lower density part of the fluid can leave the heating surface in the form of bubble-like volumes of fluid. This phenomenon would lead to higher heat transfer coefficients, hence would be another approach to explaining an IHT regime.
- **Pseudo-film boiling** is similar to the film boiling mechanism in sub-critical conditions. In this case, the low-density part of the fluid (vapour-like) prevents the high-density part of the fluid from contacting the heater surface. Since the heat conductivity of this part of the fluid is rather low, the heat transfer performance is impaired. This phenomenon would be the cause of DHT regimes following this approach.

2.3. MAIN FINDINGS FROM THE LITERATURE REVIEW

In view of the fundamental issues found in this field of research, it is of no surprise that the main topics of experimental studies are the variation of the heat transfer coefficient with important process parameters [4], [8], [9] like the mass flux, heat flux and temperature, as well as the mechanisms that lead to these results [10]–[14]. Due to their relevance for the refrigeration of advanced nuclear plants and for energy conversion via high pressure power plants, the scientific literature on supercritical fluids focuses essentially on water and carbon dioxide. However, due to the lower temperature involved, a vast majority of the experimental studies is based on carbon dioxide. The analysis of the specialistic production clearly depicts a field of research characterized by contradicting results and by a number of open issues.

Regarding the effect of mass flux, different trends were reported depending on its magnitude. Different authors [9], [14] tried to set a threshold value for considering a mass flux to be "high" or "low" and observed different trends of the HTC on opposite sides of the threshold.

With respect to the heat flux, Guo et al. [8] reported that the HTC decreased when increasing the heat flux, whereas Peng et al- [9] suggested that the trend was the opposite. Similarly, Zhang et al. [12]

observed that the heat flux effect was not significant at low mass fluxes, while on the contrary others suggested that increasing this parameter lead to higher HTC also at low mass fluxes [9].

Flow direction is also an open question regarding the presence of Deteriorated Heat Transfer or Improved Heat Transfer. Some studies have reported DHT in horizontal configurations [8], [14], whereas only the latter performed direct comparisons between the HTC obtained in vertical up-flow and horizontal conditions. They concluded that the vertical up-flow resulted in smaller values of the HTC when compared to horizontal flow.

Only a few articles mentioned the effect of the hydraulic diameter on the HTC. In addition, two opposite results were reported. Wang et al. [11] concluded that smaller diameters lead to higher HTC, while Liao and Zhao [15] reported the opposite trend. The tubes used in these studies did not differ much in diameter and were below 3 mm in both cases.

In contrast, the effect of the operating pressure was reported by many authors in a homogeneous way. It was shown to be significant only at temperatures close to the pseudo-critical temperature. Higher values of pressure lead to a lower HTC in most cases [8], [9], [11], [12], [15].

On a different note, other authors approached the DHT phenomenon and focused to study its onset. Among others, Kline et al. [10] pointed out that a reliable method for the prediction of DHT onset had yet to be established, but emphasized the importance of the inlet temperature for the occurrence of a DHT regime for different values of diameter.

3. ALTERNATE REFRIGERANTS FOR FUTURE UPGRADES

3.1. WARM-OPERATED DETECTORS

With the progressive banishment of synthetic refrigerants harmful to our environment, natural refrigerants seem to be the logical choice for the thermal management of future detector, due to their low environmental impact and their excellent thermal-, fluid- and transport properties. Water is at present the most used natural refrigerant for detectors that do not require below-zero operational temperatures. However, although featuring a very high thermal capacity and a good thermal conductivity, water is electrically conductive, and its viscosity may give a raise to high pressure drops in small diameter pipes. On the other hand, CO_2, already largely adopted in subcritical evaporative cycles for present detectors requiring low operational temperatures, reaches its supercritical conditions above 31.1 °C and 73.8 bar.

Since detector electronics can be safely operated at temperature levels even above 50 °C, supercritical CO_2 (or sCO_2) appears to be the natural candidate for all cases when the radiation levels do not impose low temperatures for long-term operation of silicon sensors.

3.2. COLD-OPERATED DETECTORS

More complex is the selection of the most suitable refrigerants for future cold applications. These not only include potential future detectors to be designed for the next generation of proton-proton colliders, but also – on a much shorter time scale – further upgrades of HL-LHC detectors after the LS4 (Long Shutdown n°4). Such applications will require cooling at much lower temperatures [5] than what is currently provided by CO_2 (≈ -40 °C at the detector) and even lower than the CO_2 triple point at -56.6 °C. The list of natural fluids for such low temperature range is very limited and includes few options such as ethane, ethylene, nitrous oxide, mixtures of carbon dioxide and nitrous oxide (N_2O-CO_2), and the noble gases Krypton and Xenon. Thermophysical properties and thermal-hydraulic performance, as well as radiation hardness are the main criteria's in the choice of the most promising working fluid as described in the following subchapter. Due to the lack of knowledge and reliable correlation in the supercritical region, as a first degree approach only flow boiling properties may be considered.

Thermal analyses are particularly relevant where efficient cooling must be achieved along the cooling lines. The cooling pipes have in general lengths of a few meters and do have also small diameters for mass saving reasons. The main requirement to achieve optimal performance is to use a high-pressure fluid. Indeed, a high-pressure fluid is less sensitive to pressure drops resulting in a more homogenous temperature profile across all detectors. Furthermore, the smallest pressure drops allow much higher velocity inside the channels and better heat transfer coefficients, impacting positively the so-called Thermal Figure of Merit (TFM). A new definition of heat transfer coefficient introduced the first time in [6] called Volumetric Heat Transfer Coefficient (VHTC), is the simplest method to find out the most performant working fluid for a detector application (Figure 3).

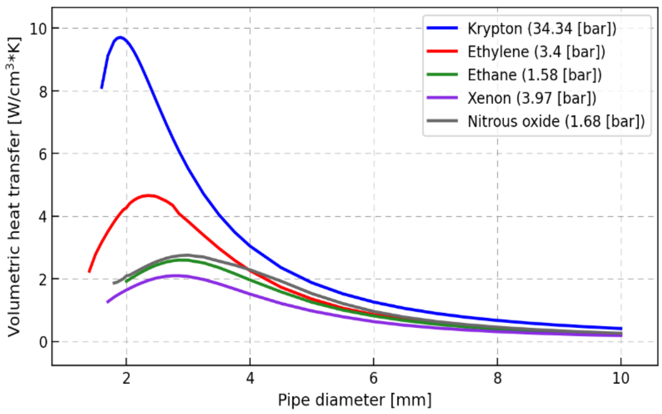


Figure 3: Volumetric heat transfer coefficient of the different candidates considering standard detector geometry (Lenght = 2[m], Heat load = 200 [W], Temperature = -80 [°C], vapor quality range = 0-35%).

The noble gas Krypton overcomes all the other candidates due to a much higher working pressure, and it shows an optimum diameter in the same range of what is currently in use with CO_2 (mini-channels ≈ 2 mm).

The p-h diagram of Krypton is shown in ***Error! Reference source not found.****4* and indicates two interesting features: the first one is that the fluid is in supercritical state (sKr) down to temperatures in the order of -64 °C, and is therefore also the best fluid candidate for cold supercritical cooling systems. The second interesting feature is that it also shows favorable properties in subcritical conditions, allowing to imagine a direct extension to this field of operation if future requests for detector operational temperature are pushed to even lower limits, e.g. down to -80 °C.

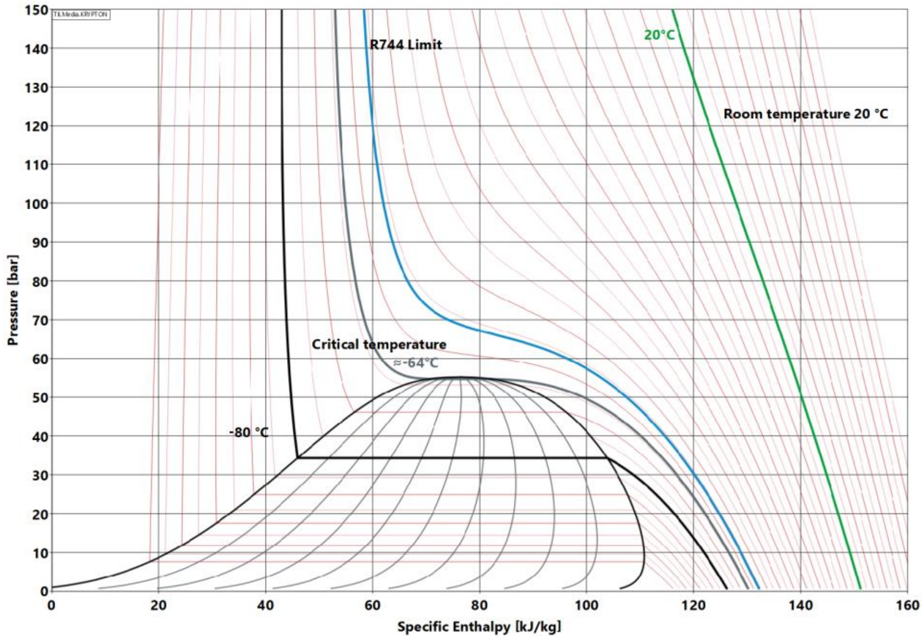


Fig. 4: Pressure-enthalpy diagram of Krypton with some important temperature levels highlighted (green = startup T°, blue = CO2 freezing T°, gray = critical T°, black = lowest T° expected).

4. NOVEL HYBRID COOLING CYCLE AND PASSIVE EVAPORATOR LOOP

Different from CO_2, which can be liquified by pressure at room temperature, a Krypton cycle must be able to be started with only vapour in the entire unit at ambient temperature conditions. The startup in the gas phase of Kr requires a completely new cycle able to cool down slowly the detector without damaging the sensors (= no thermal shock). On the other hand, during the detector operation at much lower temperatures where the power from sensor and electronics must be dissipated, the fluid must reach the detector either in supercritical cold conditions or in subcritical conditions of subcooled liquid (to ensure that in this latter case boiling starts at the entrance of the evaporator). *Figure 5* illustrates the new cooling concept based on an ejector – vapor compression system which relies on oil-free turbomachines.

The system can be considered as two loops: the ejector (red) & the evaporator (blue) cycle. The ejector loop comprises a turbo-compressors rack, two-stage of gas cooling where the heat is rejected to a multi-evaporating CO_2 system, an internal heat exchanger (IHX), the liquid receiver, a CGBV (cold gas bypass valve) and an ejector. The evaporator loop includes the concentric line, inlet-outlet manifold, cooling lines (evaporators) with dedicated expansion devices (capillaries).

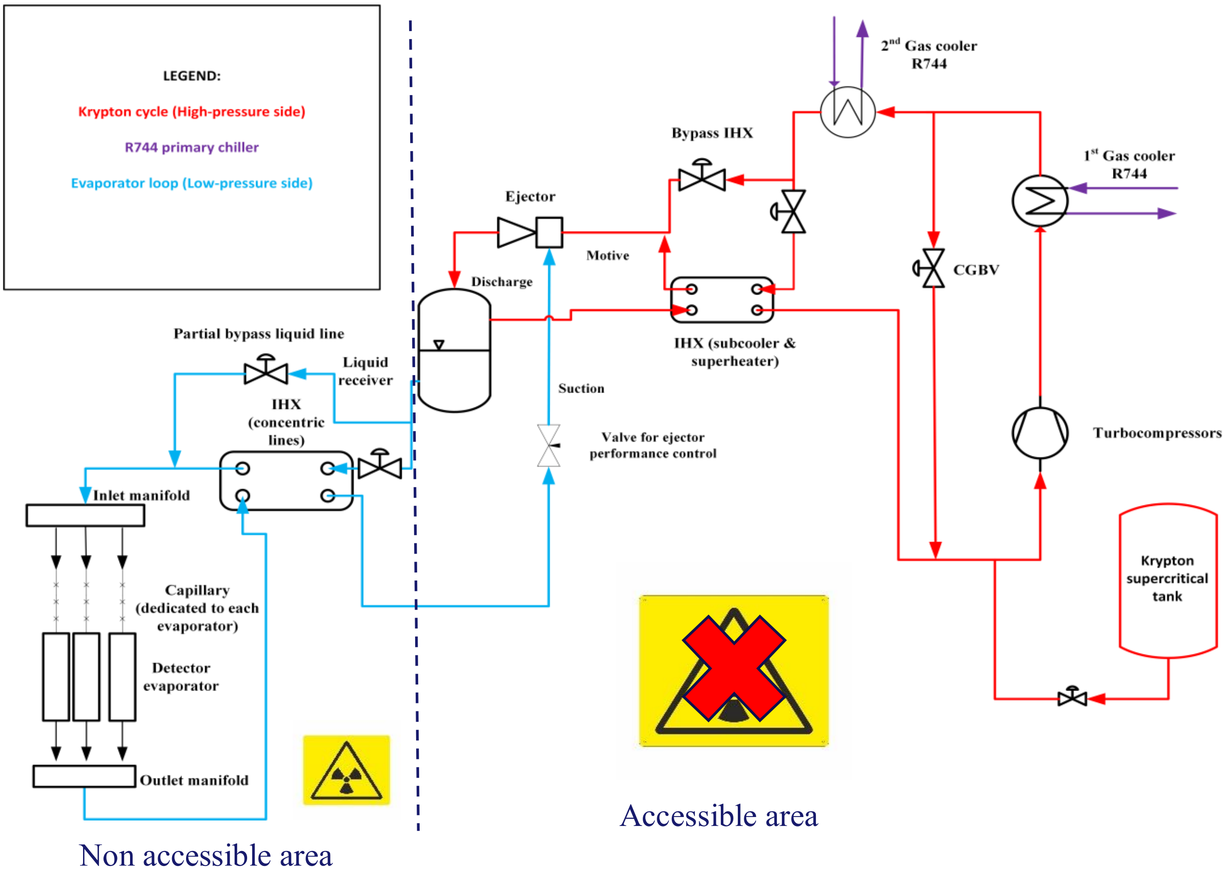


Figure 5: Simplified PI&D of the hybrid cycle with Krypton.

Three important steps have been identified and can be graphically represented on the p-h diagram (*Figure6*): startup, transition to flow boiling operation (supercritical to trans-critical), trans-critical operation. The startup begins in supercritical state, where pressure-temperature are independent to each other. Charging the unit will pre-condition the starting point, avoiding a fast overcooling of the detector thanks to the high-operating pressures (far from the critical point). Initially the system can start in the triangle cycle loop and then slowly a part of the flow is sent to the rest of the loop. By further cooling down the high-pressure side, the pressure will start decreasing. In supercritical state, an almost isobaric cooling at high-pressures can be achieved by further charging the unit from the Krypton tank. In this sense, the cooling cycle moves gradually from the right hand side to the left hand side in the pressure-enthalpy diagram according to the detector temperature.

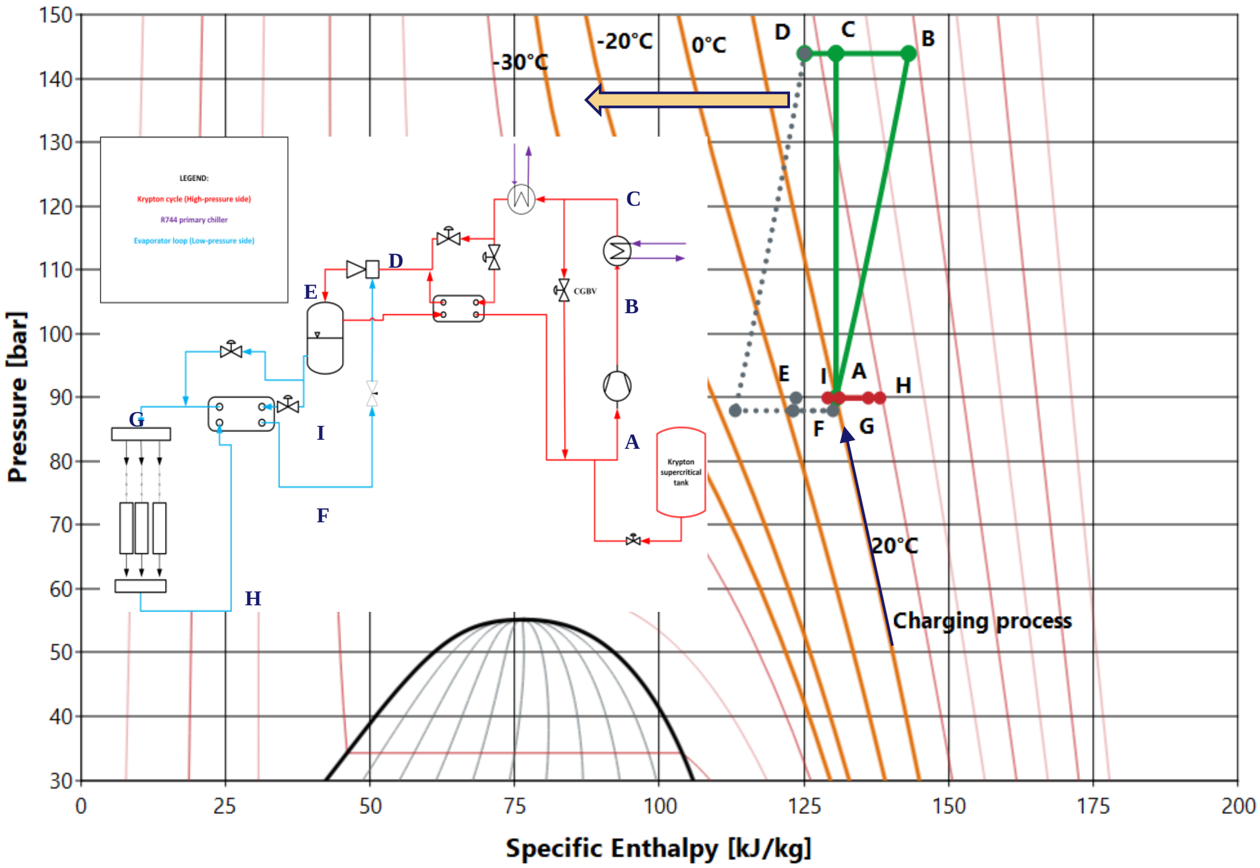


Figure 6: Startup of the cycle in supercritical conditions.

A very interesting feature of this innovative / novel Krypton cycle is that it can be tailored to operate with continuity delivering at the detector either supercritical fluid – if the requested temperature delivered at the detector is above -64 °C); or saturated (subcritical) fluid – if the new temperature requests fall below the critical point of Kr (i.e. in the range -70 to -80 °C) and flow boiling conditions are needed. The system will work as described in Figure7. The refrigerant is first compressed and then cooled down in the gas cooler section before entering the ejector. From the bottom of the receiver, the phase separation allows to send saturated liquid into the long concentric line where the liquid is subcooled before entering the capillary section. After the expansion, the Krypton is vaporized absorbing heat from the electronics inside the detector before entering the return vapor line where it is further vaporized by subcooling the liquid at the entrance of the main manifold. The outlet two-phase flow is recirculated back to the receiver by the ejector.

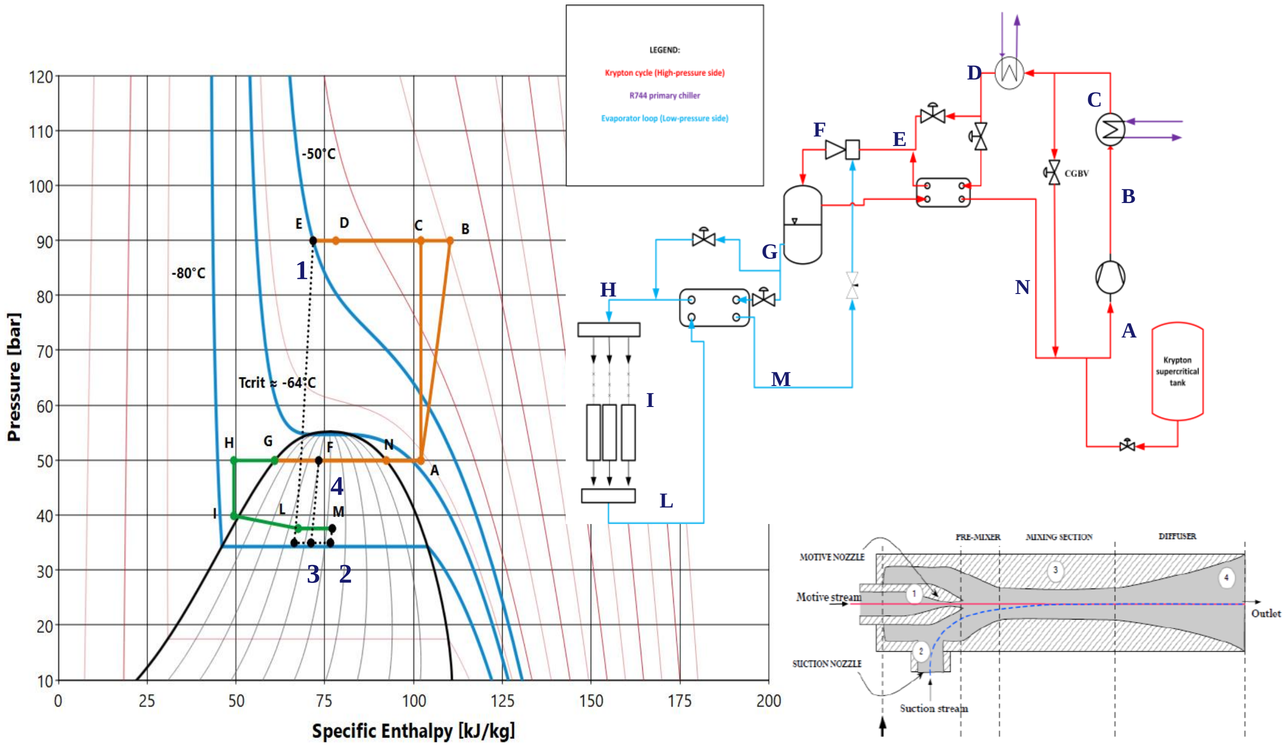


Figure 7: Trans-critical operation & ejector working principle (right bottom).

5. P&ID AND PROCESS DESCRIPTION OF THE NEW TEST FACILITIES

5.1. NEED FOR TWO EXPERIMENTAL FACILITIES

The studies conducted until now clearly show the need for two dedicated test facilities: one dedicated to precise and systematic measurements of sCO_2 to define the optimal conditions of use for detector cooling and develop more reliable performance prediction methods; and another one to demonstrate the new hybrid cycle defined in Section 4.

It has to be noted that, considering that the applications at warm and cold temperature are meant to deal with different fluids but at a similar range of reduced pressure, fluid-to-fluid scaling research is also planned to be taken into consideration in the first setup in order to inform the optimal design of the hybrid cycle in its final configuration.

5.2. CARBON DIOXIDE PRECISION MEASUREMENT FACILITY

In view of these diverse observations and statements found in the specialized literature, open questions were considered to define the necessary test conditions to study the heat transfer performance of carbon dioxide above the critical point. Some fundamental questions relate to how the important parameters (mass and heat flux, diameter, flow orientation) affect the HTC trend. Additionally, other unknowns of importance are the conditions that lead to Deteriorated Heat Transfer as well as a unified method to predict this regime.

Figure 8 depicts the Process and Instrumentation Diagram (P&ID) of the carbon dioxide facility.

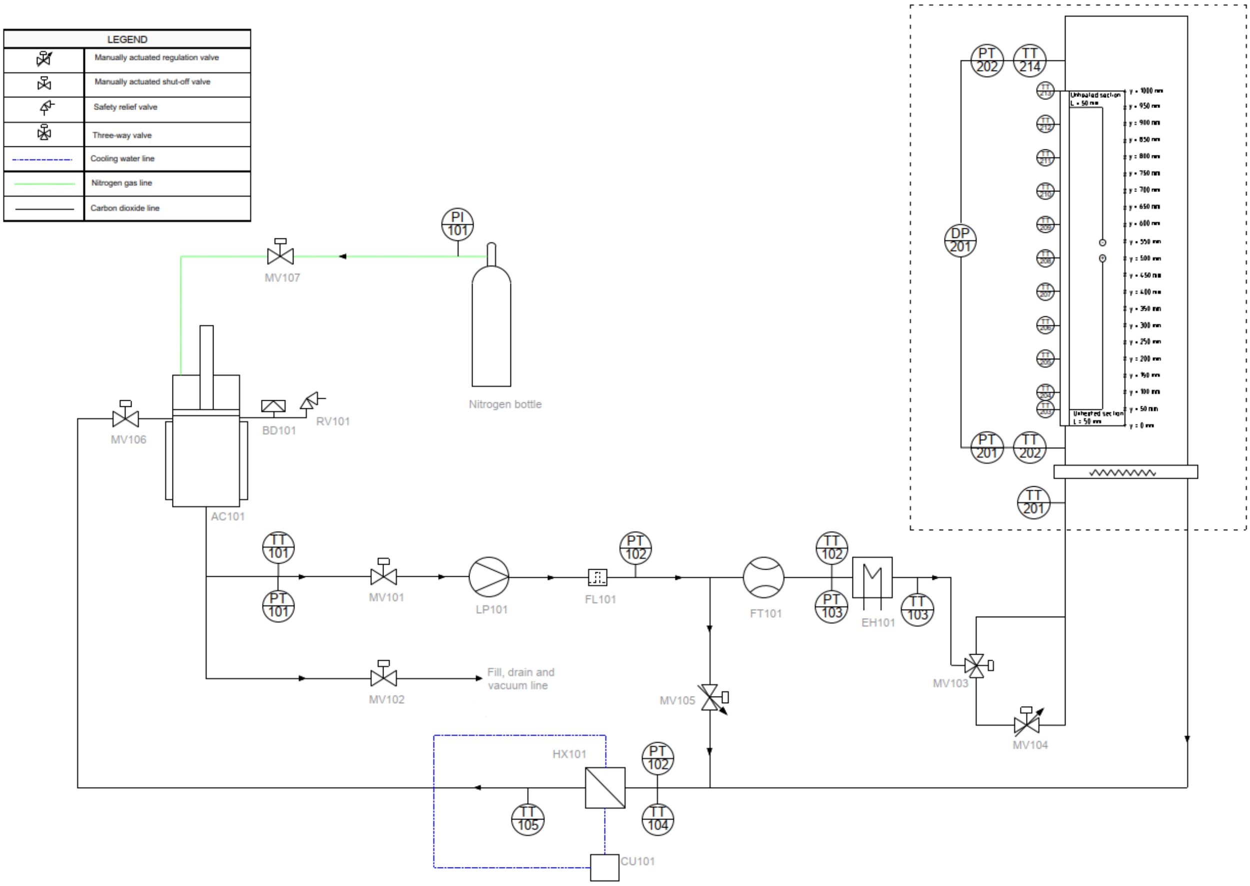


Figure 8. Process and Instrumentation Diagram of the test facility

The accumulator (AC101) is a metal bellows accumulator used to both pressurize the fluid at the desired supercritical pressure while keeping it subcooled. The fluid circulates then towards the pump LP101 and the filter FL101. The role of the pump is to overcome the pressure drops through the system. After this, the fluid is pre-heated to the desired inlet temperature in EH101. At this point, after the three-way valve MV103, there are two options: one of them is supercritical operation, for which the fluid continues just flowing across the test stand; while the other one is subcritical operation, where the valve MV104 (expansion valve) is used to reduce isothermally the pressure. In this way it will be possible to study with precision the fluid properties when passing across the critical point, a subject of general scientific interest but also extremely important for a smooth operation under all conditions of the new hybrid cycle designed for Krypton. The test sections are equipped with temperature and pressure measurements, as well as pressure drop measurements across the tube.

After the test section, the heat exchanger HX101 cools the fluid back to the temperature set for the accumulator AC101. HX101 is connected to an external chiller (CU101), which supplies cold water on the cold side of the heat exchanger. Pressure and temperature measurements are taken in different point along the whole circuit in order to provide maximum control over the test conditions.

The test section will be mounted on a rotatable panel connected to the main circuit by flexible metal hoses, therefore allowing for producing flow in different orientation with respect to gravity.

In the test section, a Peltier element is inserted to regulate further the inlet temperature in the subcritical operation, to make sure that the fluid is saturated at the inlet. Temperatures will be recorded uniformly along the tube and the pressure drop across the 1-meter section will be measured. Joule heating will be used to provide a uniform heat flux.

The conditions tested will be the following:

- Mass flows from 0.29 kg/h to 40.7 kg/h.
- Tube diameters from 1 to 3 mm.
- Pressures from 60 to 120 bar.
- Temperatures from 20 to 100 °C.
- Flow orientations: vertical up and down-flow and horizontal flow.

5.3. HYBRID CYCLE XENON FACILITY

The new cooling concept developed for ultra-low temperature applications should be verified experimentally. To demonstrate the concept in a more manageable environment (in terms of temperature levels), it is planned to use Xenon instead of Krypton. Xenon is pressure characteristic-wise identical to Krypton, however, at much warmer conditions (critical temperature ≈ +17 °C vs -64 °C for Krypton). Its pressure-enthalpy diagram is shown in Figure 9, where the red line represents the heat needed to bring the starting point in the supercritical phase as it would normally occur with Krypton during the start-up.

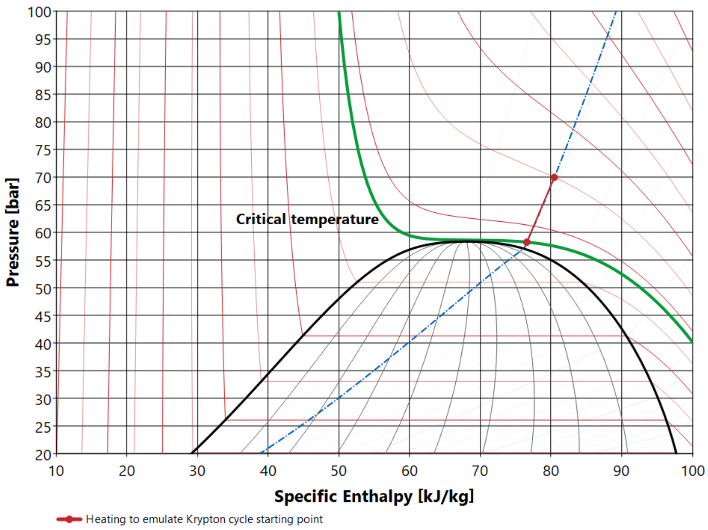


Figure 9: Pressure-enthalpy diagram of Xenon (green = critical temperature ≈ 17°C, blue dotted line = isochoric line).

The simplified P&ID of the test facility is presented in Figure 10. Because of the lack of oil-free machine for Xenon and for extreme high-dynamic system, a standard piston compressor for CO_2 is used in this case. The use of an oil-lubricated compressor introduces additional challenges in the system. The density inversion phenomena, for which the oil becomes lighter than the coolant, affects the oil return from the low-pressure side and occurs during trans-critical conditions. The yellow line and the buffer tank are specifically introduced to overcome this issue. The recovery of the oil from the low-pressure side is performed after every operation period of the unit: the correct setting of the metering and three-way valve would allow to discharge part of the liquid Xenon into the buffer tank so that after being heated by ambient temperature, the pressure-density is such to collect the oil at the bottom of the receiver. Afterwards, the liquid Xenon previously stored will turn into supercritical fluid before being restored into the main loop by the compressor.

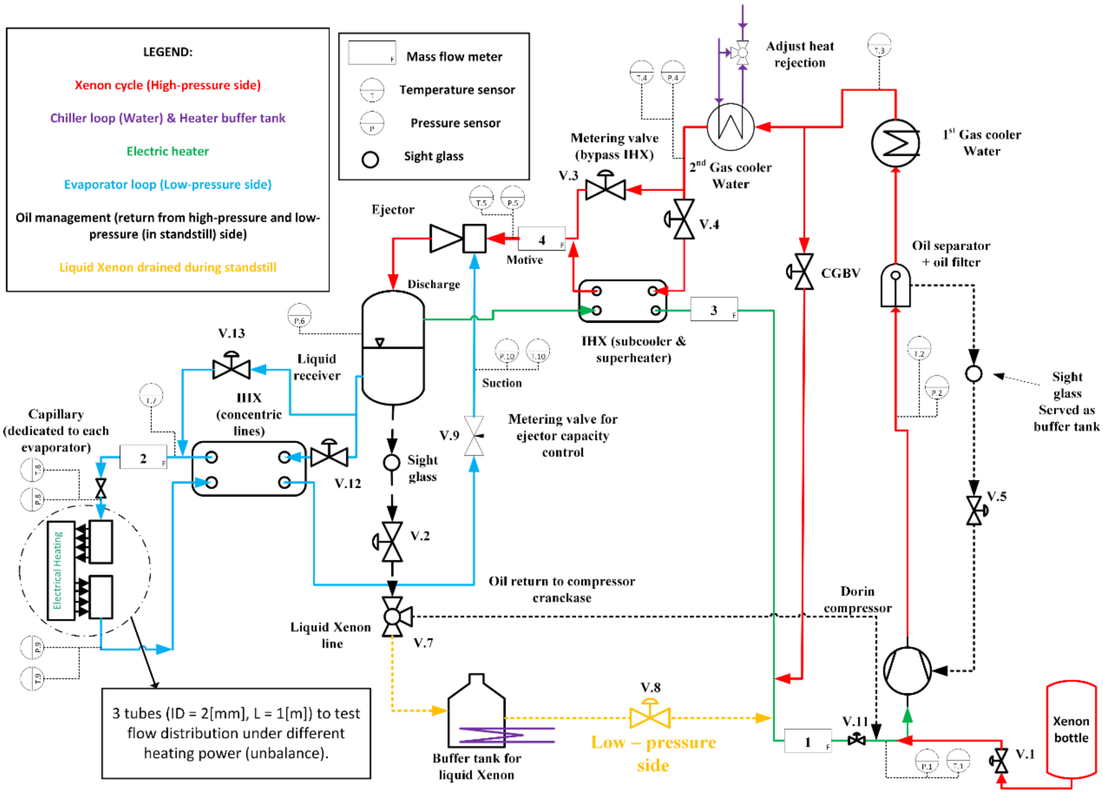


Figure 10: Simplified PI&D of the Xenon cycle used to emulate the Krypton cooling concept.

The evaporator loop (blue) is almost fully-passive, except for the bypass on the liquid line that enables the tuning of the coolant at the entrance of the different evaporator sections. To guarantee a proper operation and controllability of the detector outlet conditions two section are interconnected. Firstly, the evaporator loop was designed according to the expected thermo-hydraulic performance, considering small channels of 2 mm (evaporators) and high-reduced pressure (≈ 0.87 to 0.66 as for Krypton). According to flow conditions and pressure drop across the entire loop, the ejector can be designed to work efficiently as a liquid/two-phase recirculation device. Numerical simulations have been performed with single fixed geometry ejector, proving the suitability of an available small CO_2 ejector as temporary solution. On the other hand, to ensure that there is enough potential in the ejector to lift the outlet flow from the detector back to the receiver, a tuning of the compressor via the Cold Gas By-pass Valve (CGBV) will be needed to meet the requirements in terms of pressure and flow rate through the motive nozzle. The evaporator loop & ejector were designed such to provide a constant pressure lift over all the temperature range (during flow boiling).

6. SUBTASK TIMELINE

The following table shows the planned timeline for the activities mentioned in this report.

Activity	**From**	**To**
Krypton – Theoretical studies	September 2021	November 2021
2PACL working principle and design Detector requirements		
Krypton – Design	December 2021	Ongoing
Concept of Kr cycle Design of Xe test facility		
Carbon dioxide – Preliminary studies	January 2022	September 2022
Literature review Test stand concept and design		
Carbon dioxide – Procurement	October 2022	February 2023
Both – Building	Q1 2023	Q3 2023
Both – Commissioning	Q4 2023	
Both - Data acquisition	2024	

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ANNEX: GLOSSARY

Acronym	**Definition**
HTC	Heat transfer coefficient
Nu	Nusselt number
P&ID	Process and Instrumentation Diagram
Pr	Prandtl number
Re	Reynolds number
sCO_2	Supercritical carbon dioxide
sKr	Supercritical Krypton
Tb	Bulk temperature
Tm	Pseudo-critical temperature