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CO_2 Cooling Developments for HEP Detectors

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Two phase (evaporative) CO_2 detector cooling is gaining significant interest as a demonstrated alternative to traditional cooling techniques in High Energy Physics (HEP). The upgrade programs of the inner detectors of ATLAS and CMS are investigating evaporative CO_2 cooling as an alternative to the current fluorocarbon cooling systems. CO_2 as coolant has superior thermo dynamical properties compared to other coolants used in HEP detectors leading to significant smaller diameter cooling pipes and hence lower mass inside the detector. Two operational HEP detectors use evaporative CO_2 cooling as part of the thermal management of their silicon detectors; the LHCb-VELO and the AMS02-Tracker. Both CO_2 systems use the 2-Phase Accumulator Controlled Loop (2PACL) technique developed at Nikhef. The 2PACL method is an ideal method for HEP detectors as it is very stable, uses only passive components inside the detector volume and it is easy to control. This paper describes the experiences gained with CO_2 cooling in the past and looks at possible future applications within HEP experiments. Special attention is paid to the amount of material needed inside the active detector volume when CO_2 is used.

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[1] Speaker

1. Introduction

Two phase (evaporative) CO_2 cooling is a promising technology for tracking detectors in high energy physics experiments. CO_2 cooling offers the combination of high heat transfer coefficients (one order of magnitude higher than traditional refrigerants) with low mass cooling structures. In addition it has a relatively high evaporation pressure so the produced vapour volumes stay small, resulting in small diameter tubing. CO_2 also has a large latent heat of evaporation, which allows for a reduced fluid flow. This allows for even smaller tubing diameters. At the moment two HEP detectors are cooled with CO_2: The AMS02-Tracker [1] and the LHCb-VELO [2]. Both systems use the same technology for circulating and conditioning the CO_2. The success of these cooling systems has inspired the HEP community to consider CO_2 cooling as a credible candidate for future tracking detectors.

2. History of CO_2 cooling

CO_2 cooling is not only a new technology for thermal management in HEP, it is also an active area of research and development within many industrial and commercial applications. In the late nineties CO_2 was proposed by Nikhef as a coolant for the LHCb-VELO detector. Preliminary tests using a “blow-off system” were carried out to demonstrate the cooling capabilities of evaporative CO_2 [3]. In parallel and at the same time as the developments at Nikhef, CO_2 was also under investigation as an alternative “green” refrigerant in the wider refrigeration community. CO_2 is a natural alternative to the synthetic refrigerants as it has no ozone depleting properties and has a limited greenhouse effect. Nowadays CO_2 is becoming a standard in commercial refrigeration. Before the development of the synthetic refrigerants, cooling systems use natural gasses like: air, NH_3, SO_2 and as well CO_2. CO_2 was widely used in the late 19th century but at that time the high pressure of CO_2 was considered a problem. It is for this reason that low pressure synthetic refrigerants were developed and CO_2 defectively disappeared as refrigerant in the 1930s. A good introduction to the history of CO_2 cooling was written by Pearson [4].

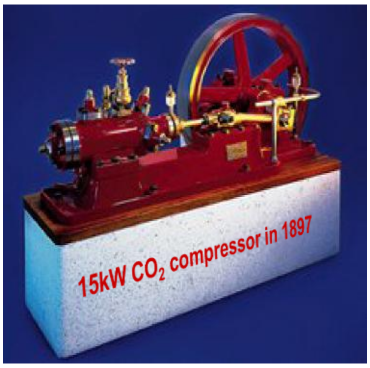

Figure 1: A CO_2 compressor from 1897

3. Cooling tube dimensioning.

3.1 Calculation example: sizing the Atlas IBL cooling tube

To demonstrate the superiority of CO_2 cooling we present calculations of the dimensioning of cooling tubes for both CO_2 and C3F8 as a refrigerant. C_3F_8 is a radiation hard cooling fluid used to cool the ATLAS inner detector [5]. In this particular example we base our requirements on those of the Insertable B-Layer (IBL) [6] which will be installed into the existing ATLAS detector in 2014. Each stave is 800 mm long and produces around 100 Watt of heat which needs to be removed by an efficient cooling system. The requirements of a low mass structure are critical for the successful operation of the IBL detector. Therefore a small cooling pipe is mandatory. The method for dimensioning a cooling pipe was presented in detail at TWEPP08 by Verlaat [7].

The IBL stave must have low thermal gradients, both in axial and radial directions. The radial gradients arise due to the heat transfer coefficient between the coolant and cooling structure, the axial gradients are due to pressure drop of the boiling liquid and the homogeneity of heat transfer coefficient along the cooling pipe. Figure 2 shows the pressure and hence axial temperature gradient for both CO_2 and C_3F_8 as a function of the tube diameter. A threshold value for the axial temperature gradient of 1ºC was chosen. The optimal tube diameters are 1.4mm and 3.6mm for CO_2 and C_3F_8 respectively. Figure 3 shows the heat transfer coefficient over the pipe length for the selected tube diameters. The 2nd figure shows the radial and axial temperature distribution due to the heat transfer and pressure drop. The calculated example clearly shows the advantage of CO_2 when compared with C_3F_8. The tube diameter is much smaller, and despite the smaller heat transfer area the overall thermal performance is superior to C_3F_8 with the larger diameter.

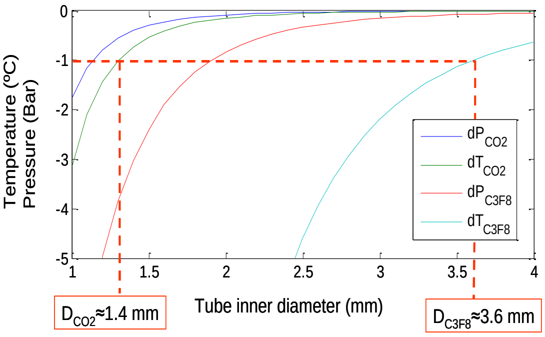

Figure 2: Diameter calculation of the IBL tube for CO_2 and C_3F_8 at -25 ºC,150 Watt and 40%exit vapor quality

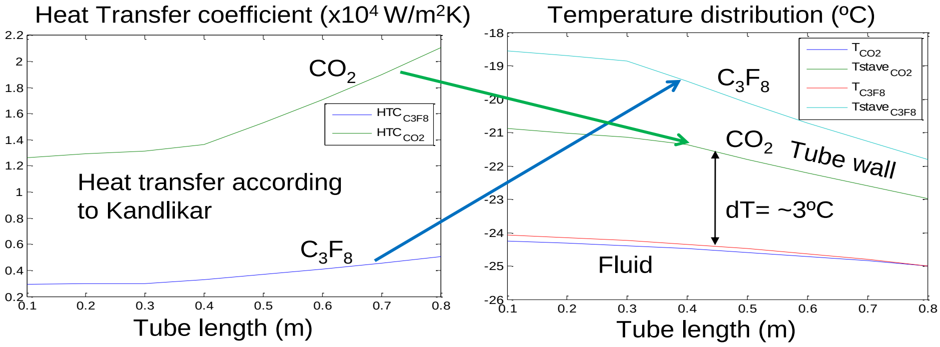

Figure 3: Heat transfer and temperature distribution of a 1.4mm CO_2 and 3.6mm C_3F_8 pipe.

3.2 Pressure safety

It is often incorrectly stated that the high pressure of a CO_2 is a safety problem. The relation between pressure and evaporative temperature is shown in figure 4. At cooling temperatures of -25 ºC, CO_2 has a vapour pressure of 10.5 times higher than C_3F_8 (16.8:1.6 bar). The Pressure Equipment Directive (PED) [8] classifies the safety of

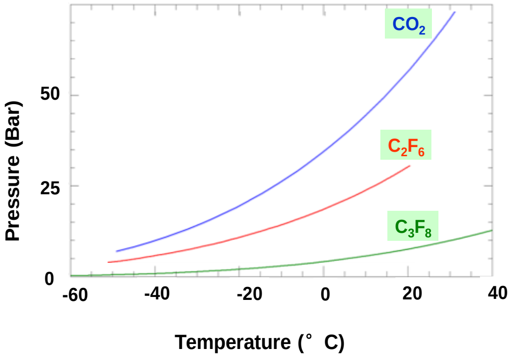

Figure 4: Saturation pressure curves for CO_2, C_3F_8 and C_2F_6

pressurized equipment by the stored energy which is the product of the maximum pressure and the volume. The maximum pressure in a system is the pressure at the highest possible temperature, added with extra head pressure caused of the pump. For a CO_2 system a reasonable design pressure is 100 bar, while for a C_3F_8 system it is 15 bar. Therefore the stored energy in the tubes with diameters that we calculated in section 3.1 is therefore 15.4 J/m for CO_2 and 15.3 J/m for C_3F_8. So when considering the on detector evaporator volumes a 100 bar CO_2 system is as safe as safe as a 15 bar C_3F_8 system.

3.3 Cooling system mass and radiation length

One of the most important figures of merit for a vertex detector is the amount of material seen by a particle, measured in radiation lengths, as it leaves the interaction point and traverses the detector volume. CO_2 needs smaller diameter tubing but this tubing needs to be stronger to withstand the higher pressures. The wall thickness of a tube with respect to the yield stress can be calculated according to equation 1. To calculate the wall thickness with respect to the tensile stress one must replace the subscript.

$$t_{wy} = \frac{SF_y * MDP * D_i}{2 * \sigma_y} \qquad \textit{Equation 1}$$

The necessary wall thicknesses for both fluids are shown in table 1. We believe that a cooling tube with wall thicknesses below 100mm is impractical for most applications so we choose a working wall thickness of 0.1 mm for further calculations. In addition, when calculating the number of radiation lengths, we include the mass of the fluid itself, where we take the worst case scenario with the tube full of liquid. Table 1 shows the masses of the tube and fluid for the CO_2 and C_3F_8 options for a 316L stainless steel tube. A CO_2 cooling tube has a much lower mass compared to a C_3F_8 tube. Figure 5 shows the radiation length for the two tube options: the CO_2 tube show much less material in a smaller space.

Table 1: Overview of tube and fluid masses

	CO_2	C_3F_8
Inner Diameter (D_i [mm])	1.4	3.6
Max. Design Pressure (MDP [bar])	100	15
316L Yield stress (σ_y [N/mm^2])	190	190
316L Tensile Stress (σ_t [N/mm^2])	460	460
Wall Thickness Yield [SF=1.5] (t_{wy} [mm])	0.055	0.021
Wall Thickness Tensile [SF=4] (t_{wt} [mm])	0.061	0.023
Tube wall thickness (T_w [mm])	0.1	0.1
316L tube density (ρ_t [kg/m^3])	8000	8000
Relative tube mass (m_{rt} [g/m])	3.8	9.3
Fluid density (ρ_f [kg/m^3])	1054	1564
Relative fluid mass (m_{rf} [g/m])	1.6	15.9
Total relative mass (m_{rtot} [g/m])	5.4	25.2
Relative stored Energy (Q_{rst} [J/m])	15.4	15.3

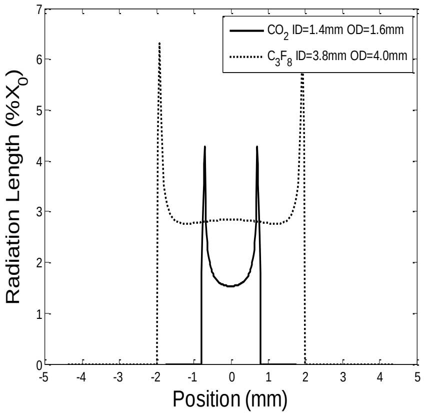

Figure 5: Radiation length of the CO_2 and C_3F_8 tube including the liquid fluid.

4. Operational CO_2 cooling systems in High Energy Physics.

4.1 The AMS Tracker Thermal Control System

The AMS-Tracker Thermal Control System (AMS-TTCS) [9] is a mechanically pumped 2-phase CO_2 cooling loop controlling the temperature of the AMS-02 silicon tracker [1]. Two 11m long cooling tubes connects all the electronics in series. Blow system tests at Nikhef [10] have shown that a 2.6 mmID tube was sufficient to cool the 150 Watt of the AMS02-Tracker.

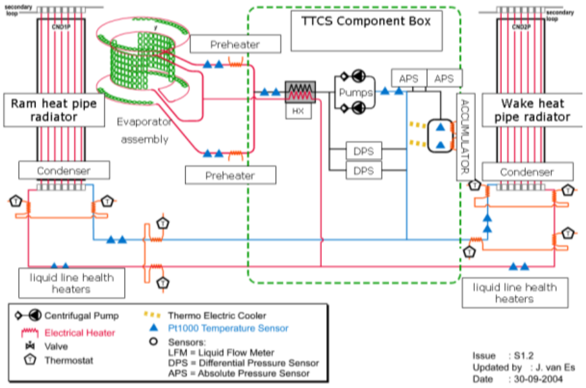

Figure 6: AMS-TTCS schematic layout.

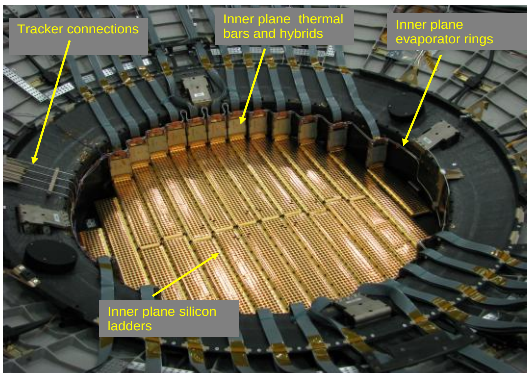

Figure 7: TTCS evaporator tubes in the AMS-Tracker

An external circulation system was designed using standard technologies from satellite thermal control. The evaporator pressure was controlled using a 2-phase accumulator as used in capillary pumped loops [11], the liquid pump was an upgraded version from Mars-pathfinder mission [12]. The orbital variations in the sub cooled CO_2 temperature were compensated by an internal heat exchanger between the in and outlet of the evaporator [13]. This heat exchanger made an active heater obsolete, saving expensive and rare electricity in space.

The concept of the TTCS was developed at Nikhef with help from National Aerospace Laboratory (NLR) in the Netherlands. The final construction of the system was done in an international collaboration of physics institutes and aerospace companies under supervision of NLR. Figure 7 show a picture of the evaporator rings which were made at Nikhef. The TTCS is installed on AMS in October 2009. In April 2010 The TTCS was successfully tested in the ESA-ESTEC space simulator. The launch of AMS in the Space Shuttle is foreseen at the end of 2010.

4.2 The LHCb Velo Thermal Control System.

The LHCb Velo Thermal Control System (LHCb-VTCS) [14] is in principle a large scale copy of the AMS-TTCS. The control method 2PACL (2-Phase Accumulator Controlled Loop) was developed from the AMS-TTCS. For the LHCb experiment the significant benefit of the 2PACL principle is the absence of any active components inside the detector. Only small diameter tubing is inside the detector volume, while all the active hardware are placed in a distant cooling plant accessible in radiation free zones. Figure 8 show the 2PACL of the VTCS.

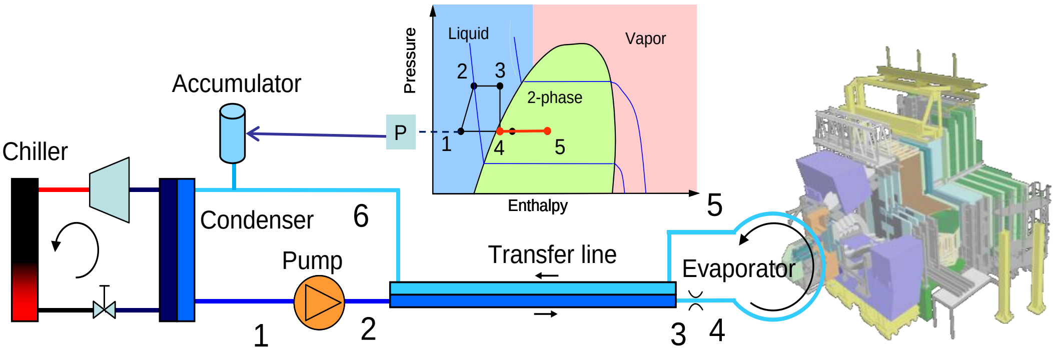

Figure 8: The 2PACL of LHCb-VTCS

The control of the system work as follows; the accumulator vessel needs to be maintained at a fixed temperature and hence pressure set-point. The pressure drop between the evaporator (4-5) and the accumulator connection (6) is low, therefore the accumulator directly controls the pressure of the evaporator. The internal heat exchanger (2-3) heats up the pumped sub-cooled liquid to saturation, causing the inlet of the evaporator always to be saturated (point 4 within green 2-phase zone of the pressure-enthalpy diagram). The system works with an overflow of liquid. The fluid state in the evaporator is per definition 2-phase, and independent from the absorbed heat. The independence of heat absorption is ideal for detector cooling as they need to be kept cold all the time, even if there is no power to reject. The returning vapor is condensed in the condenser (6-1) which is cooled by a standard chiller. The sub cooled liquid (1) is pumped back into the system by a liquid pump (1-2). The chiller of the VTCS remains always cold (around -40ºC, depending on heat load) and the accumulator can be set between 0ºC and -35ºC. Figure 9 show the transient temperature of the detector and the evaporator at powering up at an accumulator set point of -25ºC, followed by a set point change to -5ºC and a power down. The VTCS is installed in 2007 and was finalized with all the automatic back-up procedures early 2009. It has run almost continuously the last 2 years, without any significant problems. Figure 10 show a VELO module with the cooling connection, and the VTCS plant on the UXAC3 platform of LHCb.

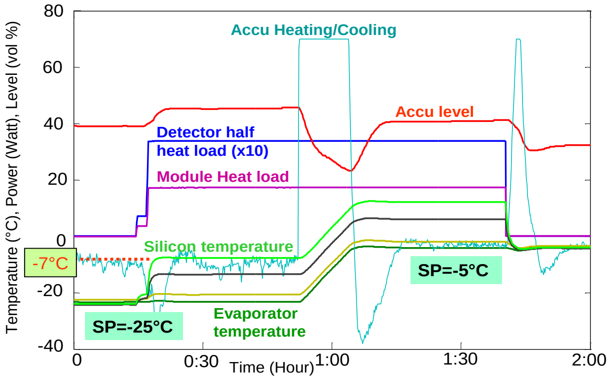

Figure 9: Temperature response of the VTCS to a detector power up and a set-point change

Figure 10: Velo module with CO_2 evaporator and the cooling plant at the UXAC3 platform

5. The “CO_2ol” future.

5.1 CO_2 cooling for CMS and Atlas.

The successful implementation of CO_2 cooling in AMS and LHCb has inspired other HEP detector collaborations to consider it as a candidate cooling technology for the future detector systems. CO_2 cooling is adopted as the baseline option for the CMS inner detector upgrade thermal management. The change from the current C_4F_{10} liquid system [15] to a 2PACL like system with CO_2 is relative easy as the already insulated transfer pipes can be reused. The ATLAS inner detector upgrade is currently evaluating CO_2 cooling as a replacement for their current C_3F_8 system [5], but their current infrastructure of pipes are not insulated. A 2PACL system can therefore not be used if the pipes need to be recycled. There is a strong desire of the upgrade detector development teams in ATLAS to switch to CO_2 and solve the pipe recycle issue. Different or modified 2PACL principles are under investigation as well as the complete pipe replacement.

5.2 CO_2 cooling as a replacement for water cooling.

Lots of applications require room temperature cooling, which is often achieved with water cooling. The gridpix technologies [16] for example require room temperature cooling. Evaporative CO_2 works very well around room temperature. A simple 2PACL system cooled by cold water works very well and is a possible replacement for any water cooling system. The advantages of a warm CO_2 system above water systems are the ability of smaller pipes, more efficient heat transfer and very important: no water leaks inside expensive equipment. CO_2 only vaporizes when it leaks, this does not harm the equipment. Personal safety however becomes an important issue as CO_2 is asphyxiating in large concentrations.

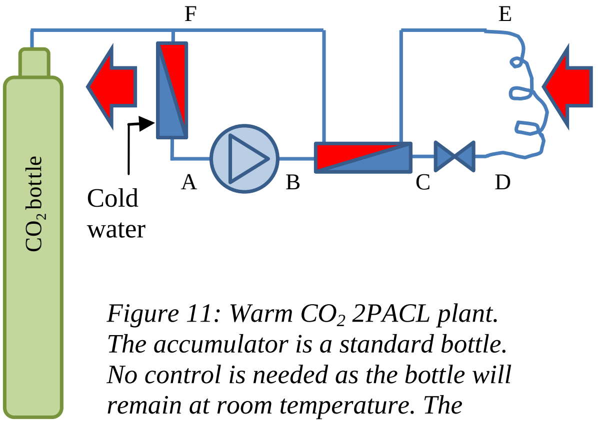

Figure 11: Warm CO_2 2PACL plant. The accumulator is a standard bottle. No control is needed as the bottle will remain at room temperature. The condenser is cooled with cold water.

5.3 Current CO_2 cooling activities.

Many HEP laboratories are organizing themselves to set-up test CO_2 facilities to support their detector development programs. Many blow systems are built as a quick solution to fulfil pressing needs. Most of the circulation systems which are under development use the 2PACL principle from LHCb and AMS. Blow systems have been built by CERN-DT, IPN-Lyon, SLAC and the university of Karlsruhe. 2PACL systems are under construction at RWTH-Aachen, CERN-DT, IPN-Lyon, Nikhef and SLAC. At CERN cryolab a vapour compression system has been build using cryogenic equipment.

Figure 12: Several CO_2 test plants. L2R: CERN-cryo, IPN-Lyon, CERN-DT, Aachen, SLAC & Nikhef

5.4 Nikhef Cooling Laboratory

At Nikhef a cooling laboratory is under construction to support all of the in-house cooling requirements and developments. A 2PACL plant is under construction [17]. A warm prototype is operational and is used to test the new gear pumps and control mechanisms. The warm plant is currently being upgraded to a cold plant able to cool experiments down to -40ºC. In figure 13 the laboratory is shown with the main infrastructure. The 2PACL research plant will be a fully automatic system able to scan prototype structures automatically for their thermal performance. The temperature, mass flow and inlet enthalpy can be set by the PC with PVSS software to the 2PACL plant. A Siemens PLC controls the system to meet the set-point requirements. The PVSS software controls the power and reads the sensors of the experiments which are in an insulated test box.

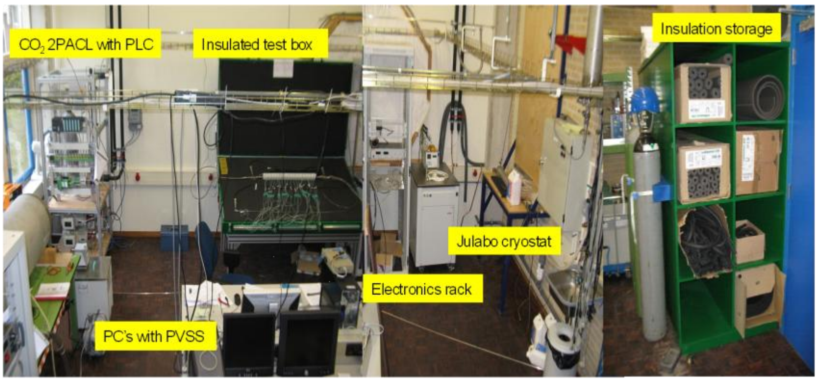

Figure 13: Overview of the Nikhef cooling laboratory

5.5 Future cooling plants

The 2PACL for AMS is a 150 Watt system. The principle was successfully scaled up to a 1.5 kW system for the LHCb-VELO. Atlas and CMS upgrade systems will require 100 kW or more. Scaling of the 2PACL principle to these large cooling powers is challenging. One favourable approach is the scaling up of the system to an intermediate power system in the order of 20-30kW and use several identical plants in parallel. This approach is easier to prototype and has advantages for operation. Maintenance can be as easy as swapping to a spare cooling unit. Also different cooling temperatures can be set to several detector structures.

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