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Evaporative cooling in ATLAS—Present and future

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A B S T R A C T

The ATLAS Inner Detector cooling system is the largest evaporative cooling system used in High Energy Physics today. During the installation and commissioning of this system many lessons had to be learned, but the system is now operating reliably, although it does not achieve all original design specifications in all its circuits.

We have re-evaluated the requirements for the cooling system for the barrel SCT, in particular for the evaporation temperature, over the full ATLAS operational lifetime. We find that the critical requirement is for thermal stability at the end of LHC operation. To predict this we have developed a simple thermal model of the detector modules which yields analytical expressions to evaluate the results of changes in the operating conditions. After a comparison of the revised requirements and the actual present cooling system performance we will discuss various modifications to the system which will be required for future operation.

In parallel we are developing a cooling system for the ATLAS phase II upgrade (sLHC) tracker, for which a set of requirements has been specified. Two technologies, based on different coolants, fluorocarbons or CO_2, are being pursued.

1. Introduction

Evaporative cooling is gaining interest in the particle physics community, due to the promise of reduced material, good temperature uniformity, and the wide range of temperatures accessible. The largest such system to date operates in the ATLAS Inner Detector (ID), where it removes the heat from the semiconductor detector systems (Silicon strips (Semiconductor Tracker, SCT) and Pixels) [1].

The ATLAS ID evaporative cooling system is a single-stage compressor cycle with warm transfer pipes (see Fig. 1) with C_3F_8 as cooling fluid. The system condenses at 20 °C and 17 bar_a. The coolant is then transferred to the detector in warm (above the cavern dew point) feed lines with a distribution to the individual circuits on the cavern wall, just outside the ATLAS detector. Close to the ID the coolant is sub-cooled in internal heat exchangers (HEXs) by the return fluid of the same circuit. The sub-cooling lowers the vapour quality at the start of the evaporator and thus allows for smaller mass flows. The coolant pressure is subsequently reduced in capillaries, which define the onset of the boiling. The target evaporation temperature in the on-detector cooling pipes is −25 °C which corresponds to a saturation pressure of 1.6 bar_a. This pressure is controlled by a back pressure regulator in the return lines in the distribution racks outside ATLAS. The system operates at fixed flow to cope with load fluctuations due to varying power consumption in the front-end electronics, and varying powering states. The excess return liquid needs to be boiled off, and the fluid then heated to above the cavern dew point to allow for warm (uninsulated) return lines. This is done in electrical immersion type heaters inside the return pipe. All components downstream of the feed distribution, down to the back pressure regulation and the return line distribution are inaccessible on a timescale of less than several months. Finally, the warm return vapour is transferred back to the compressor plant. The minimum suction pressure of the compressors is 0.8 bar_a, which results in a very demanding compression ratio of $\sim 1:20$, which is achieved by two-stage oil-free compressors. This system is capable of delivering ~ 60 kW of cooling power to the 204 circuits. It is the largest evaporative cooling system in HEP to date by more than a factor 10.

The commissioning of this system has been challenging. The spectrum of challenges ranged from project management issues (components for this system fall into different ATLAS ID subsystem responsibilities, specifications were not always consistent), pure engineering issues (leaks and electrical faults) over combined engineering-thermodynamics issues (high compression ratio requirements for the chosen cycle leads to excessive wear on the compressors) to the fluid dynamics of two-phase flow

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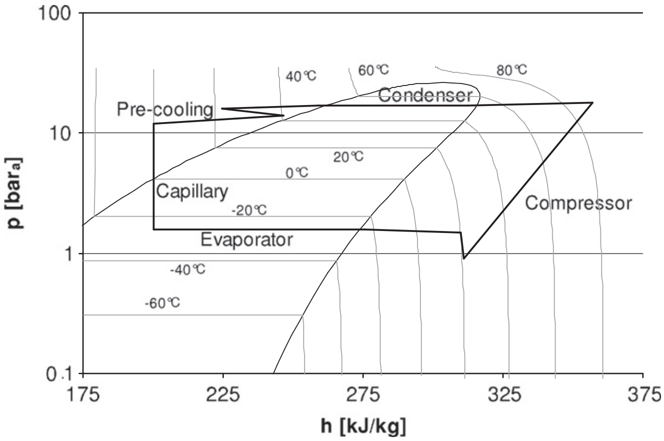

Fig. 1. Phase diagram for C_3F_8 and design thermodynamic cycle of the ATLAS Inner Detector evaporative cooling system.

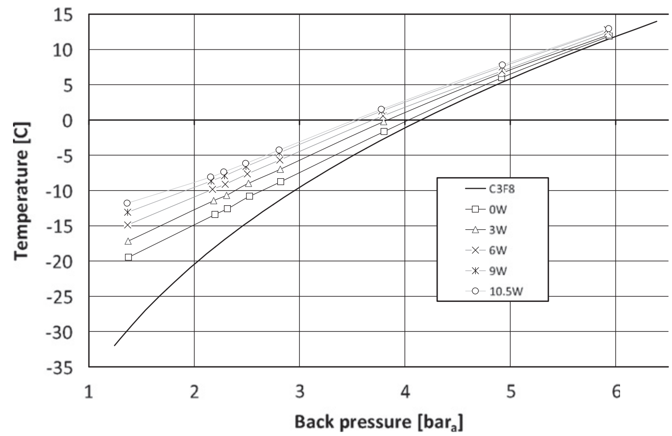

Fig. 2. Measured evaporation temperature as a function of the back pressure for different detector power. For comparison the saturation curve for C_3F_8 is shown.

(larger than anticipated pressure drops over the detector structures and return lines). Despite these difficulties the system is now operating reliably. The total operational period (time × number of circuits) to date is 55 y. During LHC beam operation the duty cycle of the system was 100% in 203 circuits, with the remaining circuit inoperable due to an inaccessible leak. However, during the commissioning doubts about the ability of the system to achieve the target evaporation temperature ($-25\,^{\circ}$C) in all subsystems emerged and we have embarked on several studies to verify these observations and understand their implications on the operation of the ATLAS ID.

The cooling temperature in a Silicon detector system is an important parameter in two aspects: First, it affects the sensor temperature-dependent annealing processes, which impact the sensor depletion voltage and leakage current at a reference temperature after irradiation and secondly, it affects the actual, sensor temperature-dependent leakage current, and with it the actual leakage power which needs to be removed to maintain thermal stability of the modules. The former is a long-term effect, where the cooling temperature during the whole of ATLAS operation is relevant, whereas the latter has an instant dependence on the cooling temperature. The latter will become particularly of concern at the end of ATLAS operation, when the leakage power at reference temperature will be highest.

2. Measurements of achievable evaporation temperature

The most critical subsystem of the ATLAS ID is the barrel SCT, as it requires the largest cooling power per circuit, which results in the highest pressure drops in these circuits. To study pressure drops and coolant temperatures in detail we built a test setup representing a cooling loop of the ATLAS barrel SCT, and cooling system components (transfer pipes, heaters, HEXs, etc.) as used in ATLAS and arranged in a similar geometry, but with additional sensor instrumentation.

The evaporation temperature is controlled by the back pressure regulator. However, the pressure drop in the on-detector and return pipework provides an offset of the evaporation pressure to this set pressure, which ultimately limits the temperature in the evaporator. In our system the lowest possible back pressure is given by the minimum compressor suction pressure (~ 0.8 bar$_a$). We find that for a realistic detector load (6 W per module) we cannot achieve an evaporation temperature below $-15\,^{\circ}$C (see Fig. 2). Even if we extrapolate to zero back pressure an evaporation temperature of $-25\,^{\circ}$C appears out of reach.

Table 1
"Hamburg model" [2] and parameters [3] used for the prediction of the depletion voltage (Φ is the NIEL fluence after time t at a temperature T).

$\Delta N_{\mathrm{eff}}(\Phi,t) = N_a(\Phi,t,T) + N_C(\Phi) + N_Y(\Phi,t,T)$	
Donor removal & stable acceptor	$N_C(\Phi) = -N_{C0}(1-\exp(-c\Phi)) - g_C\Phi$
Unstable acceptor	$N_a(\Phi,t,T) = -g_a\Phi\exp(-\Theta_a(T)t/\tau_a)$ $\Theta_a(T) = \exp(E_a(1/T_R - 1/T)/k_B)$
Reverse annealing	$N_Y(\Phi,t,T) = -g_Y\Phi\left(1 - \frac{1}{1+\Theta_Y(T)t/\tau_Y}\right)$ $\Theta_Y(T) = \exp(E_Y(1/T_R - 1/T)/k_B)$
$N_{\mathrm{eff},0} = 1.026 \times 10^{12}\ \mathrm{cm}^{-3}$ $N_{C\,0} = 0.7 N_{\mathrm{eff},0}$ $c = 0.075\ \mathrm{cm}^{-1}/N_{C\,0}$ $g_a = 0.018\ \mathrm{cm}^{-1}$ $\tau_a = 55\ \mathrm{h}(T_R = 20\,^{\circ}\mathrm{C})$	$E_a = 1.09$ eV $g_C = 0.017\ \mathrm{cm}^{-1}$ $g_Y = 0.059\ \mathrm{cm}^{-1}$ $\tau_Y = 480\ \mathrm{d}(T_R = 20\,^{\circ}\mathrm{C})$ $E_Y = 1.33$ eV

We also measured the pressure drops in the different sections, with the aim to identify possible choke points which might be improved constructively. However, we find that the pressure drop stems dominantly ($\sim 80\%$) from parts which are inaccessible (detector loops and manifolds, and internal HEXs).

For the pixel and endcap SCT subsystems the return line pressure drops are smaller due to smaller loads and line impedances, and different heat path design on the detector modules makes the evaporation temperature less critical.

3. Predictions of radiation damage and annealing

Based on models in the literature [2–4] we have made predictions of the depletion voltage (V_{dep}) and leakage current (I_{leak}). These predictions were made for the innermost SCT barrel (B3) on the assumption of 342 d/y with cooling (216 d/y with electronics on) at different cooling temperatures, and 23 d/y of maintenance without cooling. The calculations use a plausible LHC luminosity profile over up to 12 y of LHC operation, where approximately 1 ab^{-1} would be reached after 10 y (nominal LHC operation).

The depletion voltage has been computed according to the "Hamburg model" [2] (see Table 1), and the leakage current using the equations listed in Table 2 [4]. We find that both properties depend only weakly on the cooling temperature as long as there are three weeks of maintenance at room temperature (see Figs. 3 and 4). Although the models and the parameters contain significant uncertainties for our sensors results from irradiation