

Development of Fluorocarbon Evaporative Cooling Recirculators and Controls for the ATLAS Pixel and Semiconductor Tracking Detectors.

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Abstract

We report on the development of evaporative fluorocarbon cooling recirculators and their control systems for the ATLAS Pixel and Semiconductor Tracking (SCT) detectors.

A prototype circulator uses a dry, hermetic compressor with C₃F₈ refrigerant. The mass flow rate and operating pressure in each circuit is individually tuned via feedback according to the circuit load variation, using analog air pressure-piloted regulators. A hard-wired thermal interlock system automatically cuts power to individual silicon modules should their temperature exceed safe values.

All elements of the circulator and control system have been implemented in prototype form. Temperature, pressure and flow measurement and control use 150+ channels of standard ATLAS LMB ("Local Monitor Board") DAQ and DACs on a multi-drop CAN network administered through a BridgeVIEW user interface. Prototype 16 channel interlock modules have been tested.

Highly satisfactory performance of the circulator under steady state, partial-load and transient conditions were seen with proportional fluid flow tuned to varying circuit power. Future developments are outlined.

I. INTRODUCTION

The front-end electronics and silicon substrates of the ATLAS SCT and pixel detectors collectively dissipate around 60kW of heat, which must be removed from the inner detector cavity through ~ 400 separate evaporative cooling circuits. For an operational lifetime of around 10 years in the high radiation field close to the LHC beams, the silicon substrates of these detectors must operate at a temperature below ~ -6 °C, with only short warm-up periods each year for maintenance. Evaporative cooling is chosen since it offers minimal extra material in the tracker sensitive volume.

Following our studies of evaporatively-cooled Pixel and SCT thermo-structures [1], we have addressed the development of evaporative fluorocarbon recirculators, their control systems and services plant for use with perfluoro-n-propane (C₃F₈)¹ at an evaporation temperature (pressure) of ~-25 °C (~1.7 bar_{abs}).

II. APPARATUS AND PRINCIPLES

A prototype circulator Figure 1 is centred around a hermetic, oil-less piston compressor² operating at an aspiration pressure of ~ 1 bar_{abs} and an output pressure of ~ 10 bar_{abs}.

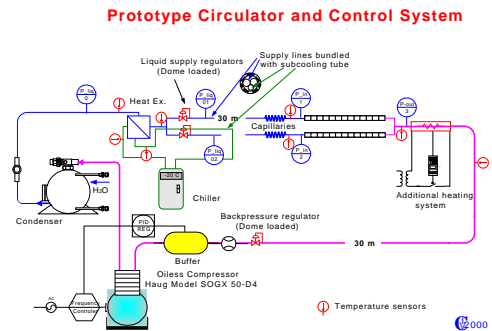


Figure 1: Schematic of Prototype Evaporative Recirculator

Aspiration pressure is regulated via PID variation of the compressor motor speed from zero to 100%³, based on the sensed pressure in an input buffer tank. A thermal simulator of 22 barrel SCT individually-powered silicon

¹ PF5030 Mfr: 3-M Corp. Specialty Chemicals Division, St. Paul, MN55113-3223, USA

² Model SOGX 50-D4; Mfr: Haug Kompressoren CH-9015 St Gallen, Switzerland

³ Via Motor Speed Controller: Model CIMR-XCAC41P5, (400V 3 phase, 3.7 kVA).

Mfr: Yaskawa Co., 1-16-1 Kaigan, Minato-Ku, Tokyo, 105-6891 Japan

strip modules is used as a variable load in these studies. Each module is equipped with a PT100 and a negative temperature coefficient (NTC)⁴ thermal sensor, which is used to trigger the thermal interlock to its power supply (section IV.1).

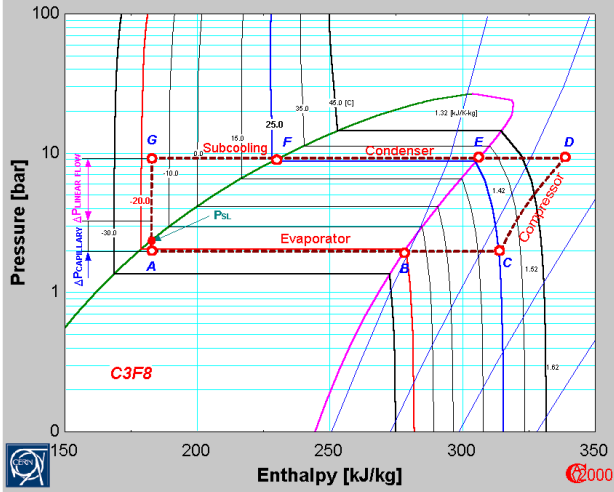


Figure 2: Cooling cycle on the P-h diagram

Figure 2 shows the closed thermodynamic cycle. High pressure C_3F_8 vapor is condensed (EF) and passed to the detector loads in liquid form, at a flow rate dependent on the pressure upstream of injection capillaries with typical diameters 0.6-0.8mm. The refrigerative power depends on the product of mass flow rate ($kg\cdot s^{-1}$) and enthalpy ($J\cdot kg^{-1}$). Since typical enthalpies are in the range $50-100\text{kJ}\cdot kg^{-1}$ (depending on liquid sub-cooling), liquid flow rates of $\sim 10-20\text{gs}^{-1}\text{kW}^{-1}$ are typical. These flows are less than $\sim 1/20$ those typical in mono-phase liquid cooling systems, and allow a correspondingly reduced fluid service ($\%X_o$) overhead close to the detector. The arrival temperature of liquid at the capillary also determines the available enthalpy. As an example in Figure 2, an enthalpy of $\sim 100\text{kJ}\cdot kg^{-1}$ (AB) is available with evaporation at -20°C when C_3F_8 arrives at -17°C .

At a given coolant arrival temperature, the higher the pressure available upstream of the capillary, the wider the available proportional range of flow through it to accommodate circuit heat load variation (e.g. varying numbers of powered silicon detector modules); the zero flow limit being set by the saturated liquid pressure, P_{SL} . Since the maximum available pressure is delimited by the condenser pressure, reduction of the liquid injection temperature (i.e. increased sub-cooling) tracks the saturated liquid locus to lower pressure and increases the linear flow range ($\Delta P_{\text{LINEAR FLOW}}$). Maximum enthalpy is possible when the liquid is injected at the evaporation temperature. For these reasons, the prototype recirculator of Figure 1 was equipped with variable temperature sub-

cooling, (coolant tubes accompanied the C_3F_8 liquid supply tube in the same insulated bundle), and with DAC-control of the liquid pressure upstream of the capillary. The C_3F_8 supply and return tubing of the pixel and SCT cooling circuits must traverse the electrical services of other ATLAS sub-detectors which are mainly located in an ambient air atmosphere with dew point $\sim 14^\circ\text{C}$. These lines must therefore be insulated (and may require local surface heating in critical locations), to prevent condensation. Space for service passages is extremely limited, so efforts have been made to minimise insulation thickness by ensuring that as much as possible ($>90\%$) of the supplied C_3F_8 liquid is evaporated in the on-detector tubing, through flow regulation proportional to circuit load. These studies are discussed in section IV.2.

In the final installation, liquid will be distributed, and vapor collected from ~ 400 circuits by fluid manifolds on the ATLAS service platforms. Since this zone will be inaccessible to personnel during LHC running (with local radiation levels and magnetic fields beyond acceptable levels for a wide range of commercial control electronics) the local regulation devices will be mechanical, and will be remotely-piloted with analog compressed air from remote electro-pneumatic actuators situated in an accessible zone.

The evaporation pressure in the on-detector cooling channels of each parallel circuit will be maintained at the set point by an individual back-pressure regulator. For example, at $1.9\text{bar}_{\text{abs}}$ the C_3F_8 evaporates at -20°C . The recirculator of Figure 1 was equipped with DAC-control of the boiling pressure within the cooling circuit. Such individual control of operating temperature is impossible in parallel circuits of a mono-phase cooling system with a single liquid supply temperature.

III. DATA ACQUISITION AND CONTROL SYSTEM ELECTRONICS

All elements of the circulator and control system have been implemented in prototype form.

A. Cooling Fluid Control

Figure 3 illustrates the two stage electro-pneumatic implementation in the present recirculator.

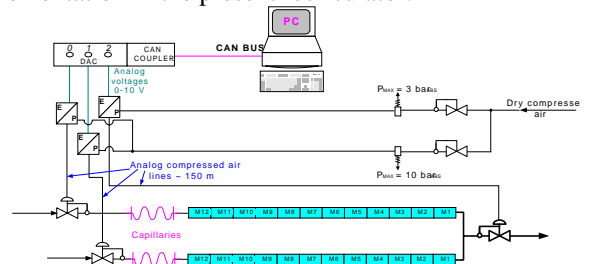


Figure 3: Electro-Pneumatic Control Schematic

⁴ Semitec AT series: $10\text{ k}\Omega @ 25^\circ\text{C}$, $t(K)=1/(9.577E-4 + 2.404E-4\ln(R)+2.341E-7\ln(R)^3)$. Mfr: Ishizuka Electronics Co. 7-7 Kinshi 1-Chome, Sumida-ku, Tokyo 130-8512, Japan

Flow rate is proportional to the output pressure of a “dome-loaded” pressure regulator⁵ piloted by air in the range 1-10 bar_{abs} from an electro-pneumatic actuator⁶, which receives an analog set point from a DAC⁷. Circuit boiling pressure is controlled by a similarly-piloted dome-loaded back-pressure regulator⁸.

B. Data Acquisition

Temperature, pressure and flow measurements in the circulation system, and on prototype SCT and pixel thermo-structures under test, are made using prototypes of the standard I/O system of the ATLAS DCS (“Detector Control System”). The industrial field-bus CAN [2] is used to read out distributed nodes, called LMBs (“Local Monitor Boards”) [3], running the CANopen protocol [4]. The LMBs are designed to serve for the controls of all ATLAS sub-detectors, and contain different analog and digital I/O functions. They are specified to tolerate a radiation dose of 1 Gy and 10^{11} neutrons $\text{yr}^{-1}\text{cm}^{-2}$ and a magnetic field of 1.5T, and can hence be placed everywhere in the ATLAS experimental cavern outside of the calorimeter. In the present system, 6 LMBs, each with up to 64 analog inputs multiplexed onto a 16 bit ADC, are read out. The ADC range, polarity, and digitisation frequency are set through the CAN bus. The individual channels are mapped onto an ad-hoc implementation of a multiplexed PDO, inspired by the initial proposal in [5].

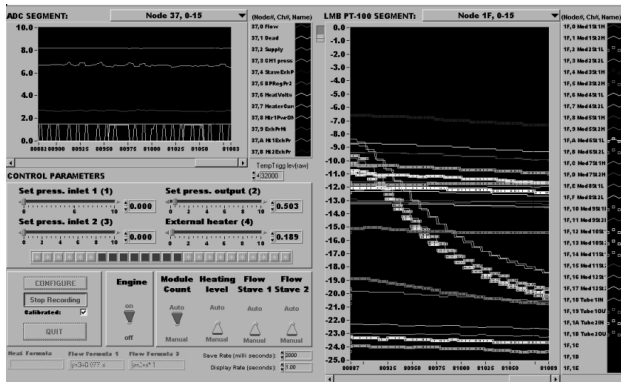


Figure 4: Typical Screen from the BridgeVIEW User Interface

Flow and pressure are controlled by commercial DACs, which are located on the same CAN bus as the LMBs. The bus is interfaced⁹ to a commodity PC. A functionally-restricted CANopen protocol allowing for PDO and SDO transfers, but lacking a local object dictionary and node-guarding support, has been implemented for this card in form of a BridgeVIEW VI

⁵ Model 44-2211-242-1099: Mfr: Tescom, Elk River MN 55330, USA

⁶ Model PS111110-A: Mfr Hoerbiger Origa GmbH, A-2700 Wiener-Neustadt, Austria: Input 0-10V DC, Output pressure 1-11 bar_{abs}

⁷ Model 750-556: Mfr Wago GmbH, D32423 Minden, Germany controlled through Model 750-307 CAN Coupler

⁸ Model 26-2310-28-208: Tescom Corp

⁹ Model 184726C-02 PCI-CAN/2 Communication card: Mfr: National Instruments Corp, Austin TX 78759, USA

server. The server is able to handle both standard DS 301 PDOs, as well as the multiplexed PDOs used by the LMB. Based on this protocol, a BridgeVIEW application has been designed that permits a simplified configuration by allowing the CAN network to be scanned for attached CANopen devices.

Figure 4 shows a typical on line display of temperatures on the 22 SCT module thermo-structure used as a load in these tests, together with system flows and pressures and the module interlock status bit pattern (square green indicators). In one implementation (IV.2.1), this was used to regulate coolant flow proportional to the number of powered modules.

C. Hard-wired Thermal Interlocks

1) General

In the final installation, a hard-wired thermal interlock system will automatically cut power to individual silicon pixel [6] and micro-strip modules if their temperatures exceed safe values for *any* reason. Cases include latch-up, failure of coolant flow to a particular parallel cooling circuit, and de-lamination of a particular module from its cooling channel.

Two prototype 16 channel interlock modules (“I-Boxes”) were used in combination with NTC sensors attached to the dummy silicon modules. The signals from the sensors were split between an LMB with 2.5V full-scale range, and the I-Boxes, in which comparison was made with hard-wired voltages representing upper (“POWER DISABLE”) and lower (“POWER RE-ENABLE”) limits of the acceptable module temperature band.

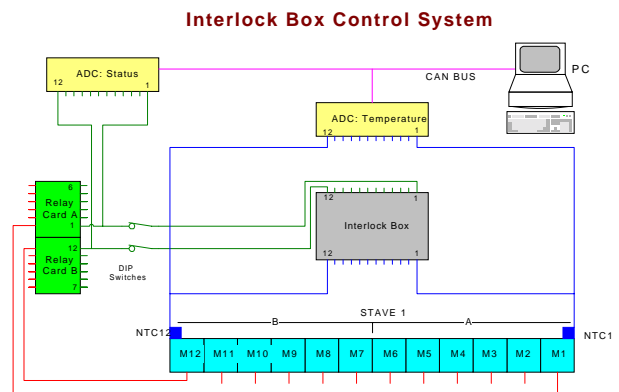


Figure 5: Interlock Study of a Stave of 12 Silicon modules

A second LMB with 5V full scale was used to read the status of module power. In some of these studies (IV.2.1), the counted number of module “POWER ON” bits was used to vary the flow rate of coolant to the circuit

2) Choice of temperature sensor for the interlock connections

As in the final experiment, the temperature sensors, which act as inputs to the I-Boxes, are mounted on the detector

substrates. High radiation tolerance is required of these devices. The constraint of two-wire readout over cable lengths of up to 40m predicates relatively high resistance and large $\Delta R/R$ per Kelvin. NTC resistors fulfil these requirements, and are available as 10 k Ω devices with 1% tolerance at 25 °C with 4 % ΔRK^{-1} .

In the very compact region of the ATLAS pixel detector only SMD devices can be installed. Samples of NTC SMD resistors from Taiyo Yuden and Semitec were irradiated with 25 GeV/c protons up to 1.2×10^{15} p/cm². Neither has shown significant sensitivity to irradiation. Dispersion before and after irradiation corresponds to $\Delta T < 0.3K$, which is within the acceptable maximal error limits for the sensors of 0.5 K.

IV. EXPERIMENTAL RESULTS FROM THE PRESENT STUDY

1) Studies of Heater Interlock Hysteresis

To reduce the influence of noise, the comparator circuits of the I-Box are equipped with hysteresis. The hard-wired switching temperatures of two comparators are defined with a fixed resistor network. In the pixel detector, the interlock signal (“POWER DISABLE”) is set at 0.15 °C and reset (“POWER RE-ENABLE”) at -0.79 °C.

To simulate the behaviour of the final power supplies in the present tests, relays were put between the power supplies and the dummy modules Figure 5. The I-Box channels controlled these relays. Starting from stable running conditions of the cooling system a coolant run-out condition was provoked. The interlock transition temperatures of all channels were recorded, and found to be centred on the nominal values within an error band of ± 1.0 K, including effects of the I-Box electronics and NTC resistance. The sensors used were chosen at random, as is foreseen for the final experiment.

2) Studies of Fluid Flow Proportionality

The mass flow rate to each circuit will be individually tuned via feedback according to the circuit load variation, using pressure regulators in the liquid supply lines. We have studied the performance of the circulator and the temperature distribution on powered silicon modules under steady state, partial-load, interlock-trip, start-up and shutdown conditions using two methods of proportional fluid control.

2.1) I-Box Bit Counting.

In the first, the number of powered modules was counted via I-Box bits asserted, and the flow varied according to a protocol;

$$P_{\text{CAPILLARY}} = P_{\text{SL}} + m^*(\#\text{powered modules}) \quad (1)$$

$P_{\text{CAPILLARY}}$ is set by the WAGO DAC output acting through the E2P driver to the dome loaded supply regulator. The constant of proportionality m is the

incremental pressure required to drive sufficient mass flow of C₃F₈ liquid through the capillary to evacuate the power of a single pixel or SCT module (~ 10 Watts max).

Temperature sensors and analysing heaters were mounted on the exhaust tubing downstream of the Silicon detectors to determine the amount of un-evaporated C₃F₈. Results were good over a wide range of circuit power (number of powered modules), and indicated that very little un-evaporated liquid was entering the exhaust. However, the protocol is vulnerable to variations in individual module power, unless adapted to:

$$P_{\text{CAPILLARY}} = P_{\text{SL}} + m^* \sum_i (\text{POWER}_{\text{module}(i)}) \quad (2)$$

where m^* is the pressure/power conversion constant (mbarW⁻¹). This protocol requires (i) DCS access to the monitored voltages and currents on several supply rails per module, and (ii) that the power supplies continue to supply this information.

2.2) Direct PID control of Fluid Flow.

Direct PID control of circuit flow on the basis of sensed exhaust temperature has proved an effective means of control. In a first study, a commercial PID controller¹⁰ directly piloted the E2P driver. In a second study, a PID algorithm was implemented directly in a microcontroller chip¹¹ of the same family as that used¹² for system programming and monitor functions in the recently-developed “Embedded-LMB”: [7], currently under test. In a third study, PID control was implemented using BridgeVIEW PID extension toolkit, using WAGO DAC modules to pilot the E2P drivers.

In each case, it was possible to maintain the temperature at a point ~ 50 cm downstream of the evaporation zone a significant margin (>10 °C) above the evaporation temperature, over the full range of circuit power: i.e. from one module powered to all modules powered.

Importantly also, in all cases, temperatures on powered modules stayed within allowable limits with a variation of ± 0.5 °C during the transient (ramp-up/ramp-down of varying numbers of modules on the cooling circuit). The right-hand plot of Figure 4 illustrates the variation of temperature on powered and un-powered modules following a partial shut-down of six modules, with flow reduced under PID control to accommodate only the remaining powered modules. The reduction in temperature of the un-powered modules toward the evaporation (tube) temperature is seen, while the powered modules remain roughly constant in temperature. In setting up the PID parameters, care was needed to ensure that the lower pressure limit was not less

¹⁰ Model G9FTE-R*E1R-88-N; Mfr: RKC Instrument Co, 16-6 Kugahara 5-Chome Ohta-Ku, Tokyo, Japan

¹¹ AT90S8515; Mfr: ATMEL Corp, San Jose CA 95131, USA: programmed from C via GNU toolkit

¹² ATMEL ATmega103 128k RISC flash μ controller

than P_{SL} , during operation or PID auto-tuning. The results indicate that with proportional flow control, uniformity in temperature of remaining powered modules is achievable, and that a relatively simple insulation scheme will suffice to maintain the outer surface of the exhaust tubing above the local dew-point.

V. FUTURE PLANS

A 6kW “demonstrator” recirculator with ~25 parallel cooling circuits is currently under construction. It will use a high capacity hermetic piston compressor¹³ with a local control system modelled on the present recirculator, and is aimed to evacuate the power dissipation of ~ 1/8 the barrel SCT and pixel detectors, with extra circuits for forward SCT and pixel detector assemblies.

Table 1 shows the numbers of cooling circuits, their individual powers, and the numbers of flow and boiling pressure regulators required. The number of circuits and total power is similar to that of the full ATLAS SCT tracking layer 4. The compressor and circuit flow and pressure control system is therefore a prototype for the first such installation at an assembly site for the ATLAS SCT and pixel detectors. In the final ATLAS installation, a total of seven such systems will be required. Some will be employed at assembly sites before coming to CERN.

Table 1: Power and Cooling Channel Count in the Demonstrator Recirculation System

Layer	Circuits	Supply Capillaries / circuit	Power/ Circuit (W)	Flow Regs	Boiling. Pr. Regs
SCT 4	2	2	480	4	2
SCT 3	2	2	480	4	2
SCT 2	1	2	480	2	1
SCT 1	1	2	480	2	1
Pixel 2	4	1	208	4	4
Pixel 1	3	1	208	3	3
B layer	2	1	144	2	2
SCT disk/4	1	3	110	3	1
Pixel disk/6	2	1	96	2	1
TOTALS			5146	26	17
TOTAL: SCT 4			6720	28	14

VI. CONCLUSIONS

Following on from our measurements on thermal prototypes of ATLAS SCT and Pixel Detector elements presented at LEB99 [1], we have developed the control system for a multiple parallel channel C_3F_8 evaporative cooling recirculator.

Power interlocks and proportional control of refrigerant flow have been successfully demonstrated. During transient conditions, powered modules remained stable in temperature, while the exhaust tubing of the evaporative cooling circuits could be stably maintained a significant margin above the C_3F_8 evaporation temperature (and at a higher temperature than in a mono-phase liquid cooling system), simplifying the insulation in the final ATLAS installation.

The use of μ controller-based PID algorithms for flow control is particularly interesting, and offers the possibility of implementation of either smart (PID) or transparent DACs in the new ATLAS DCS embedded local monitor board.

VII. REFERENCES

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- [7] ATLAS Embedded Local Monitor Board (“E-LMB”) http://atlasinfo.cern.ch/ATLAS/GROUPS/DAQTRIG/DCS/LMB/SB/elmb_1.html

¹³ Haug QTOGV125LM; 80m³hr⁻¹ C₃F₈ vapor; P_{in(out)} 1 (10) bar_{abs}