THE CONTROL SYSTEM FOR THE CO2 COOLING PLANTS FOR PHYSICS EXPERIMENTS

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Abstract

CO_2 cooling has become interesting technology for current and future tracking particle detectors. A key advantage of using CO_2 as refrigerant is the high heat transfer capabilities allowing a significant material budget saving, which is a critical element in state of the art detector technologies. Several CO_2 cooling stations, with cooling power ranging from 100W to several kW, have been developed at CERN to support detector testing for future LHC detector upgrades. Currently, two CO_2 cooling plants for the ATLAS Pixel Insertable B-Layer and the Phase I Upgrade CMS Pixel detector are under construction. This paper describes the control system design and implementation using the UNICOS framework for the PLCs and SCADA. The control philosophy, safety and interlocking standard, user interfaces and additional features are presented. CO_2 cooling is characterized by high operation stability and accurate evaporation temperature control over large distances. Implemented split range PID controllers with dynamically calculated limiters, multi-level interlocking and new software tools like CO_2 online p-H diagram, jointly enable the cooling to fulfil the key requirements of reliable system.

INTRODUCTION

Detectors and Their Cooling Systems

The high energy physics experiments constructed for the Large Hadron Collider at CERN (LHC), sitting 100m underground, include high precision semiconductor tracking detectors. Silicon sensors of such detectors, as well as their read-out electronics, need light weight and radiation-hard cooling systems in order to minimize the possible interference with the recorded particle tracks. To limit the radiation damage, the targeted temperature of the silicon sensors is between -10^{0}C to -40^{0}C both in operation and stand-by conditions. CO_2 evaporative cooling has been selected as the key technology for the two largest CERN Experiments and their next future tracker: the ATLAS Pixel Insertable B-Layer (IBL) [1] and the CMS Pixel detector Phase I Upgrade [2]. The main benefits of CO_2 with respect to the currently used Fluorocarbons are favourable thermo-physical properties allowing to apply very small diameter tubing, as well as the reduced operation cost and environmental impact [3].

The CO_2 cooling systems developed for the ATLAS and CMS detectors use a concept called the 2 Phase Accumulator Controlled Loop (2PACL) [4], already successfully implemented in the LHCb Experiment at CERN. The 2PACL is a 2-phase pumped loop where the detector evaporation temperature is indirectly controlled by the accumulator pressure. The accumulator is a vessel filled with a mixture of liquid and vapour CO_2, on the return line from the detector, whose internal pressure is regulated by cooling and heating action. Cold liquid CO_2 is pumped to the detector where it expands to the desired pressure set point and becomes two-phase coolant removing detector's heat. Returning mixture of vapour and liquid CO_2 is condensed by means of a primary chiller before being pumped again in closed loop, see Figure 1.

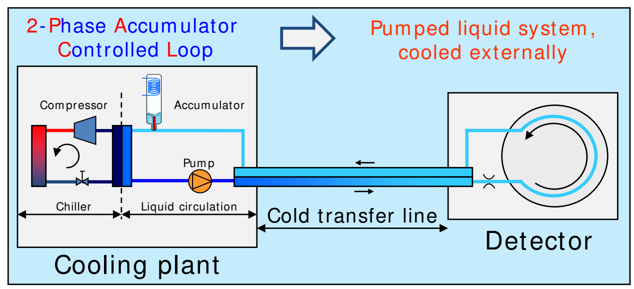

Figure 1: The 2PACL scheme.

As the number of the installed CO_2 cooling systems is bound to increase, it is necessary to develop a control system standard which covers three system layers: software, hardware and safety.

CONTROLS

Controls Architecture

Each cooling unit is equipped with about 330 I/Os. The CO_2 instrumentation is distributed over 100 m distance which separates the radiation protected cavern, where the control system cabinets are placed, with the experimental cavern, where part of the instrumentation sits. Industrial ETHERNET IP field network connects independent system elements. They are equipped with WAGO and FESTO ETHERNET IP couplers together with one Schneider Premium Programmable Logic Controller (PLC) running about 16 control loops and 360 alarms and interlocks. To cope with the high reliability standard required by the experiments, CO_2 cooling system often features a redundant design. In the case of ATLAS IBL, two CO_2 units and one Vacuum system, each equipped with a single PLC are combined to ensure a 24/7 operation.

The user interface is based on a SCADA (Supervisory Control And Data Acquisition), based on Siemens WinCC

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OA. The control software conforms to the UNICOS CPC6 (Unified Industrial Control System Continuous Process Control) framework of CERN [5] [6].

PLCs are placed on the CERN Technical Network physically detached from the outside world for security reasons. Communication between the SCADA server, placed in the CERN Control Center (CCC), and PLCs uses the MODBUS protocol.

Additionally, to ensure the operability of the cooling system in case of major network failure, each unit is equipped with a SIEMENS local touch screen. It contains basic operation and maintenance functionalities, keeping the same synoptic "look and feel" as in the WinCC OA user interface.

Operators, via the terminal servers, are able to connect from their Operator Work Stations (OWS) placed on the CERN General Purpose Network (GPN) for maximum flexibility.

Overall CO_2 cooling control system architecture scheme is presented on Figure 2.

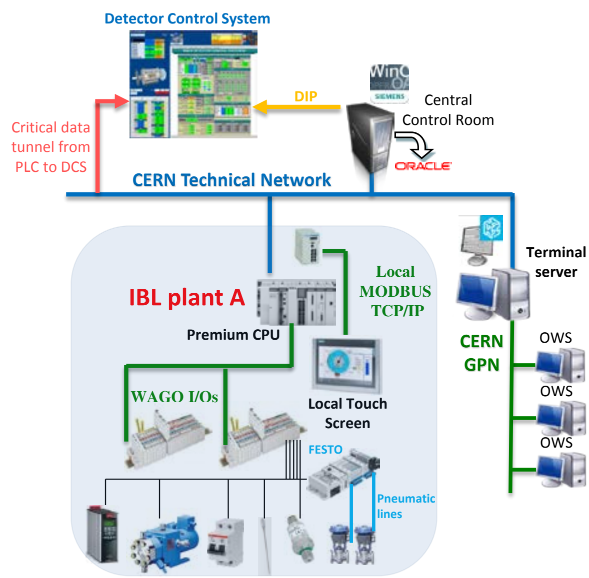

Figure 2: CO_2 cooling control system architecture.

Operability – PCOs, Sequencer

The process logic is supervised by the hierarchy where the master is the CO_2 system Process Control Object (PCO). In the case of CMS, below the master there is one PCO per subsystem. The system PCO handles several operational option modes: operation, stand-by, bake-out and maintenance with an associated allowance table. This table defines permitted option mode changes when the system is running. In addition, the "operation" and "stand-by" modes are equipped with a sequencers designed for safe system start-up and operation handling different system phases and the transitions in between them, see Figure 3.

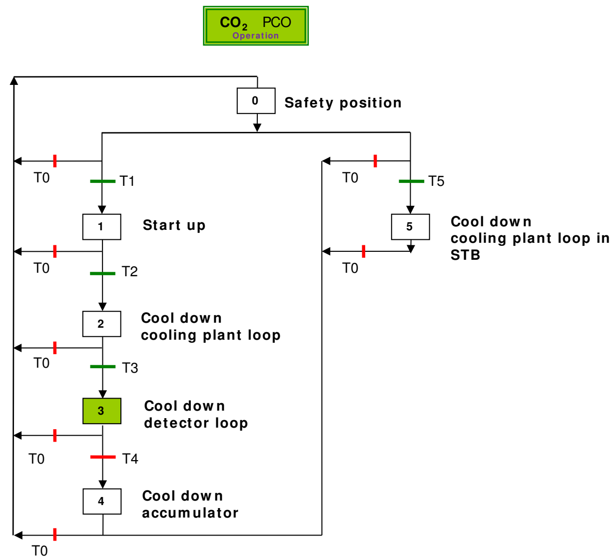

Figure 3: CO_2 cooling control system sequencer.

Availability

The system is designed to be autonomous, not requiring the operator presence during start-up nor nominal operation conditions. In order to keep the highest possible availability, redundant hot swappable 24V DC power supplies were selected to power system electronics and instrumentation.

To make the system resistant to sudden power cuts or power network failures in the ATLAS experiment the CO_2 cooling system is also connected to uninterruptible power supply.

Safety

The CO_2 cooling system is high pressure equipment and special safety precautions have to be taken. Each cooling line segment which can be sectioned, by malfunctioning of the control system or by operator mishandling of valves, has to be equipped with a safety valve, which releases possible overpressure created by evaporation of the trapped liquid.

On control system side to ensure safety of both the machinery and operators the system is protected against dangerous situations by software and hardware interlocks.

Each cooling unit is usually equipped with several direct heaters in the range of few kW, closed in small volume and thoroughly covered with thermal insulation. In order to avoid over heating due to insufficient cooling a three level safety interlock philosophy has been introduced:

- The first interlock (software), stops single heater when first level temperature threshold is exceeded. The temperature is measured at the heater surface with a thermocouple type K.
- The second interlock (software), stops all system heaters when second level temperature threshold is exceeded (measured on the same sensor as first

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interlock). In this way accidents caused by possible miswiring of the interlock sensor are prevented.

- The third interlock (hardware), thermal protection switch, which cuts power to all system heaters when sensor contact opens.

High level protection guarantees that even in the case of two safety level failures we still have the third one available.

In case an interlock is triggered the operation team is always informed by email or SMS notifications.

All individual alarms and interlocks are grouped in the functional sections and sent to CCC, Detector Control System (DCS) and Detector Safety System (DSS).

Databases

The monitoring data need to be stored for long term, in order to facilitate off-line analysis of system operation or failures. Each CO_2 cooling unit SCADA system is connected to the LHC Logging ORACLE database where all the historical data are stored. This feature allows, even after several years of operation, to compare and debug some typical system problems.

Accumulator Control

A precise accumulator pressure regulation is the key element guaranteeing the required high system operation stability. The accumulator is controlled by two elements: an electrical heater (or a heater array) placed in the bottom and a cooling spiral on top. The cooling action is managed by a control valve, which regulates the mass flow of the primary refrigerant passing through the cooling spiral. Gaseous CO_2 condenses on the spiral surface and decrease pressure. On the opposite, the heater action increases the CO_2 pressure by liquid evaporation.

Both active components are driven by a “Pulse With Modulation” type signals, passing through individual zero-crossing solid-state relays.

One split range PID controller, with a 5% cross-over deadband, drives the heater and the valve. Additionally, to optimize the control, two dynamically calculated limiters are implemented. The first one protects the liquid pump against loss of sub cooling and the second protects the heater from dry-out phenomena.

User Interface

A clear and understandable Human-Machine-Interface (HMI) is a critical element of the overall control system, since it must be usable not only by control expert but also by mechanical engineers and non-expert scientists, see figure 4. The CO_2 cooling control system user interface is composed of several synoptic panels, with navigation in between, allowing for controlling and monitoring of all instrumentation. The main panel represents the simplified mechanical Process and Instrumentation Diagram, with a graphical representation of the real system components. The other panels bring more detailed views of subsystems electrical and alarm diagnostics. Each instrument is represented by an independent widget with associated faceplate holding all status information e.g. current value, error, mode, historical trend etc.

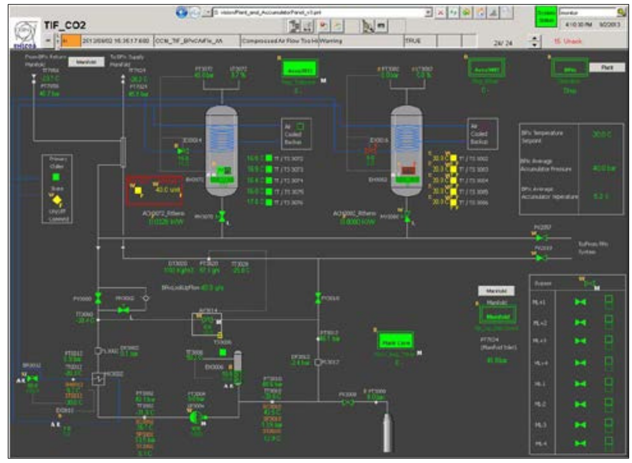

Figure 4: Main panel of the CO_2 cooling synoptic.

Access Control

The protection of the WinCC OA HMI of the CO_2 cooling control system is implemented using the CERN Joint COntrols Project (JCOP) Framework Access Control component [7]. It preserves machinery from undesirable actions (such as operator errors) by enabling/disabling system components. It is a role-based authorization mechanism with four levels of privilege. Users can be granted access into the system with their CERN credentials as the user data are synchronized with central user-management resources at CERN. Each group of people holding the same role and privileges is defined into a specific e-group.

SOFTWARE TOOLS

On-line Pressure-Enthalpy Diagram

To monitor performance and to facilitate commissioning of the cooling plant a dedicated WinCC OA Control Extension tool has been developed. It is an on-line Pressure – Enthalpy Diagram (p-H) operational for Windows and Linux Platforms. The WinCC OA user interface panel links by dynamic libraries to NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) to retrieve the coolant properties. The figure 5 shows in real time the saturation line of the coolant, several isotherms and the thermodynamic cycle of the cooling unit drawn on the basis of current measurements. At present this tool is mainly used for CO_2 and R404a, however it’s ready to work with any coolant included in NIST REFPROP.

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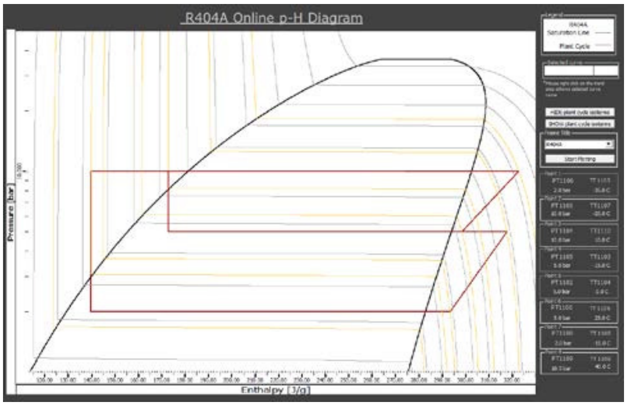

Figure 5: Real-time p-H diagram for R404a.

CONCLUSION

CO_2 evaporative cooling is becoming the technical choice for many particle detectors, thanks to its excellent thermodynamic performances and the lightweight structures it can fit into. In this framework, a new standard for the control system of the CO_2 cooling plants has been developed and put in place at CERN. A well-defined basis for software, hardware and interlocking allows for fast system design, implementation and commissioning and it is fully independent from the size of the system.

Standardized approach for user interface, communication protocol, software development framework and hardware, simplifies the operation and maintenance activities both for the experts and the basic operators. Also, using the newest solutions available for control system applications makes the CO_2 cooling control system state of the art in detector technologies and allows for long perspective in the adopted standard lifetime. The dedicated software package developed for on-line monitoring of the cooling system thermodynamic behaviour is an additional feature which brings forward the capacities of debugging and process analysis.

Such control system organization has already been successfully implemented on the prototype for the CMS Pixel detector Phase I Upgrade, today in commissioning phase, and the next step will be the commissioning of the ATLAS Pixel Insertable B-Layer (IBL) CO_2 cooling system which begins September 2013.

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