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Cooling in HEP Vertex and Tracking Detectors

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A large variety of cooling systems for the detectors mentioned above, currently exist. Each of them have particular advantages and challenges. We compare the different systems of the LHC experiments and focus on CO_2 cooling which is now considered a prime candidate for future cooling systems including upgrades for LHC detectors. Starting with a description of the CO_2 systems that are currently operational in detectors we continue with an overview of the many prototypes and test systems that are currently available or under construction. Finally we summarize the important ingredients that are needed in order to achieve successful and reliable operation of a cooling system.

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1 Speaker

1. Introduction

Before discussing a cooling system, it is good to contemplate on the question: “How does a Tracking detector look, from a cooling system point of view?” Using the CMS tracker as an example, one sees that we have a highly distributed heat load of about 35 kW, serviced by more than 4000 meters of cooling tube with diameters between 2 and 3 mm. Operation is at -20 ºC or lower and the detector typically needs supply and return lines with lengths of 50 meters. Other detectors vary in size but the principal issues remain the same. The goals to achieve are reliable cooling at temperatures between -40 ºC and +20 ºC and at the same time reducing the amount of material inside the active volume to the minimum. Several engineering issues complicate the task. The choice of coolants is limited by the radiation in the detector. The coolant shall be as radiation hard as possible and the products of radiation damage should not be corrosive in order to avoid damage to the tubing. Radiation shall also not create polymerisation, which could lead to a reduced heat transfer or blockage of thin tubes. Radiation as well as magnetic field, limit the choice of components. One must also keep in mind that the system is often inaccessible during long periods of time. Depending on the location, the time between accesses can be years. Reliability is served by minimising the number of components, especially the number of active components. Active components shall be located as much as possible, in accessible places. A variety of systems is currently in operation at LHC.

2. Operational cooling systems in LHC

The 4 main LHC detectors Alice, Atlas, CMS and LHCb have all different methods to cool their inner tracking detectors. Below an overview of the different cooling systems used is given.

2.1 ALICE-SPD

The ALICE-SPD uses a two-phase system using C_4F_{10} as the working fluid [1]. The normal working temperature is +15 C, resulting in an operation pressure of 1.9 bar absolute. This low pressure does not allow for much pressure drop in the return line, which as a result needs a larger diameter. This can be problematic in places where the space for detector services is limited, which is often the case. The system uses chilled water as the primary cold source, which uses standard industrial technology.

2.2 ATLAS – SCT

This detector uses a two-phase system using C_3F_8 as the working fluid [2]. The normal operating temperature is -25 C, resulting in an operating pressure of 1.7 bar absolute, also a low pressure that leaves little margin for pressure losses along the return line, thus requiring a larger pipe diameter. This system works with supply and return lines at room temperature, which is a distinct advantage but requires the presence of carefully controlled heaters. The system uses the C_3F_8 in a vapour compression cycle. Due to the radiation, one is not allowed to have oil in the refrigerant, which is the standard in the refrigeration industry. This complicates the choice for suitable compressors.

2.3 CMS Tracker

This detector uses a single phase system with C_6F_{14} as the working fluid [3]. The higher mass flow in a single phase system requires larger supply and return lines. The operating temperature is -20ºC and the operating pressure is 6 to 9 bar absolute. The simple design and the use of an industrial standard R507a chiller as primary cold source are important advantages.

2.4 LHCb VELO

This detector uses a 2-phase cooling system using CO_2 as the working fluid [4]. The operating temperature is -30°C, resulting in an operating pressure of 14 bar absolute. The system is designed for maximum simplicity and robustness and uses industrial standard R507a chiller as primary cold source.

3. Why is evaporative CO_2 cooling good for HEP detectors?

CO_2 has several physical properties which all combine together, lead to an excellent performance when used in small cooling tubes such as one needs in Vertex detectors. The gain of radiation length of the cooling system hardware when compared to other common fluids used in particle detector cooling is an order of magnitude in favour of CO_2 [5]. The benefits of CO_2 are the low viscosity, the large latent heat and the high pressure. The latter looks like a disadvantage but is actually an advantage as pressure drop becomes less significant. A pressure drop in a pipe results in a decreasing pressure along the pipe and consequently a decreasing boiling temperature. The ratio of the temperature drop as a function of pressure drop is fluid dependant. The comparison of latent heat, liquid viscosity and dT/dP ratio are plot in figure 1.

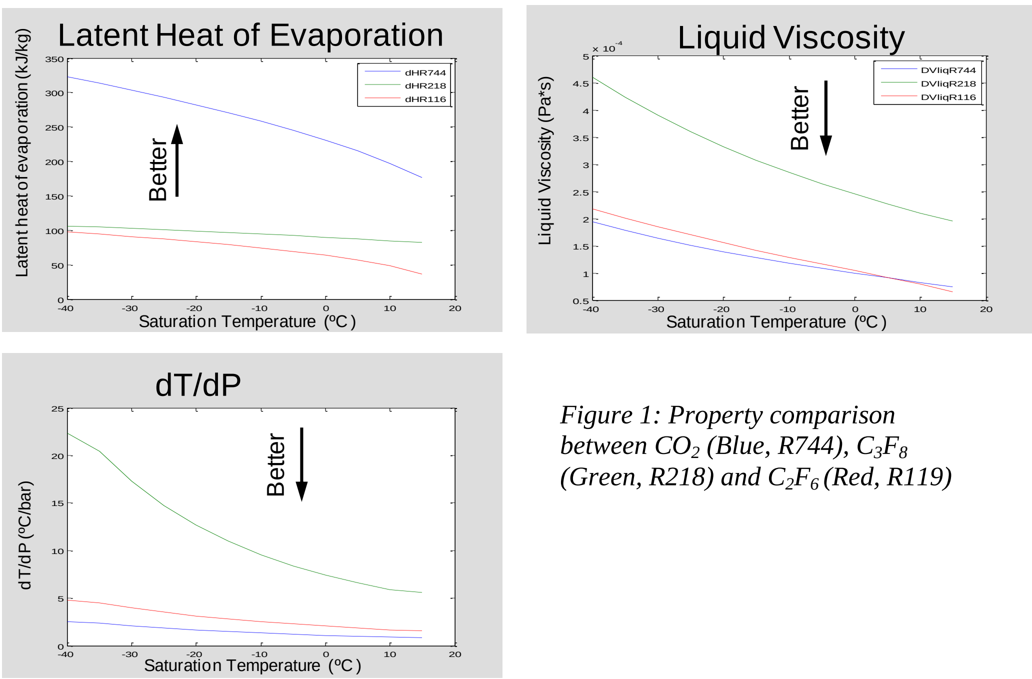

Figure 1: Property comparison between CO_2 (Blue, R744), C_3F_8 (Green, R218) and C_2F_6 (Red, R119)

The temperature in the detector and hence the cooling tube must in general be as uniform as possible. Taking the above property comparison in mind, CO_2 is clearly superior compared to fluorocarbons. The high latent heat requires a small mass flow resulting in low pressure drops. The low viscosity results as well in a lower pressure drop, while for a similar temperature uniformity a higher pressure drop is allowed since the temperature/pressure gradient ratio is much higher. All together it leads to the ability of using very small tubes for CO_2 evaporative systems.

4. CO_2 and safety

Frequently, concern is expressed because of the high pressures involved when using CO_2 systems. Safety regulations such as the Pressure Equipment Directive (PED) [6] however, correctly address the problem as a function of stored energy, which is the pressure multiplied by the volume. Apart from the accumulators, which can be safety critical devices in the higher classes of the PED, all other components are generally below class one and do not require special certification procedures, although good workmanship remains a requirement. As stated the safety class is determined by the internal stored energy (See figure 2). The pressures in CO_2 systems have an order of magnitude higher design pressures, but the volume is, due to the small piping, an order of magnitude lower. The stored energy and hence the safety impact is therefore not much different from that of low pressure systems with higher volumes.

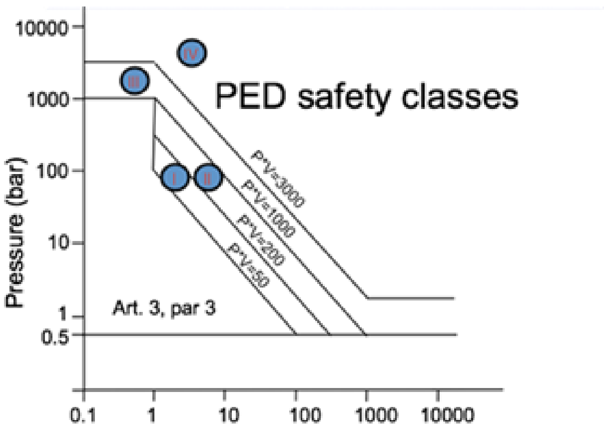

Figure 2: PED safety classes as a function of stored energy. Tubes below 32mm are Article 3.3.

Recently the existing copper tubing in CMS has been certified for the use with CO_2. A representative setup using identical tubing and identical brazing techniques was first carefully tested in order to identify the elastic limit and was then pressurized up to rupture. For the 14x12 mm tube we found an elastic limit around 120 bar and a rupture at more than 240 bar. Since large systems in underground caverns are not expected to arrive at a temperature higher than 25 ºC, we remain in the subcritical region and the pressure will thus remain below 65 bar, since the system is only partially filled with liquid. A safely valve setting at 70 bar can thus be considered sufficient and an acceptance test at 1.25x70=87.5 bar is acceptable to CERN safety. Since this is not an industrial installation the European PED does not have to be followed.

5. CO_2 systems in HEP

Actually, two CO_2 cooling systems have been developed for HEP detectors and are in operation. For the first system, the AMS-TTCS (Tracker Thermal Control System) [7], the development started already back in 1999. The experiment is installed on the International Space Station and is operating in space since 20 May 2011 (figure 3). The cooling power is 150 Watt and the operating temperature is adjustable between +15ºC to -20ºC.

The development of the second system, the LHCb-VTCS (Velo Thermal Control System) [6] started somewhat later but this system became operational before AMS. It has been continuously operating at -30ºC since 2008. The cooling power is 1500 Watt (2 parallel systems of 750 W) and the operating temperature can be adjusted from +8ºC to -30ºC. Both systems are based on the 2PACL principle developed at NIKHEF.

Figure 3: The first CO_2 system in Particle Physics and the 1st CO_2 system in Space: The AMS-Tracker Thermal Control System

6. Ongoing projects

Currently five detectors envisage an upgrade employing CO_2 cooling. They are: Atlas IBL, CMS-pixel replacement, Atlas and CMS silicon detector upgrade and the Belle-2 detector at KEK. At the moment there are at least 11 closed loop CO_2 cooling platforms for testing either operational or under construction. These systems are: CERN B187 test setup, CERN-CV ATLAS plant at SR1, the Fermilab CMS FPIX cooling plant, the IPNL Lyon CMS test setup, the NIKHEF 2PACL system and RWTH Aachen CMS cooling test setup as well as the CERN Cryolab 2PACL system and the CERN-DT / Nikhef 1kW and 100W system which are shown in figure 4. The systems at CERN and NIKHEF are open to external customers.

Figure 4: CO_2 Test systems at CERN. Left is the TRACI system (100W), the middle the Cryolab plant CORA(2kW) and right the MARCO system (1kW) which is under construction.

7. CO_2 Collaboration Partners

There are a large number of groups currently working on the development of CO_2 cooling. The collaboration is based upon a free exchange of information, sharing results as well as good and bad experiences. In alphabetic order: CERN-CMS, CERN-Cryolab, CERN-CV-Atlas, CERN-DT, EPFL Lausanne, Fermilab-CMS, HEPHY Vienna – Belle II, IPNL-Lyon – CMS, KEK Japan – Belle II, NIKHEF, NLR Amsterdam – AMS, Karlsruhe University, MPI Muenchen – Belle II, PSI Villingen – CMS, RWTH Aachen – CMS, SLAC – Atlas.

8. Cooling Success

A successful and reliable cooling system is not only depending on the selection of the right working fluid. Choosing a concept that uses the maximum amount of industrial experience and industrial technology assures maximum reliability. The system shall also be designed, keeping the very limited access in mind. Using components of a high quality will increase the initial cost somewhat but will generate the lowest overall costs in the long run. Fluids can be expensive, maintenance and refurbishments costs can be very substantial. Currently used coolants, such as C_3F_8 and C_6F_{14} have high global warming potentials and might be discontinued in the future due to environmental concerns. In very large systems, they are also an important cost item, C_6F_{14} costs up to 100 SFR per litre where CO_2 costs only 1 SFR per litre.

9. Conclusions

CO_2 cooling can be the optimal solution for cooling VERTEX and Tracking detectors. A successful and reliable cooling system requires a well chosen concept, a simple and excellent design and high quality components and manufacturing.

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