



UNIVERSITA' DI PISA

MASTER THESIS

Studies on gas systems for particle detectors at the CERN LHC experiments

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“Ad augusta per angusta.”

Latin expression

Abstract

This work focuses on the operation of the CERN LHC gas systems, which deliver the required gas mixture to the different gaseous particles detectors at the CERN LHC experiments. A fail and a consequent stop of the gas system can lead to loss of data taking during LHC Run. It is therefore fundamental to have a reliability of gas systems close to 100% that can be obtained thanks to proper intensive maintenance and consolidation programs.

One of the main task of this work was to develop new standard maintenance procedures for each functional module of the gas systems as well as to set-up a LHC-like gas system test bench in a laboratory to faithfully reproduce the operation of a real gas system. This test-bench can be used for training and it will allow to test new or different components as well as software updates. The characterization, optimisation and validation of components and new softwares in a laboratory instead of on-site allow reducing time, costs and risks related to the operation. For the development of the maintenance procedures, the gas system test bench was really useful, for instance making possible to test and validate the procedure itself and, eventually, to improve it. The generic procedure has been divided into three parts, corresponding to the different phases and working conditions in which a generic system can be operated. For each phase, an analysis of the required or feasible actions has been performed and for each component the possible failure modes and the corresponding best maintenance technique has been identified. Particular attention has been dedicated to leak tests and verification of functionality of the different gas components.

Concerning consolidation and upgrade programs for the LHC gas system, in this thesis the search and validation of new regulation valves for the CMS RPC gas system has been performed. After having defined all the technical specifications and considered the various constraints, different valves were chosen and tested under different conditions in laboratory in order to find the one which suited the best to the application requirements. Five selected valves were afterwards installed in the CMS RPC gas system and tested under real operation conditions. The study led to a final solution proposal and few more test will be needed to finally validate the selected regulation valve. In case of positive outcome, twenty-eight regulation valves will be installed in the CMS RPC gas system distribution module during LS2 period in order to be ready for LHC Run 3.

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List of Abbreviations

ALICE	A Large Ion Collider Experiment
ATLAS	A Thoroidal LHC Apparatu S
AV	A nalysis V alve
BUB	BUB bler
CERN	E uropean O rganisation for N uclear R esearch
CLOUD	C osmics L eaving O utdoor D roplets
CMS	C ompact M uon S olenoid
CPV	C harged P article V eto
CSC	C athode S trip C hamber
DPT	D ifferential P ressure T ransmitter
DT	D etector T echnologies
DT	D rift T ube
EP	E xperimental P hysics
FI	F low I ndicator
FIT	F low I ndicating T ransmitter
FIV	F low I ndicating control V alve
FS	F luidic S ystems
FT	F low T ransmitter
GC	G as C hromatograph
GCS	G as C ontrol S ystem
GEM	G aseous E lectron M ultiplier
GHG	G reen H ouse G ases
GWP	G lobal W arming P otential
HMPID	H igh M omentum P article I Dentification
HV	H andle V alve
IP	I nteraction P oint
LHC	L arge H adron C ollider
LHCb	LHC -beauty
LINAC	L INear A ccelerator
LS	L ong S hutdown
MCH	M uon C Hambers
MDT	M onitored D rift T ubes
MFC	M ass F low C ontroller
MFM	M ass F low M eter
MS	M ass S pectrometer
MTR	M uon T Rigger
MWPC	M ulti W ire P roportional C hambers
NTP	N ormal T emperature and P ressure
NV	N on-return V alve
OT	O uter T racker
PCV	P ressure C ontrol V alve
PGS	P rimary G as S ystem
PI	P ressure I ndicator

P&ID	P iping & I strumentation D iagram
PID	P roportional I ntegral D erivative Controller
PICV	PI with C ontrol V alve
PLC	P rogrammable L ogic C ontroller
PMD	P hoto M ultiplicity D etector
PS	P roton S ynchrotron
PSB	P roton S ynchrotron B ooster
PSV	P ressure S afety V alve
PT	P ressure T ransmitter
PU	P Ump
RICH	R ing I maging C herenkov
RPC	R esistive P late C hamber
SG	S urface G as R oom
SP	S et P oint
SPS	S uper P roton S ynchrotron
STP	S tandard T emperature and P ressure
TE	T emperature T ransmitter
TGC	T hin G ap C hambers
TFC	T iming and F ast C ontrol
TOF	T ime O f F light
TPC	T ime P rojection C hamber
TRD	T ransition R adiation D etector
TRT	T ransition R adiation T racker
USC	U nderground S ervice C avern
UXC	U nderground E Xperimental C avern
YV	A ctuated V alve

List of Symbols

p	absolute (relative) pressure	bar (barg)
T	temperature	K
Q	volumetric flow rate	m ³ /s
Q_N	normal flow rate	Nm ³ /s
$\dot{m}$	mass flow rate	kg/s
ρ	density	kg/m ³
ρ_N	density at NTP conditions	kg/(Nm ³)
ν	kynematic viscosity	m ² /s
d_i	hydraulic pipe diameter	m
f	friction coefficient	
ϵ	absolute surface roughness	m
Re	Reynolds number	
K_v	flow coefficient	m ³ /s
T	process time constant	s
K	process gain	
τ	process time delay	s
T_{cl}	desired closed loop speed	s
K_p	PID controller proportional gain	
T_i	PID controller integral parameter	s
T_d	PID controller derivative parameter	s
CH_2F_4	1,1,1,2-Tetrafluoroethane	freon R134a
N_2	Nitrogen	
CO_2	Carbon dioxide	
Ar	Argon	
He	Helium	
Xe	Xenon	
CF_4	Tetrafluoromethane	R-14
SF_6	Sulfur hexafluoride	
iC_4H_{10}	Isobutane	

To Life.

Chapter 1

CERN: the European Organisation for Nuclear Research

1.1 The Large Hadron Collider experiment at CERN

CERN is the European Organization for Nuclear Research and the world's leading particle physics research centre. Since its foundation in 1954, CERN has provided the means for high energy physics research.

The Large Hadron Collider (LHC) is a two-ring-superconducting-hadron accelerator and collider installed in the existing 26.7 km tunnel that was constructed between 1984 and 1989 for the CERN LEP machine. [9].

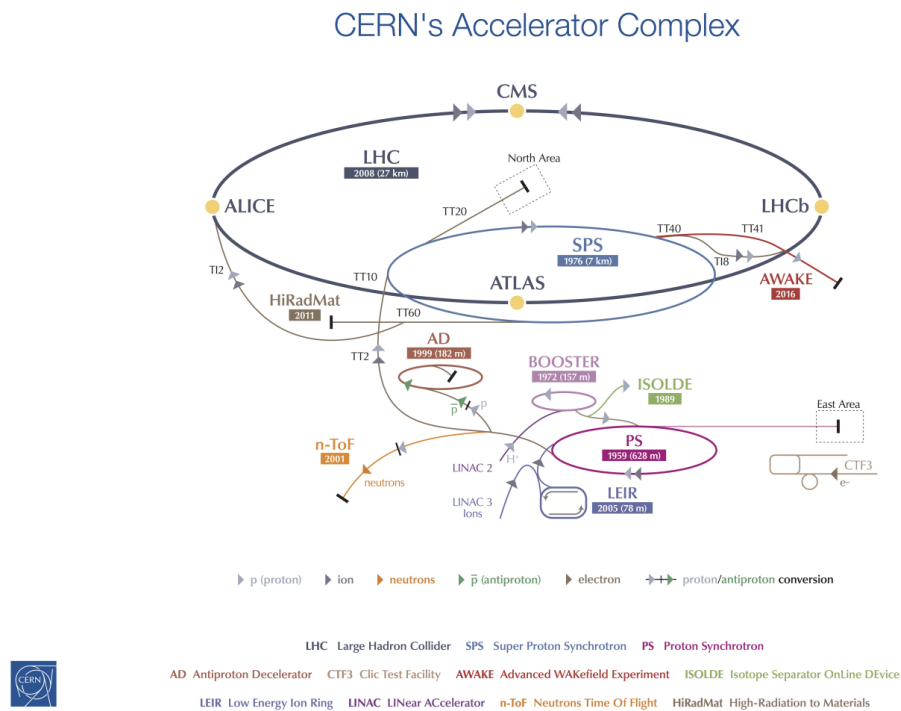


FIGURE 1.1: The CERN Accelerator complex [8]

The LHC is the most powerful particle accelerator ever built and it allows the confinement and acceleration of two proton beams, running in opposite directions. It has been designed to provide enough statistics to fulfil the requirements of the CERN physics program, oriented to studies on the Standard Model as well as to the

search of New Physics.

The particle beams are guided by 1232 superconducting magnets that can produce a maximum magnetic field of about 8.3 T. The electric current necessary to produce and maintain this field is approximately 11.8 kA which sets restrictions on geometry and heat loads. Therefore, the magnetic coils are made of superconducting cables of fine strands of Nb-Ti alloy embedded in a copper matrix. The coils are kept below the critical temperature of the Nb-Ti alloy with superfluid helium below 1.9 K.

The protons are accelerated with radiofrequency (RF) cavities which contain an oscillating electromagnetic field. Sixteen RF cavities (eight per beam) are encapsulated in four cryo-modules that keep the cavities at superconducting temperatures. Each cavity can reach an accelerating voltage of 2 MV, producing 16 MV per beam. The cavities are structured with a particular shape and size so that the electromagnetic waves become resonant and switch the direction with a frequency of 400 MHz. As a result, the oscillating field keeps the beam separated into discrete bunches.

The LHC can nominally provide a center of mass energy of 14 TeV for proton-proton collisions, created by 2808 bunches containing $1.15 \cdot 10^{11}$ particles each, with a bunch time-spacing of 25 ns.

TABLE 1.1: LHC main technical parameters

Parameter	Value
Circumference	26.659 km
Dipole operating temperature	1.9 K
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Peak magnetic dipole field	8.33 T
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/nucleon
Nominal energy, protons collisions	14 TeV
Minimum distance between bunches	$\sim 7m$
Bunch spacing	25 nm
Design luminosity	$10^{34} cm^{-2} s^{-1}$
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	$1.15 \cdot 10^{11}$
Number of turns per second	11 245
Number of collisions per second	1 bilion

The design luminosity ¹ of the collider is of $10^{34} cm^{-2} s^{-1}$. Primary protons are obtained from Helium, and they are accelerated in a first linear collider (Linac), to be then injected in the chain of circular accelerators that allows the achievement of

¹In accelerator physics, the *luminosity* is a measure of the performance of the accelerator and describes how many events N are occurring in a certain time t with an interaction cross-section σ as: $\frac{dN}{dt} = \mathcal{L} \cdot \sigma$. The *integrated luminosity* instead expresses the cumulative luminosity over a given time period and it gives a measure of the total amount of events. The High-Luminosity Large Hadron Collider (HL-LHC) project aims to increase the integrated luminosity by a factor of 10.

their maximum energy. Protons pass through the Proton Synchrotron Booster (PSB), Proton Synchrotron (PS), the Super Proton Synchrotron (SPS) and finally are injected in the LHC (Figure 1.1).

The LHC is also capable of providing heavy ions beams. When not in the pp mode, PbPb and pPb collisions can be supplied, reaching a center of mass energy of 2.76 TeV and 5.02 TeV respectively.

Four experiments were designed and built to completely exploit the physics program for proton collisions. They are located at four interaction points of the LHC, in which the actual collisions happen. Two general-purpose experiments, ATLAS (A Toroidal Lhc ApparatuS) and CMS (Compact Muon Solenoid), were designed to explore all the possible aspects of the LHC physics, from heavy-ions collisions and forward physics, to Higgs boson physics and direct search of new particles. Specially dedicated to heavy-ions physics is the ALICE experiment (A Large Ion Collider Experiment), while the LHCb has the aim to maximize the LHC potential in beauty and charm Physics.

Though the final purpose is specific for each experiment, the requirements on the detectors of which they are composed are quite the same. Their capability of identifying charged particles and measuring particles momentum with high resolution is of fundamental importance. Besides, they all need high granularity, to reduce the influence of overlapping events, and a fast and radiation-tolerant electronics for proper data acquisition.

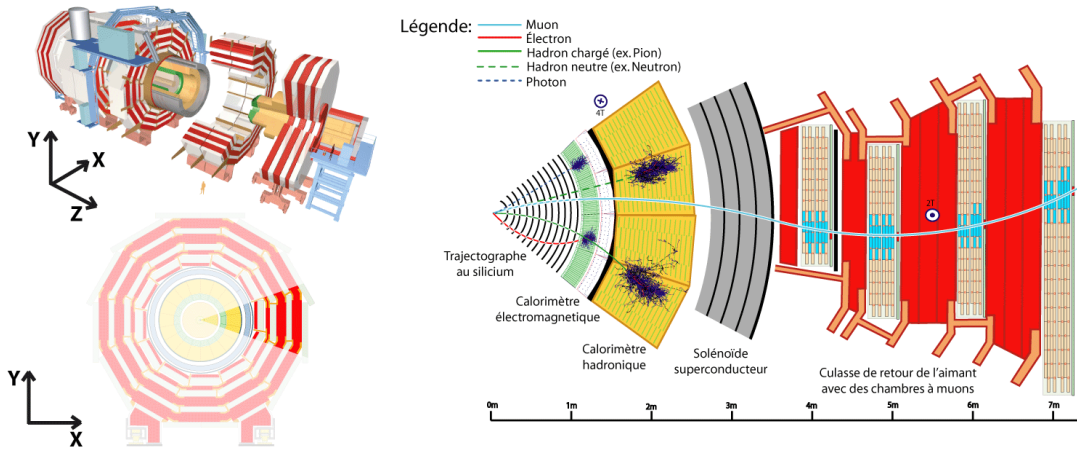


FIGURE 1.2: Slice showing CMS sub-detectors and how particles interact with them [3]

LHC experiments can be described dividing their structure into three different sections (in Figure 1.2 the CMS experiment is reported as an example):

- **Inner Detector:** They are positioned close to the collision points, allowing tracking and momentum measurement of charged particles, as well as vertices reconstruction;
- **Hadronic and Electromagnetic Calorimeters:** They measure the energy of hadrons, photons and electrons, based on the energy loss of emerging particles;

- **Muon Systems:** Since muons escape the electromagnetic calorimeter, a dedicated muon system is used to detect them. Placed at the outermost layers of the experiments, it allows to unambiguously detect the signature of many relevant events.

Although the four experiments have significantly different purposes, they all indeed rely on gaseous detectors for muon detection and tracking as well as for event triggering. The key focus of this thesis will be the gas systems for these gaseous detectors.

1.2 Muon Detection Systems at the LHC experiments

As previously mentioned in Section 1.1, each LHC experiment is equipped with a Muon Detector System. Muon detection is essential for a complete identification and characterization of collisions, since muons represent a very clean probe for many events of interest. In addition, they can provide trigger for event selection. Being rather massive, muons can quite easily penetrate matter and they escape electromagnetic calorimeters. Muon systems are then made of dedicated detectors, capable of identifying and tracking these particles. Each of these detectors operate with a specific mixture of gases. A brief summary of the main Muon System of each LHC experiment is here reported, followed by the description of how their infrastructure is sustained.

LHCb

LHCb is a single-arm spectrometer with the purpose to best exploit the statistics of the b and $\bar{b}$ production, which predominantly happens in the forward or backward region. The muon detection system (Figure 1.6a) is fundamental in the LHCb since muons are present in the final states of many b decays. The system provides fast information for muon trigger at the earliest level of online event selection, as well as muon identification for the high-level trigger and offline analysis. The muon system is here mainly composed of Multi-Wire Proportional Chambers (MWPC), except for the high rate region, where Gas Electron Multipliers (GEM) are used. GEMs are located in the inner region, where the expected particle rate would not be sustained by MWPCs due to ageing safety limits. Lastly, the outermost layer used to host the Outer Tracker (OT), that has been dismounted from the experiment in 2019 to be replaced by the Scintillating Fibre (SciFi) tracker as part of the experiment's major upgrade during Long Shutdown 2 (LS2). Then, Ring Imaging Cherenkov (RICH) detectors are also present.

CMS

The CMS experiment structure is based on a superconducting solenoid, that produces a 3.8 T magnetic field: the tracker, the electromagnetic and hadronic calorimeters are located within the field volume. The iron yoke is equipped with a muon spectrometer for identification, triggering and momentum measurement. The system is divided into five separate wheels in the barrel, with four concentric layers of detectors (Figure 1.3b). Both the positive and negative endcaps are instead instrumented with four independent disks. Different gaseous detector technologies are employed. In the barrel region, Drift Tubes (DT). In Run 3 Gas Electron Multipliers (GEM) will be used as well. Cathode Strip Chambers (CSC), located in the endcap region, allow the handling of higher rates and non-uniform magnetic field. Lastly, Resistive Plate Chambers (RPC) are employed in both the barrel and endcap region.

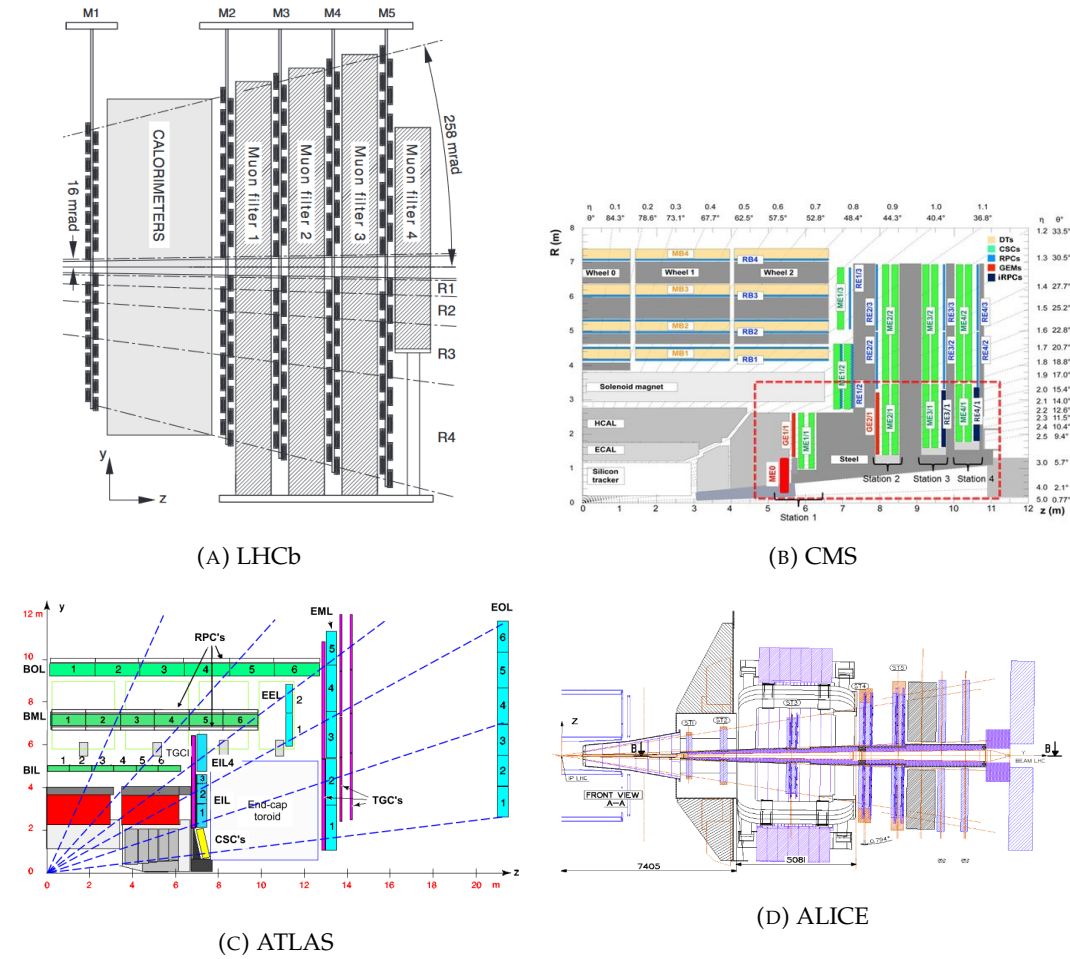


FIGURE 1.3: Muon systems in the four LHC Experiments [9]

In Chapter 4 a more detailed description for the RPC system is given.

ATLAS

The physics program of the ATLAS experiment requires high performance over the large range in transverse momentum. Its muon system includes three large superconducting air-core toroids, precision tracking chambers for accurate momentum resolution, and an effective trigger system. The latter is realized with two different detector technologies: RPCs are used in the barrel, with two layers of chambers installed in the middle station and a third layer on the outer chamber station. The endcap trigger system is instead composed of Thin Gap Chambers (TGC), multi-wire chambers operated in saturated mode. Three multi layers are located in the middle tracking station, while some others are part of the inner station (Figure 1.3c). Some Monitored Drift Tubes (MDT) then sustain high rates without aging with little sensitivity to space charge. Their surface can reach $10m^2$, requesting an extremely accurate mechanical construction to best exploit their tracking accuracy. Moreover, the use of CSCs in the inner station of the endcap allows to have optimal performances regardless the high background rate in this region.

ALICE

As previously mentioned, ALICE experiment is fully dedicated to heavy ion physics. Its muon spectrometer is shown in Figure 1.3d. Its tracking system (MCH, Muon

Chambers) is made of five stations with two detector planes each, consisting of cathode pad chambers. These detectors are multi-wire proportional chambers with a segmented cathode plane. Different pad densities are present, depending on the station position. The system is also capable of high efficient triggering (MTR, Muon Trigger), with four planes of 18 RPCs, operating in streamer mode. They are located at approximately 20 m from the Interaction Point (IP), and deliver online information to the central trigger processor.

1.3 Physics at the LHC

The Standard Model (SM) theory finds its roots in the early Sixties and it describes what matter is made of and how it holds together. In its complete formulation, the SM combines special relativity and quantum mechanics, through a gauge theory based on symmetry groups. It rests on two basic ideas: all matter is made of particles, and these particles interact with each other by exchanging other particles associated with the fundamental forces.

The basic constituents of matter are fermions and the force carriers are bosons (Figure 1.4). The names of these two classes refer to their spin. Fermions have half-integer values of spin whereas bosons have integer values.

Fermions come in two families: they are divided into quarks and leptons, each composed of three different families. The leptons have six members, with the electron being the best known of them. The quarks family contains six quarks. The up and down quarks are found inside protons and neutrons. The twelve fermions are the building blocks of matter and each one has a spin value of $1/2$. For each fermion, a correspondent anti-particle exists, with opposite quantum numbers.

Fermions interact with each other through the exchange of spin-1 particles, the gauge bosons, which are elementary particles themselves. Each of the fundamental interactions is described with a different gauge group and different mediators:

- *Electromagnetic Interaction:* It is described by the Quantum Electro-Dynamics (QED), and it is mediated by the photon, a massless boson. It is associated to a single gauge boson and one quantum number, the electromagnetic charge q ;
- *Weak Interaction:* It is mediated by the massive $W^\pm$ and Z^0 bosons. It involves all the elementary particles and it is the only interaction capable of changing quarks flavour;
- *Strong Interaction:* Mediated by gluons, it is the most intense and it is described with colour symmetry. In Quantum Chromo-Dynamics (QCD) only quarks are involved, since leptons are colourless;

In 1963, the Weak and Electromagnetic Interactions were unified with the ElectroWeak theory.

Nonetheless, all the mediators foreseen by the first ElectroWeak model were massless. Being this far from the already proved physics at the time, in 1964 a new mechanism was developed to introduce in the theory these bosons masses. It was called the Higgs mechanism, and it was worth the Physics Nobel Prize in 2013 for F. Englert and P. Higgs. The theory foresees an extra fundamental particle, the Higgs

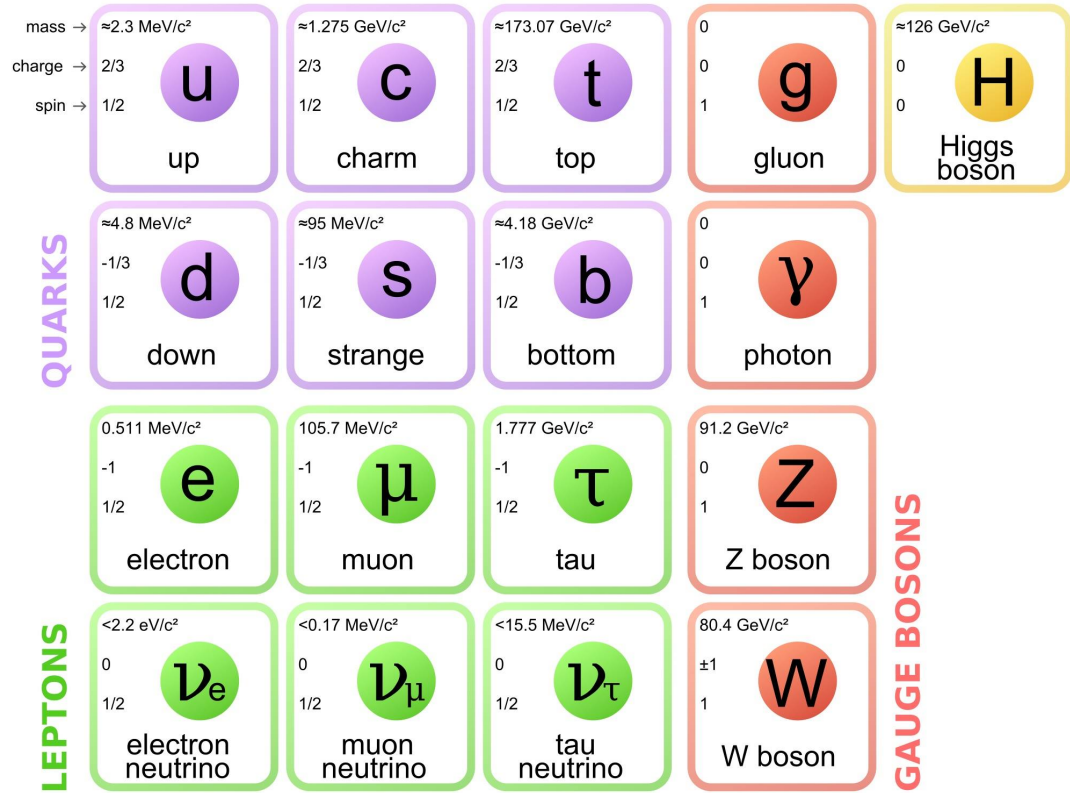


FIGURE 1.4: Standard model of elementary particles: the 12 fundamental fermions and 5 fundamental bosons [21].

boson whose interaction with ordinary particles generates their own masses.

One major problem of the SM is that it does not include gravity, one of the four fundamental forces. The model also fails to explain why gravity is so much weaker than the electromagnetic or nuclear forces.

Last but not least, the SM only describes visible matter, that is all matter we see around us on Earth as well as in stars and galaxies. But proofs abound telling us the Universe contains about five times more “dark matter”, a type of matter completely different from the one we know, than ordinary matter. Dark matter does not emit any light but manifests itself through its gravitational effects. Among all the particles contained in the SM, none has the properties of dark matter. Hence the Standard Model may give an incomplete picture of the content of the Universe, leaving room for new physics theories.

1.4 Gaseous Detectors at the LHC experiments

What is a gaseous particle detector

As charged particles pass through a gaseous medium, one of the primary ways of interaction is direct ionization. This process at the root of gas-filled detectors working principle, together with the phenomenon of gas multiplication [10].

Gas Ionization

When a fast charged particle passes through a gas, it can create ionized molecules along its path. When a neutral molecule is ionized, it results in an ion pair, i.e. a positive ion plus a free electron. Ion pairs work as the basic part of the electrical signal developed in gaseous detectors. The incoming particle must transfer a minimum amount of energy equal to the ionization energy of the gas molecule to enable the ionization process.

Nevertheless, other mechanisms by which the incident particle may loose energy exist. Those lead to the definition of the W -value, the average energy lost by the incident particle per ion pair formed, which is normally greater than the simple ionization energy. The W -value generally depends on the gas involved, the type of radiation and its energy.

Assuming W to be constant for a given type of radiation, the energy deposit will be proportional to the number of ion pairs formed in the gas.

Among the many collision processes that normally take place between free electrons, ions and neutral gas molecules, the most significant ones for gaseous detector operation are charge transfer and recombination. Charge transfer can occur when a positive ion encounters a neutral molecule, that transfers an electron to the ion, inverting the role of each. Free electrons can instead append to a neutral gas molecule during collisions, creating an ion with similar properties to the original positive ones, but with opposite electric charge. Recombination processes happen instead when positive ions collide with free electrons, catching them and returning to a neutral charge state. When the irradiation rate is significantly high, many tracks are formed in a short time, and ions and electrons from independent tracks can collide and recombine.

The influence of both phenomena can be significantly mitigated by the application of an external electric field, used to help charge mobility and subsequent collection. Electrostatic forces tend to push the charges away from their origin point, in a motion that consists in the superposition of random thermal velocity with drift velocity in a given direction.

Gas Multiplication

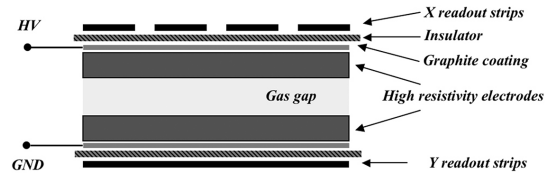
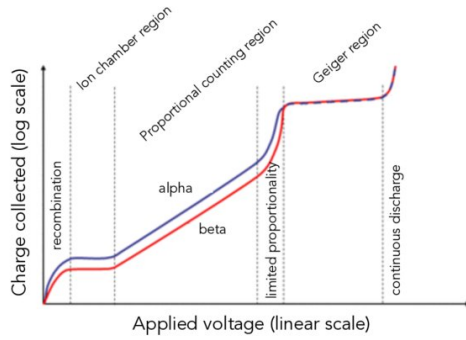
When a low electric field is applied in a gas volume, electrons and ions created by incident radiation simply drift to their collecting electrodes. Nonetheless, when the field is properly increased, gas multiplication process becomes of notable influence.

Free electrons are easily accelerated by the applied field, gaining kinetic energy. When this energy is greater than the ionization energy of the gas molecules, secondary ionization can occur in the collision between the free electron and neutral gas molecules, producing an additional ion pair.

The electron from secondary ionization will, in turn, be accelerated by the field, undergoing collisions during its subsequent drift and thus creating additional ionization. The gas multiplication process takes the form of a cascade, the so-called Townsend avalanche. Each free electron created can potentially create more free electrons².

Under proper conditions, the amount of secondary ionization events can be kept proportional to the number of primary ion pairs formed, but the total number of ions

²Assuming a uniform field, the electron density for increasing distance, as the avalanche progresses, shows exponential growth



(B) A Resistive Plate Chamber (RPC) detector. [14]

(A) Different regions of operation of gaseous detectors, given by the plot of observed pulse amplitude as a function of the applied voltage. [20]

FIGURE 1.5: Gaseous particle detectors

can be multiplied by a factor of many thousands³. Since the charge amplification occurs within the detector itself, the signal-to-noise ratio is significantly improved and the demand for external amplifiers is reduced. As shown in Figure 1.5a, it exists a region of the applied voltage, hence of the electric field inside the gas volume, for which the collected charge begins to multiply, and the observed pulse amplitude increases (Proportional Region). Over most of this region, the gas multiplication is linear, and the collected charge is then proportional to the number of original ion pairs created by the incident radiation. This region of true proportionality represents the usual operation mode of gas-filled proportional counters. If the applied voltage is further increased, non-linear effects occur, slipping in a limited-proportionality region.

Fill Gases

The most widely used gas to fill gaseous detectors is Argon, due to the optimal combination of its properties with a generally limited cost. It has, in fact, a very low electron attachment coefficient, that ensures most of the free electrons to reach the multiplication region without interference. It should, however, be taken into account that, besides simple ionization, the collision between electrons and neutral gas molecules may give rise to excitation, without the creation of a secondary electron.

The excited molecules decay to their ground state, through the emission of a visible or ultraviolet photon, that may create additional ionization elsewhere in the gas. These events are normally undesirable, since they may provoke a loss of proportionality or the presence of spurious pulses. Furthermore, they cause the avalanche to spread.

It has been found that the addition of a certain quantity of polyatomic gas, such as Carbon Dioxide (CO_2) or $i\text{C}_4\text{H}_{10}$, can suppress the photon-induced effects by absorbing the photons in a way that does not lead to further ionization. The polyatomic component is then usually present in some percentage, together with the monatomic one, as a stabilizing additive. Another crucial point is to maintain the purity of the chosen gas, that can be obtained with a continuous flow through the chamber. It can be a once-through type, in which the gas simply exhausted to atmosphere, or a re-circulation type, with the purification of the gas before re-injection. Traces of oxygen

³the gas gain factor is usually around 10^5

or other impurities must be removed, since they can cause significant losses of free electron.

1.5 Gas Systems for gaseous Detectors

Regardless of the location and scope of each gas detector inside LHC experiments, the most critical of the infrastructures is their gas distribution system. Indeed, the gas mixture is a fundamental parameter for detector operation and safety both for short and long term periods. A total of 30 dedicated gas systems deliver the proper gas mixture to corresponding detectors. Their extension can reach several hundreds of meters and they are subject to severe requirements on design and components quality to guarantee good and safe long-term detector operation. High reliability is needed in terms of stability and quality of the gas mixture, since it is the very primary element influencing detector performance.



FIGURE 1.6: ALICE WinCC-OA overview

The LHC gas system has been implemented following a modular design, so that it can be adapted to each gaseous detector requirements, but still remaining based on a common structure. The function-oriented design allows an effective construction, as well as a simpler maintenance and intervention in case of any failure. Each module is also associated with a Programmable Logic Controller (PLC), an industrial PC with basic functionalities for managing and monitoring the unit (Figure 1.6).

As it will be further discussed in this work, another key element of Gas Systems is the possibility to recirculate and re-use the gas exiting from the detectors. The gas mixture can, in fact, be collected after being used, and re-injected into the supply

lines. In this way, only a small percentage of gas (0% - 10%) is sent to the exhaust line, while the most fraction can be re-injected in the system after purification. The fraction sent to the exhaust is automatically replaced with fresh gas mixture. In this process it is fundamental to control and regulate pressures and flow rates to avoid that a wrong working point of the system could affect detector performances and even cause damages to the chambers.

In chapter 2 all the components of gas systems will be described in detail.

Chapter 2

The LHC Gas Systems for particle detectors

2.1 Introduction

As previously mentioned in section 1.4, the basic duty of a gas system is to provide a correct and stable gas mixture to the individual chambers of the different muon systems. Over the four experiments (ALICE, ATLAS, CMS, LHCb) taking data at the CERN Large Hadron Collider (LHC) more than 30 gas systems (corresponding to about 300 gas racks) are delivering the proper gas mixture to the corresponding detectors. Besides, also some non-LHC experiments have gaseous particle detectors, so they necessitate a corresponding gas system.

The gas mixture is the sensitive medium where the charge multiplication is producing the signal. Therefore, a correct and stable mixture composition is a fundamental requirement for good and stable long-term operation of all detectors.

Gas systems construction started at the beginning of the years 2000. The first systems were put in operation between 2005 and 2006. The gas systems for the LHC experiments are the result of a collaborative effort between the CERN Gas Service Team (nowadays part of CERN/EP-DT-FS) and the CERN/EN department (nowadays CERN/BE). The CERN Gas Service Team was responsible for designing, building and operating the gas systems, while CERN/EN for the development of the software controls (following the requirements provided by the CERN Gas Service Team) and the primary gas supply (PGS) procurement [15] [18].

2.2 The LHC gas systems

The LHC gas systems extend from the surface building where the primary gas supply point is located to the service balcony on the experiment following a path few hundred meters long.

The primary gas supply point is located in the surface building (SG). Nevertheless, a typical gas system is distributed over three levels (Fig. 2.1 and 2.2 show the typical layout of a closed-loop gas system): the surface gas room (SG), the underground service room (USC) and the experimental cavern (UXC). The final gas distribution system to the detectors is located in UXC, where also the experiment is installed.

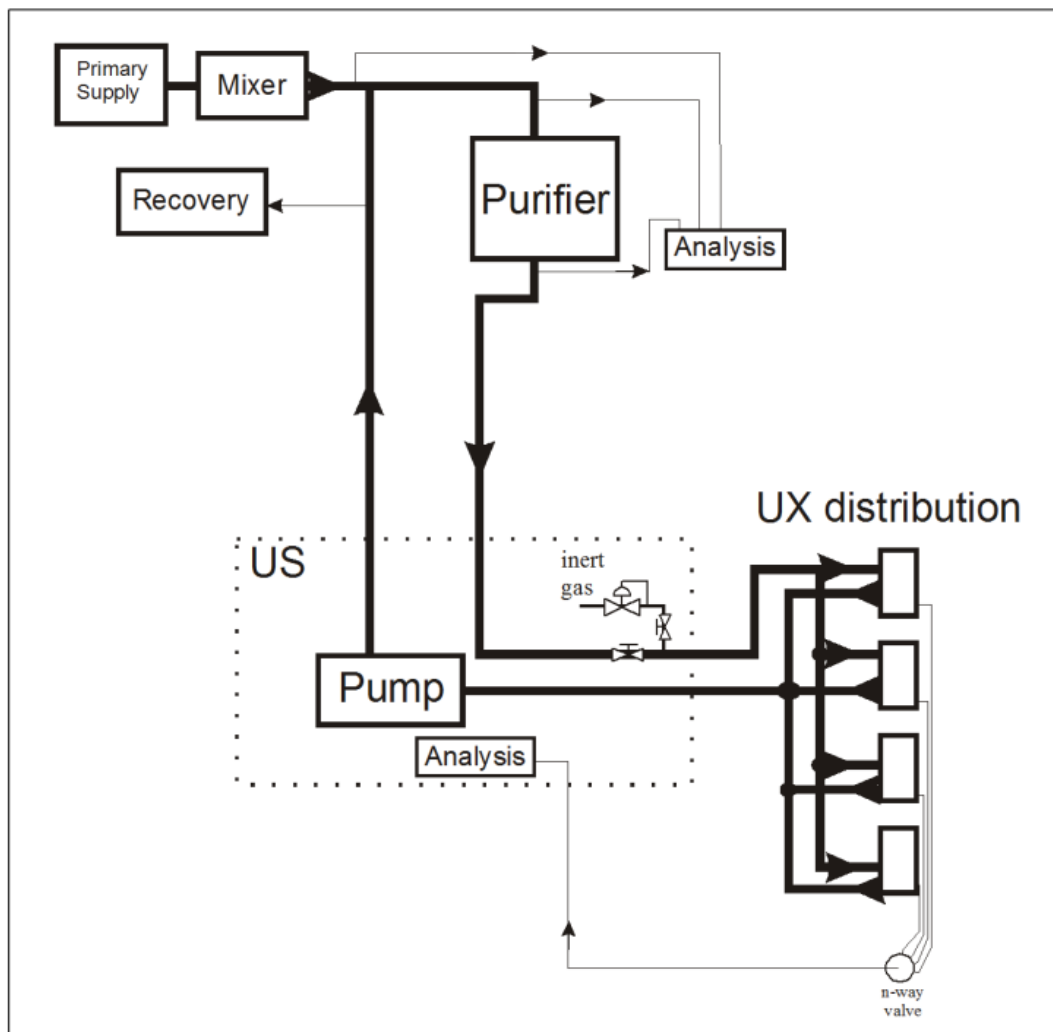


FIGURE 2.1: Typical layout of a closed-loop gas system (1) [2].

Given the large detector volume and the use of relatively expensive gas components, for technical and economical reason many systems are operated in closed-loop gas circulation with a recirculation fraction higher than 90-95%.

The operation of all gas systems is continuously followed by the CERN Gas Service Team which is also responsible for maintenance, consolidation and upgrades. Alarms potentially triggered during operation are propagated via email and SMS to the CERN Gas Service Team as well as to the detector teams. A 7/7 24h service (Piquet) is available for intervention outside working hours.

2.3 Gas Control System

The Gas Control System (GCS) provides end-user applications for the control of the whole of the gas distribution chains (mixing, distribution, pump, exhaust, analysis, purification, recuperation) as they have been defined by Gas Team for the LHC

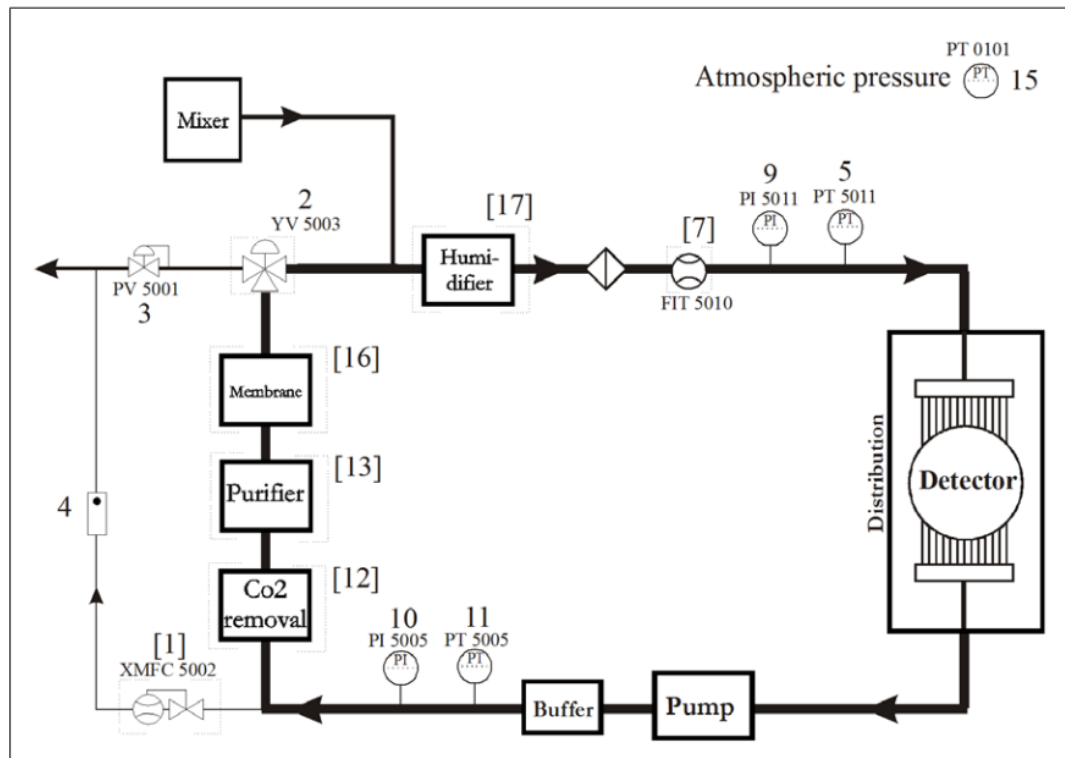


FIGURE 2.2: Typical layout of a closed-loop gas system (2) [2]

experiments. It covers the software aspects of the control system and suggests hardware choices for the interfaces to the gas system hardware. As software for the Supervisory Control And Data Acquisition (SCADA), SIMATIC WinCC Open Architecture (WinCC-OA) by SIEMENS is available.

In Fig. 2.3, the typical Human Machine Interface (HMI) of the software is shown.

The Gas system control has two specific tasks:

1. The sub-detectors GCS process control:
For each gas system, an independent GCS process control is available. It consists in PLC dedicated to this gas system only and the software implementing the process control aspects.
2. The detectors gas plant supervision:
A supervision application is available for each of the LHC experiments, the four supervision applications are completely independent. This consists in standard supervision facilities (e.g. synoptic views, alarms and log panels) for all the experiment gas systems and for the gas plant infrastructure (e.g. monitoring of common devices if any, monitoring of the control infrastructure, global alarm panel, etc.).

The control systems:

- handle all basic I/O functions to interface and interact with the gas systems hardware components (e.g. valves, pumps, measuring devices, etc). This involves digital input and output (e.g. to read valve positions, equipment status, to switch valves, to stop or start equipment) and analog input and output (e.g. to read flows or pressures, to write set-points). It might also involve handling of special hardware interfaces or other I/O as field-busses or RS232 etc.



FIGURE 2.3: Example of WinCC-OA interface for the control and monitoring of a gas system

- implement discrete proportional-integral-derivative (PID) control to interface with the process plant, handling low level control such as control loops or feedback loops, integrators, differentiators. These can be implemented as a hardware module (analog) or can be implemented in software (digital).
- are able to log events (e.g. detection of anomalies and alarm conditions, change of state of a module, reception of external commands, automatic actions taken), and to archive data. Tools are provided to analyse a sequence of events (e.g. incidents) or, ideally, play back a sequence of events and to analyse archived data (analyse trends, correlations etc.).
- provide a user friendly view of the state (including the values of various parameters) of the gas systems. These views are graphics, synoptic, tables etc. They comprehensively represent the information.
- provide the operators with a way to interact (e.g. starting and stopping of equipment, modifying set points) with the gas systems to several levels (e.g. stop all the gas, start the gas for one sub-detector, stop one module in the system, switch a group of valves, switch one valve). The access to the more detailed actions is controlled and restricted to experts.
- provide facilities to consult the state of the gas systems and their modules from a place which can be far away from the experiments control room (e.g. control rooms, an office at CERN or at home for on call experts only). It is possible to use these remote access facilities through LAN, WAN or telephone network. Access is provided to the actual status of the systems and to logged

and archived information. Experts are also able to issue commands under very strictly controlled access.

- have to cope with evolution of hardware and software as well as human resources on a long time scale. It has therefore to adapt to the technical evolution over such a lapse of time.
- are able to follow the evolution of the gas systems when the latter evolves with the experiment (e.g. modification of existing sub-detectors, introduction of new sub-detectors).
- are also able to handle the evolution of gas system modules, new options might be added to existing modules (e.g. introduction of a new monitoring device, extra valves etc.).

The gas systems (and their control systems) have to be 100% operational and available during data taking periods. During the shutdown periods however, the gas systems is only operational at a low level ¹ from a few weeks after the detector operation period, until a few weeks before the next detector operation period. During this period there is a very limited operator surveillance of the system. The GCS is operational also when data acquisition and detector control are not operational.

Standard symbols (e.g. for valves, pumps, etc.) and colours are used in the GUI for the HMI.

The control system is able to run in a modular mode; that is, it can allow to operate only one (or a few) module in a gas circuit, while other modules are switched off and bypassed. This is, for instance, a possible mode of operation during shutdown periods. The normal mode of operation is an integrated mode where the whole gas system is operational. In both cases, the control system is able to operate the gas systems in an autonomous way, that is, it is able to protect itself on the module level even with a minimum of services available. In general, as long as the gas and the 220V are available the control system is able to run.

Parts of the gas systems, in particular parts of the distribution modules, are installed in the experiments caverns. The control equipment has therefore to operate in magnetic field and in radiation environment.

The detailed operations of all the gas system designed by the Gas Team are operated by this single team. The staff of this team can easily move from one gas system to another.

The main users of the control system are:

1. EP-DT-FS Gas gas experts:

They use all of the functionality of the software. They generally have a good knowledge of the whole gas system. Most of these users use the software frequently. Since the experts (a group of 5-10 people) have responsibilities in all four LHC experiments, remote access for this group is indispensable.

¹except from some systems whose detector always needs to be flushed

2. Maintenance Crew:
These persons work under the supervision of the EP-DT-FS Gas experts, they interact with GCS when they will have to replace faulty devices.
3. Gas Piquet:
These persons are on call, they are not as knowledgeable as the EP-DT-FS Gas Expert, but they are able to diagnose the gas systems
4. Sub-Detector Gas Experts:
(i.e. physicists responsible for the definition of the requirements related to their gas system) usually only use part of the software functionality and only those parts relevant to their sub-detector. They only have macroscopic knowledge of the whole gas plant although they will have a more detailed knowledge of the systems relevant for their sub-detector.

The detailed description of the GCS functionalities is described in [2].

2.4 Typical functional modules

A typical LHC experiment gas system consists of several, relatively independent and geographically dislocated modules, individually or synchronously controlled. The main modules usually are:

- Mixer Module
- Distribution Modules
- Pump Module
- Purifier Module
- Exhaust Module
- Gas Analysis Module

Depending on the system requirements, some other modules might be present, as, for example, Humidifier modules and Gas Recuperation Systems.

In the designing phase, an effort has been made in trying to standardize as many modules as possible in these systems, allowing minimization of manpower and costs for maintenance and operation. Some modules, however, need to meet special requirements (high pressure, big volume, etc.), so these ones would be unique.

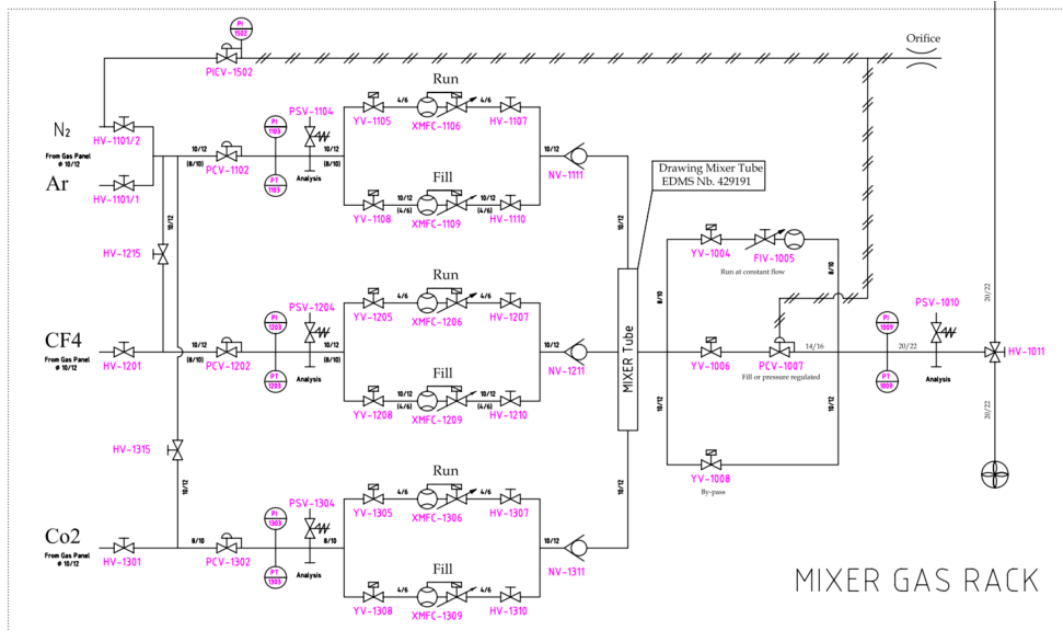
In the following sub-sections the functionalities of each module is briefly discussed.

2.4.1 Mixer Module

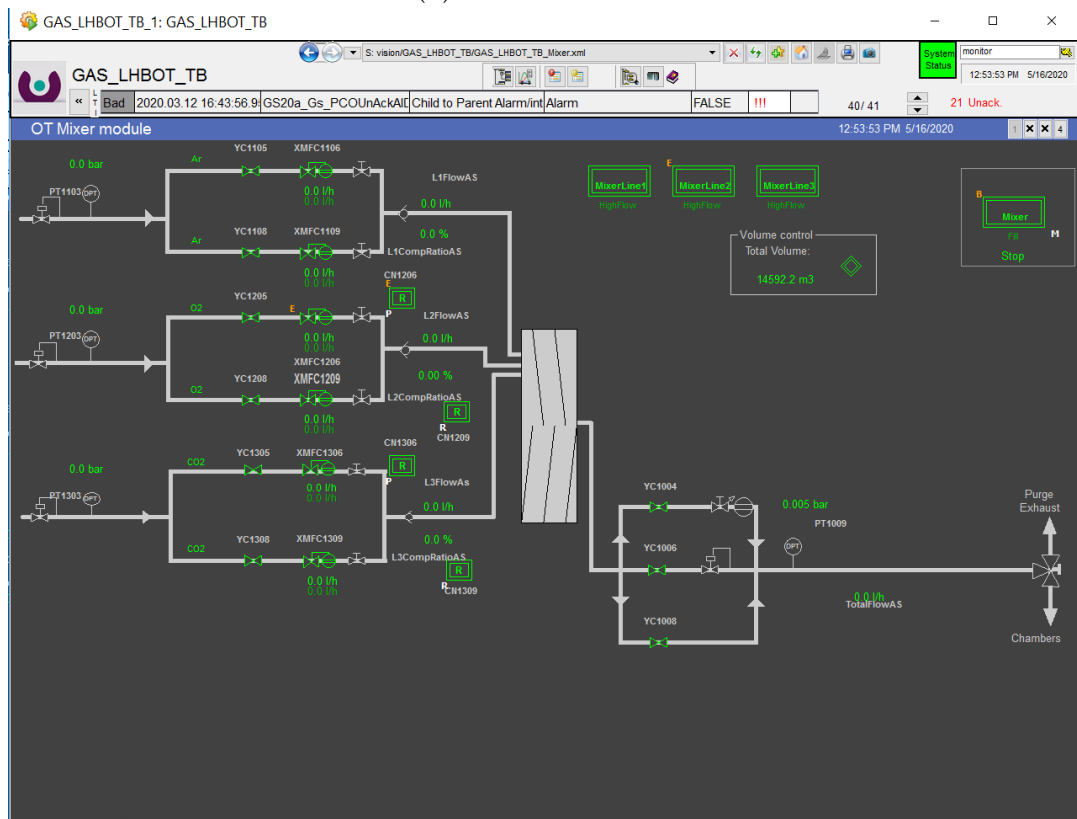
The primary task of a mixer is to provide the gas system and ultimately the detectors with the suitable gas mixture during the Run Phase.

A standard Mixer module can have up to 4 input lines. Each line can be used for gas or liquid.

All the mixer modules are located in a surface building (SG), separated from the electronics and computer for safety reasons. The mixing module can go from a running mode to the stop mode by closing electro-valves on the input of all primary



(A) Mixer module P&ID



(B) Mixer module WinCC-OA overview

FIGURE 2.4: Mixer module

gases into the mixer.

The gas mixture is transported down to the detector in a single (optionally heated) pipe. The flow is dependent on the demand of the modules downstream, the mixer module will try to adjust the flow such that a constant pressure is maintained.

Indeed, the mixture injection into the main gas system's circuit is regulated according to the detector needs: the flow is automatically tuned to guarantee the required replacement rate, to cope with detector's leak or gas recuperation efficiency, or to compensate for atmospheric pressure changes (in fact, large fraction of detectors are operated at constant relative pressure, therefore, the quantity of gas stored in the detector volume follows the atmospheric pressure changes). All values (pressures, flows, mixing ratios, etc...) are monitored. They are also used to generate alarms or interlocks to the gas systems as described in the functional analysis requirements and according to the specific detector needs. Amongst parameters to be monitored are flow rates, presence of the primary gases and maybe independent devices (e.g. Infra-Red monitor, gas chromatograph) to monitor gas composition. Results of these measurements can be used as feedback to correct the actual mixture.

During particular phases, it might also be needed to supply different gases (for example for purging the detector when the standard gas mixture needs to be evacuated, like at the beginning of a long shutdown period, or standard mixture at very high flow (for example when the detector is going to be restarted after a long shutdown, filling mode). Although rarely applied (only a few times per year) it facilitates the maintenance of the gas systems).

The GCS has to perform all necessary processing of control parameters, stabilize the gas mixture and report warnings and alarms. Also, alarm actions must assure that the sub-detector is never supplied with a wrong gas mixture.

For each primary input gas, the following equipment is present (see fig. 2.4): a pressure reducer (PCV-1X02) adjusts the pressure to a suitable level for the mass flow controllers (MFC) to work properly (typically around 2 bar). With a pressure transducer (PT-1X03) the availability of gas can be monitored.

Since the flow requirement of some detectors for "Run"² and "Fill"³ mode are very different, two sets of mass flow controllers with different ranges are present. A pair of selection valves, YV-1X05 and YV-1X08, selects either of these two controllers, XMFC-1X06 or XMFC-1X09, to use. The mass flow controllers, from Bronkhorst, make use of thermal technology [12] and they need to be calibrated for the specific gas on each line. They use digital technology for the gas hardware and a fieldbus-ready interface (Profibus) to communicate with a PLC. A static volume with some baffle-plates inside (Mixer Tube) mixes the primary gases to the final mixture. It mixes the gases turbulently with a passive process (there is no moving element involved in the actual mixing of the gases).

In "Run" mode, the gas is supplied to the sub-detector via valve (YV-1004) and a manual constant flow adjuster (i.e. rotameter FIV-1005). However, in certain conditions like after a storm when the atmospheric pressure can be rising very fast, this constant flow might not be enough to meet the demands of the detector. For this case, additional gas can be injected via YV-1006 and a pressure regulator (PCV-1007). The latter one has a rather low pressure setting and comes into action only if the chamber pressure is below that value, signalling that more gas is needed. In "Fill" and "Purge"⁴ modes, the gas will be provided only via YV-1006 and PCV-1007 since these modes require rather large flow rates. With the bypass valve (YV-1008),

²The purpose the "Run" mode is to provide the detector with a suitable gas mixture during nominal and regime conditions.

³The purpose of the "Fill" state is to fill the detector with process gas (e.g. at start, after a shutdown period). The total flow is usually larger than in Run.

⁴The purpose of the "Purge" state is to replace the gas mixture in the detector by some purge gas.

a gas expert can supply the detector without any restriction, which is typically necessary in “Direct Mode⁵”, where the gas mixture results from the bare setpoints of the mass flow controllers and not from an active control feedback of the GCS (as in “Run” and “Fill” modes).

With a three-way valve (HV-1011) the gas flow can either be sent to the system or vented to exhaust.

2.4.2 Pre-Distribution and Distribution Modules

The gas is delivered from SG to a PreDistribution modules (see Fig. 2.5a) in USC. From there, there is a first splitting into different lines which go to different zones in the experimental cavern (UXC), where the actual Distribution modules are located.

A Distribution module is composed of distribution racks (from 1 to about 26), which can be physically assembled in groups of racks (Fig. 2.6). From each distribution module the gas is divided into as many channels (Fig. 2.7 and 2.8) as the number of the chambers to supply and sent to the different detectors. Then some return pipes transport the gas to the Distribution module and further up to the Pre-Distribution Output module in USC (Fig. 2.5b).

So, per sub-detector there is one distribution module consisting of at least one distribution rack (the actual number depends on the topology of the sub-detector and the layout of the cavern). The distribution racks are located in the experimental cavern, which is not accessible during LHC Run periods due to radiation levels.

In order to keep the sub-detector chamber pressure constant, pressure regulation is typically done by regulation valves installed in the Pre-Distribution Output module USC using the pressure chamber. These regulation valves will be in detail investigated for the CMS RPC system in Chapter 4. Further downstream, all output lines from the distribution racks are collected into one line leaving the underground experimental cavern.

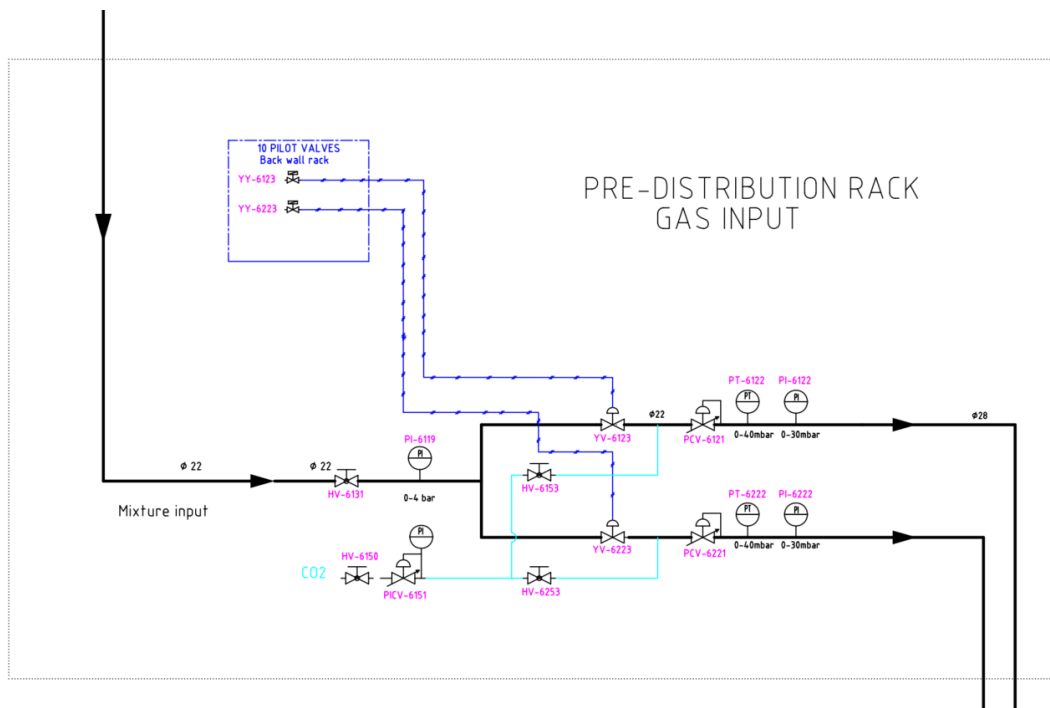
For all channels, where it is technically and economically possible, the gas flows to and from the sub-detector elements are measured by some custom-made flow-cells in order to be able to spot gas leaks. The granularity of these flow measurements depends on the topology of the piping. In addition, each output channel can be connected to an analysis chain to measure gas quality, if requested.

Part of the actual hardware (valves) can be located in the experiment thus difficult or not at all accessible. The gas-output of the distribution module (all distribution racks as a whole) can for some gas systems be vented or, for systems using expensive gases, re-circulated. In the latter case the gas has to be properly cleaned by purification modules before sending it back into the sub-detector elements.

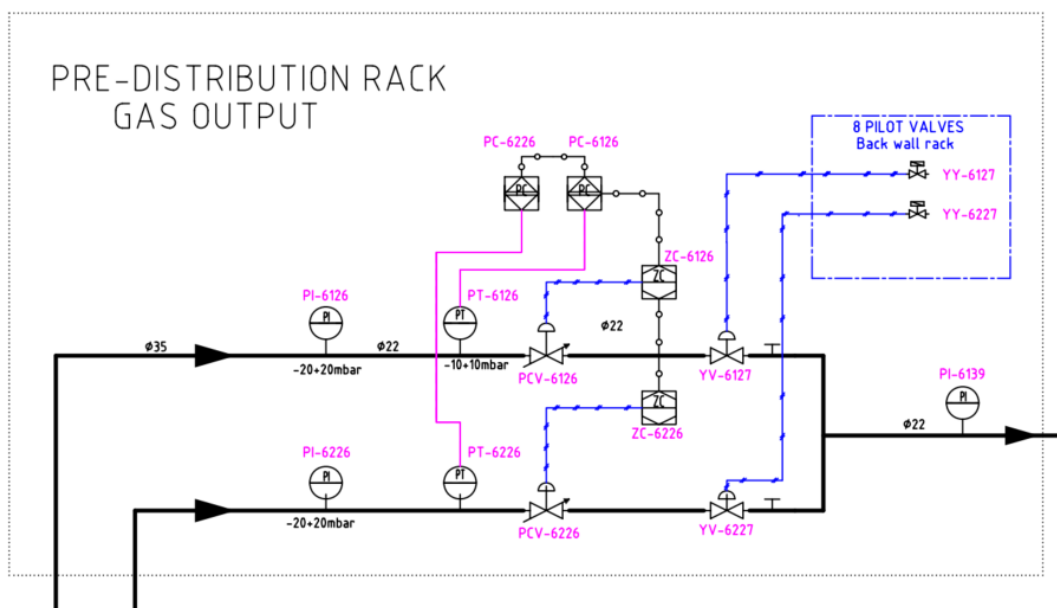
2.4.3 Pump Module

A recirculation pump is needed to pump the gas up from the UXC to USC and then, especially, from USC to the surface. Usually, more pumps are installed in parallel to make the system redundant and more reliable. So, in case of failure or maintenance requirement of the working pump, it is possible to switch to another one and let the

⁵“Direct” mode delivers gases in a ratio which is not controlled. The flows of the individual gases are set to a constant value.



(A) Pre-Distribution Input module P&ID



(B) Pre-Distribution Output module P&ID

FIGURE 2.5: Pre-Distribution module

system be able to keep on running without need to stop nor to vent the gas. When several (up to four) pump devices are fitted in the module, they have all the same characteristic: type, model, operation range, number of temperature sensors, pressure transmitter, etc... Different parameters are monitored by the GCS (Fig. 2.10) in order to supervise and eventually perform maintenance (e.g. running hours of the pumps, pump heads temperatures, etc..).

The pump itself is not enough for stable and reliable operation since pressure

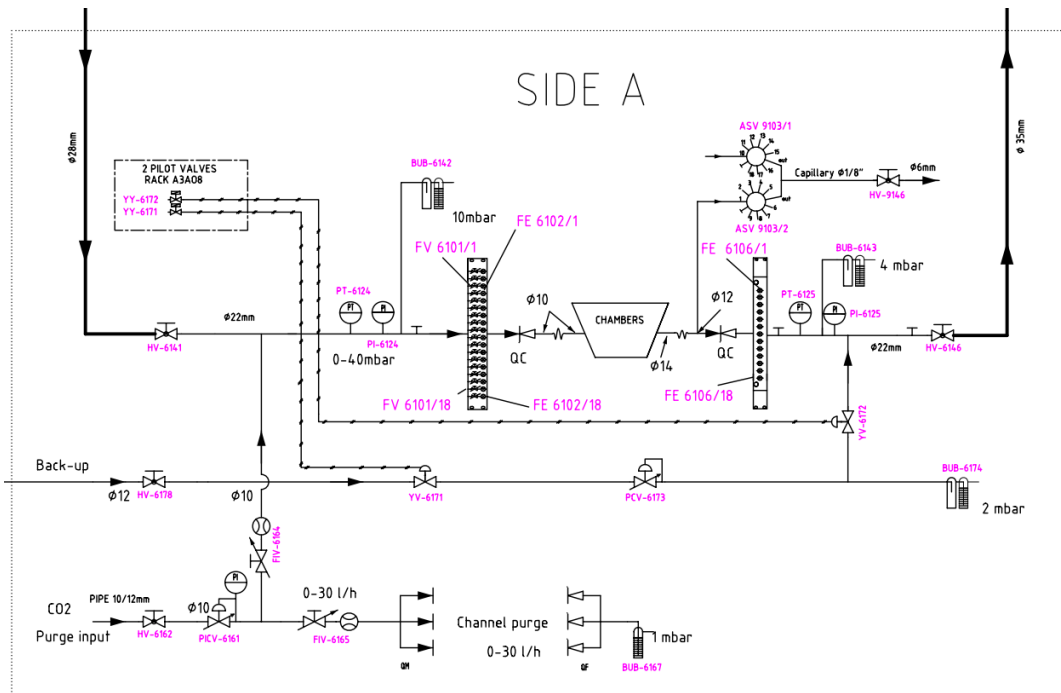


FIGURE 2.6: Distribution module P&ID

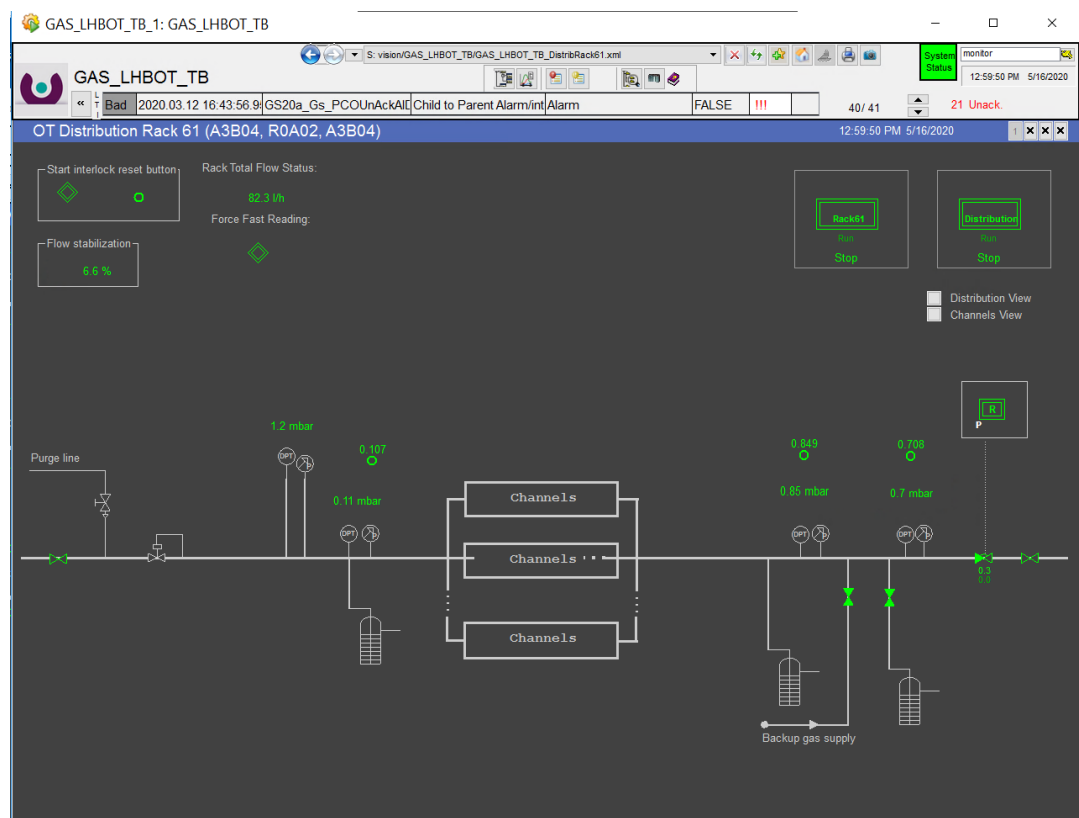


FIGURE 2.7: Distribution rack WinCC-OA view

fluctuations can be produced by changes in the atmospheric pressure and/or ambient temperature. Moreover, not all pumps have the possibility to modulate the frequency so to adapt the pump flow. To solve this issue, a by-pass loop has been

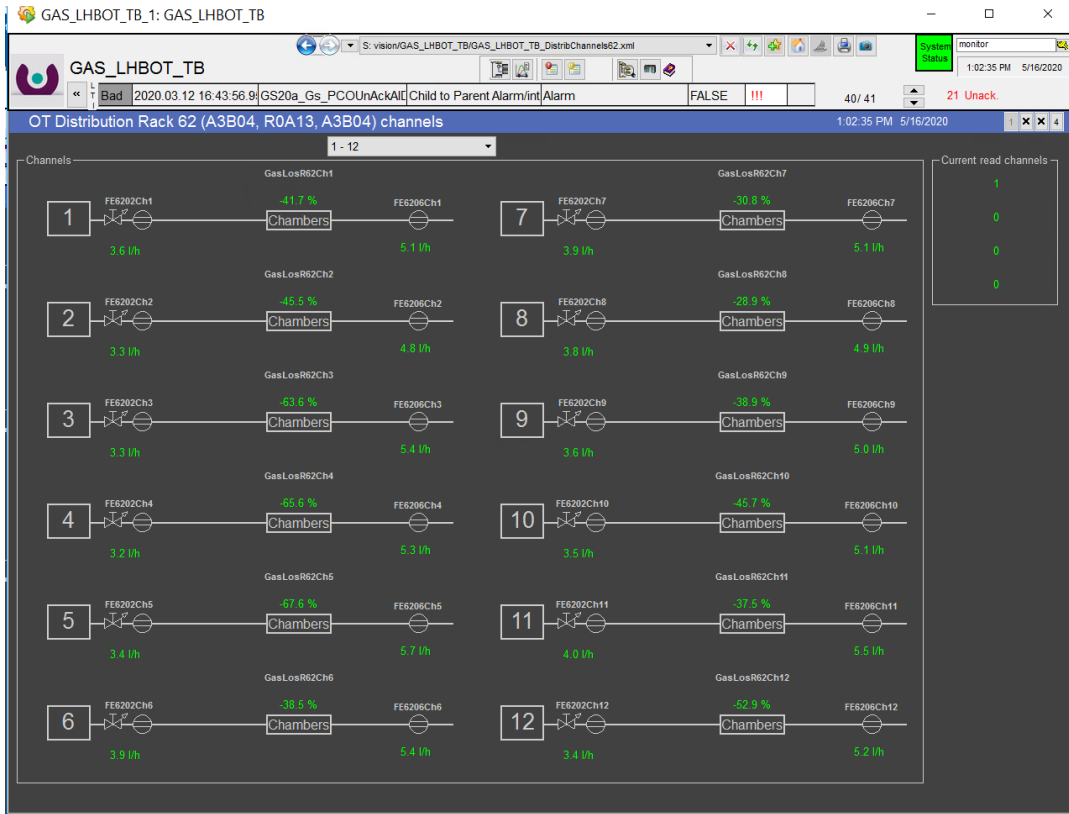


FIGURE 2.8: WinCC-OA distribution channels view

added across the pump and equipped with a mechanical forward pressure regulator (in Fig. 2.9, PCV-4018) and a regulation valve (HV-4030). The pressure regulator keeps constant the input pressure to the pump by regulating the flow in the by-pass loop. In case the detectors connected to the system require a flow much lower than the pump capacity (so that a higher by-pass flow is needed), the regulation valve is used for a first order regulation while PCV-4018 continues to do the fine pressure adjustment [16].

A buffer is also present as storage and to damp for pressure oscillations.

2.4.4 Purifier Module

As already mentioned, most of the gas systems are operated in gas re-circulation mode in order to contain the operational costs and to reduce the emission of potentially harmful gases (like greenhouse gases). However, during gas re-circulation, several impurities start to accumulate into the gas flow. Common impurities that can accumulate are O_2 , N_2 and H_2O . Other impurities might come from the breaking of the main gas mixture components under the combined action of electric field, charge multiplication and high radiation background. A certain number of sub-detectors will then require gas purification in order to prevent deterioration of gas quality. The purifier modules will be located at the surface.

Fig. 2.11 shows the P&ID of the purifier module. The module contains two 24 liters cartridges which can be filled with the suitable purifier agent: in general,

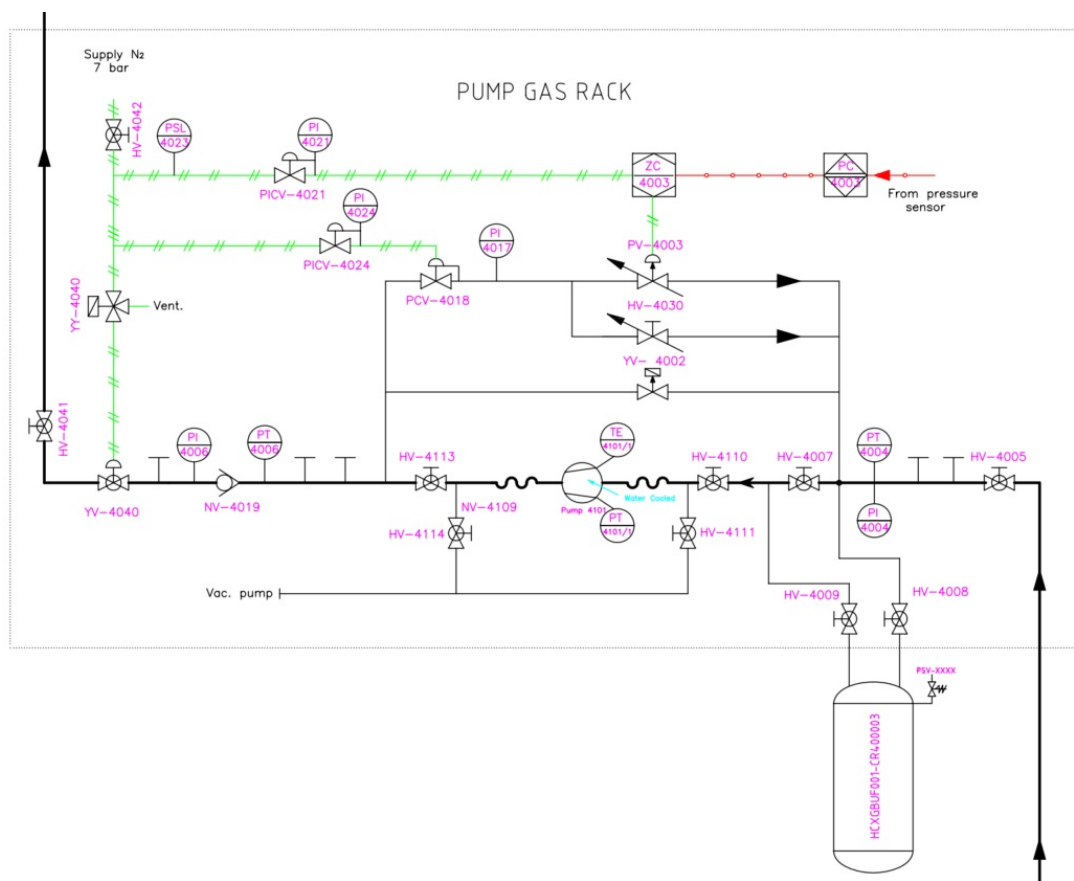


FIGURE 2.9: Pump module P&ID

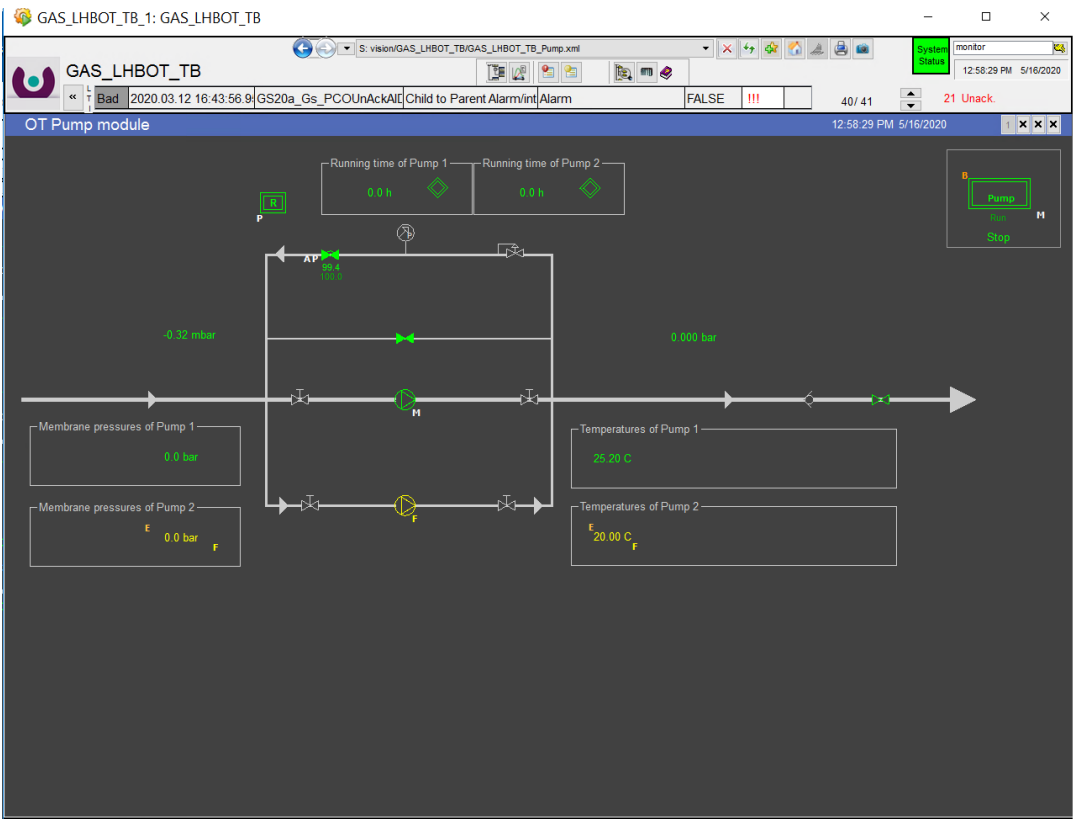
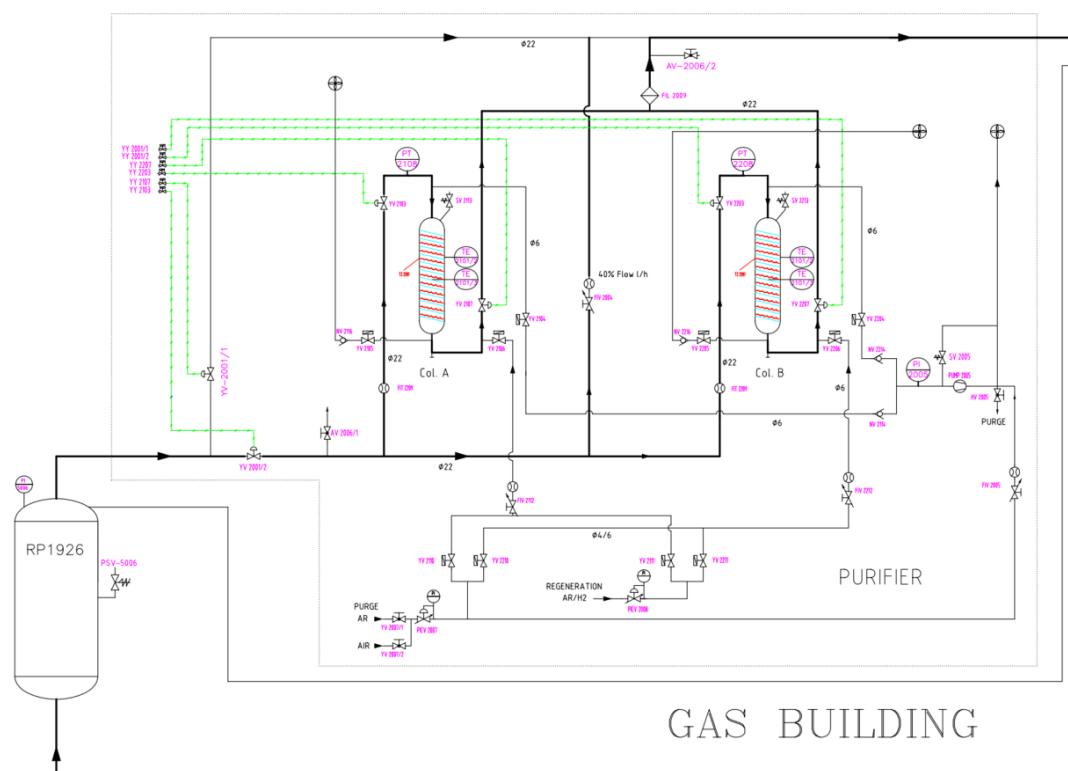
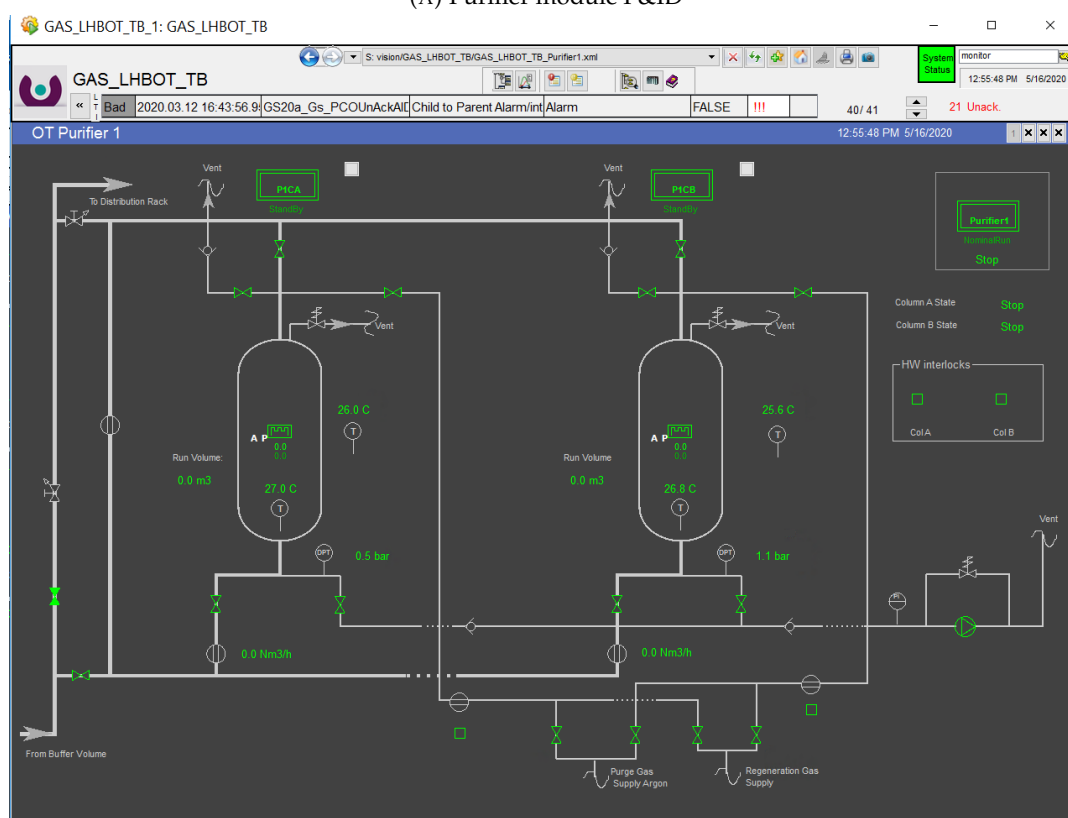


FIGURE 2.10: Pump module WinCC-OA overview



(A) Purifier module P&ID



(B) Purifier WinCC-OA overview

FIGURE 2.11: Purifier module

molecular sieves are used for water removal, metallic catalysts for oxygen absorption or other specific materials. During normal operation the gas mixture is passing through one column, while the other is in regeneration or it has just completed the regeneration cycle and it is ready to be used.

After saturation, these reagents will have to be regenerated in a process using a regeneration gas and high temperatures. "Regeneration" handles the removing of the trapped impurities in the purifying agents. The column has to be heated to accelerate the process. The column is heated up with purge gas circulating in order to prepare the column for regeneration. The temperature will be regulated around a pre-defined setpoint. Regeneration gas is flushed and vented or a pump is used to extract impurities (CO_2 and H_2O vapour). It takes about 4 hours to remove the impurities.

In general, during regeneration process some side reactions can occur, according to the kind of purifier material: for example, molecular sieves tend to absorb certain gases (e.g. CO_2 producing a fast decrease of the pressure, whereas metallic catalysts like copper can provoke an exothermic reaction with Ar that makes the temperature (and then pressure) increase.

The process control monitor pressures, flows, temperatures and gas quality before and after the module as well as to control a set of electro-valves. Automatic procedures monitor and supervise several sequences necessary for the module.

2.4.5 Exhaust Module

The function of the exhaust module is obvious for open systems, while for recirculated ones it allows to adjust the percentages of fresh gas provided from the mixer in the loop and the vented gas, exhausting to the atmosphere the gas in surplus inside the system. See in Fig. 2.12 and 2.13.

The quantity of exhausted gas is controlled by a MFC (XMFC-5002) with PID pressure regulation, allowing the exhaust pressure regulation and recording the exhausted gas flow. Sampling points for gas analysis are usually present. The position of the valve YV-5003 determines the behaviour of the system, if in loop or open mode (all the gas is exhausted). The fresh mixture from Mixer module joins the recirculated one from Purifier module in the Exhaust rack from valve HV-5014. Normally, a filter (FIL-5030) and a loop flow meter (FIT-5010) are also present.

2.4.6 Gas Analysis Module

Gas analysis modules consist of devices used to analyse and continuously monitor with automated cycles the gas mixture composition coming from the gas system.

There are two main types of modules: the first (type A) makes use of standard electro-valves for the selection of the gas stream, while the second (type B) uses special pneumatic n-ways valves. A n-way valve can have either 6, 10 or 16 inputs pipes, it has one output pipe. The sample chains may be organised in several physical location. The operation of the sample chains are completely independent. Figg. 2.14, 2.15, 2.16 and 2.17 show typical schemes of a gas analysis module of both kinds.

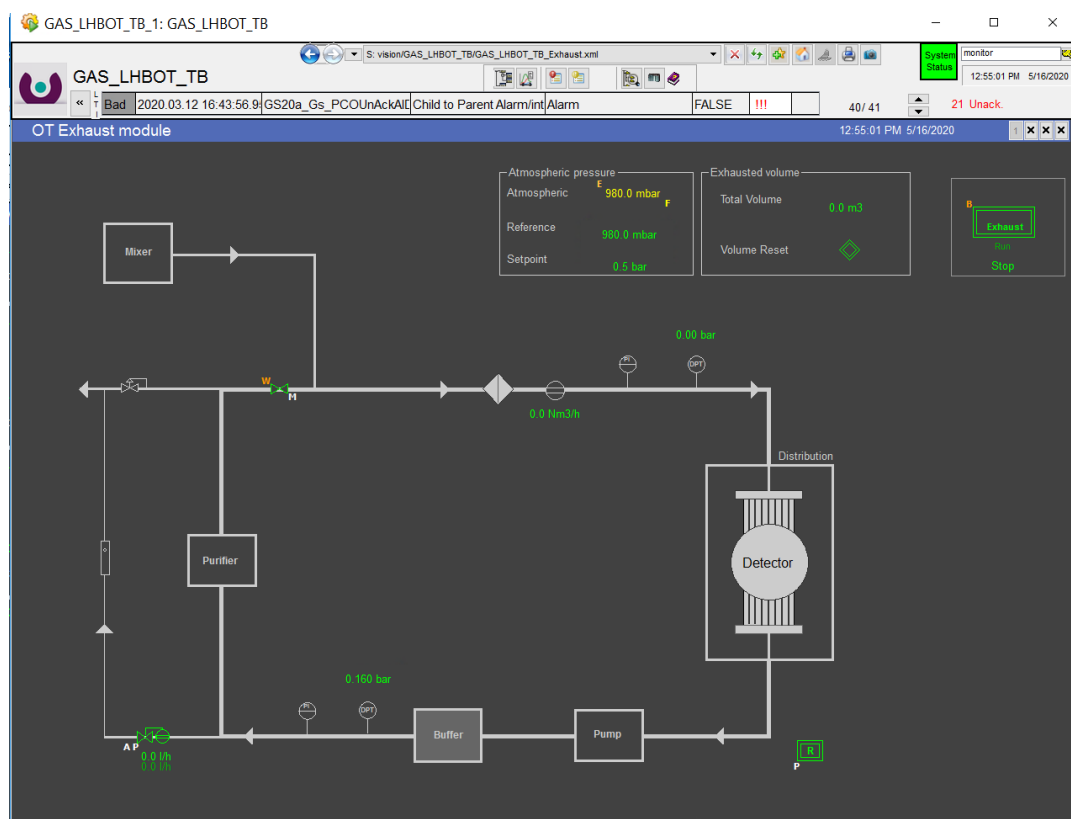


FIGURE 2.12: Exhaust (loop) WinCC-OA overview

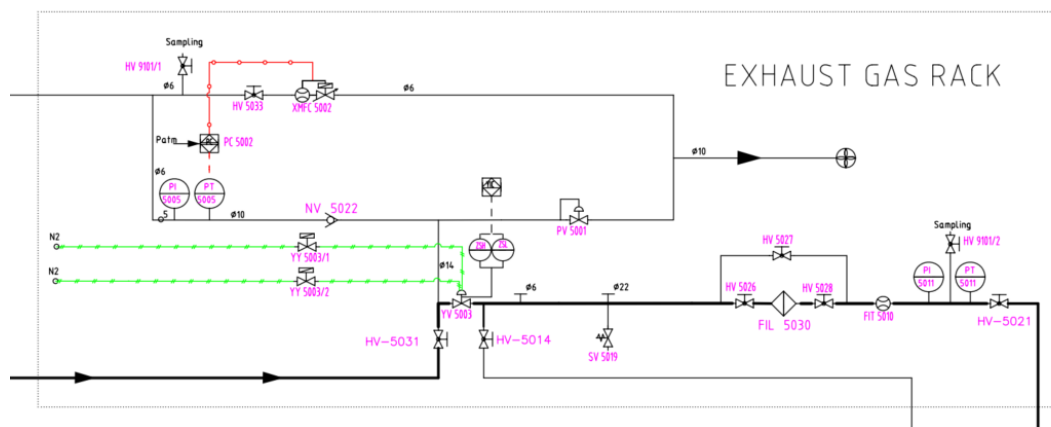


FIGURE 2.13: Exhaust module P&ID

All analysis modules are completely automated: they can be programmed to cyclically sample all gas streams including references or calibration gases. Expert operators can trigger remotely the analysis of specific lines at any moment.

Analysis modules are also used for safety purposes, (e.g. for continuously monitoring the mixture flammability level with IR sensors). In general, there are many situations in which a gas analysis module can be very useful: for example, the gas of a given source may or may not be re-circulated in the gas system without risks for this one; the gas of a given source may have damaged a certain measurement device or, for some sources, a wrong concentration of gas may require to stop the gas system. Some analysis lines are also connected to gas chromatograph (GC) analysers allowing more specific studies. In particular, GCs are used to check the mixture

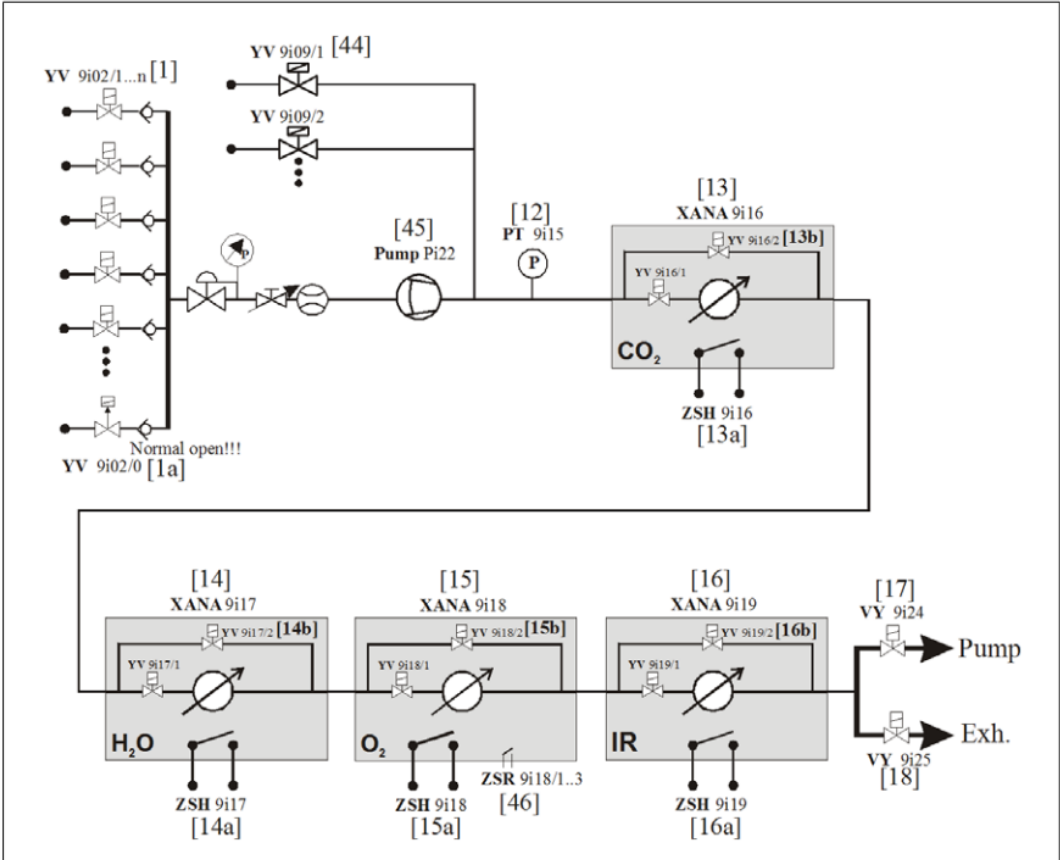


FIGURE 2.14: Analysis type A [2]

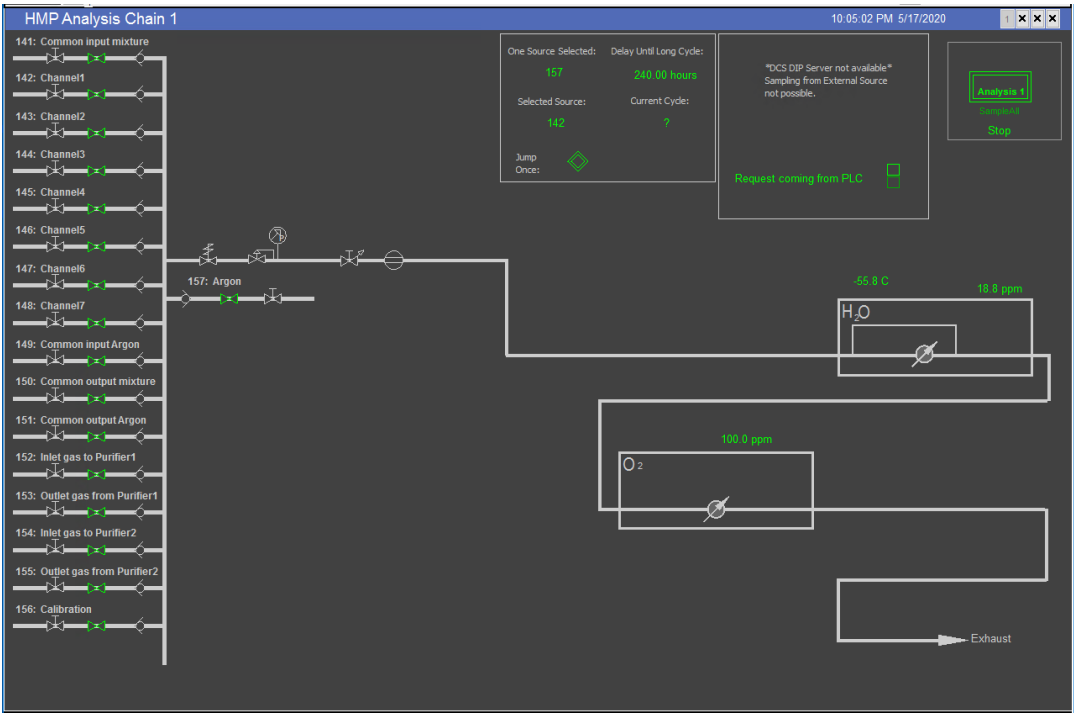


FIGURE 2.15: Analysis WinCC-OA overview

composition and/or the presence of more complex impurities.

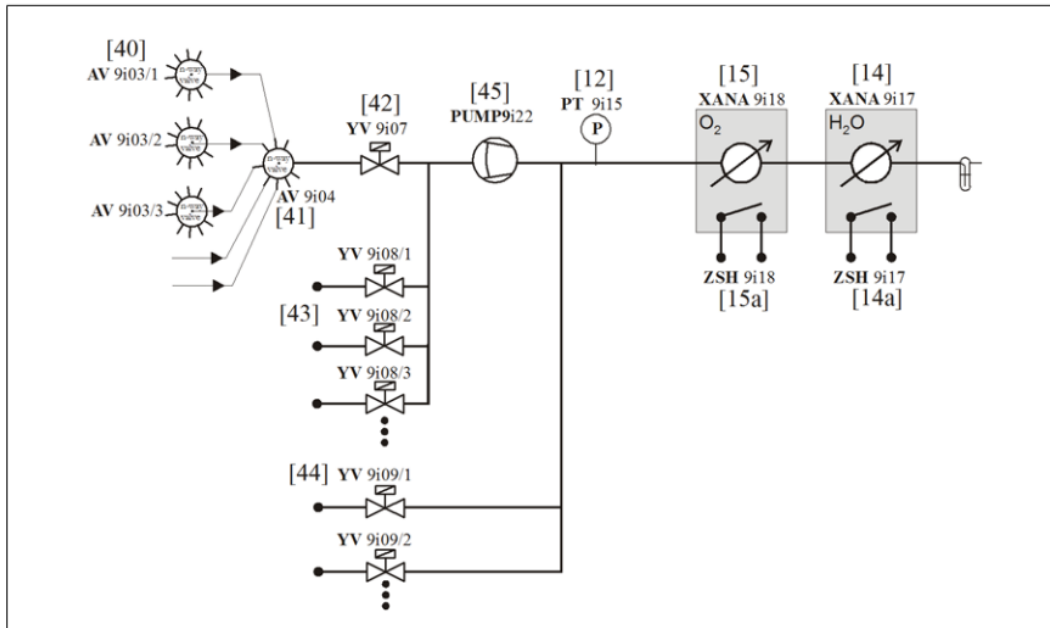


FIGURE 2.16: Analysis type B [2]

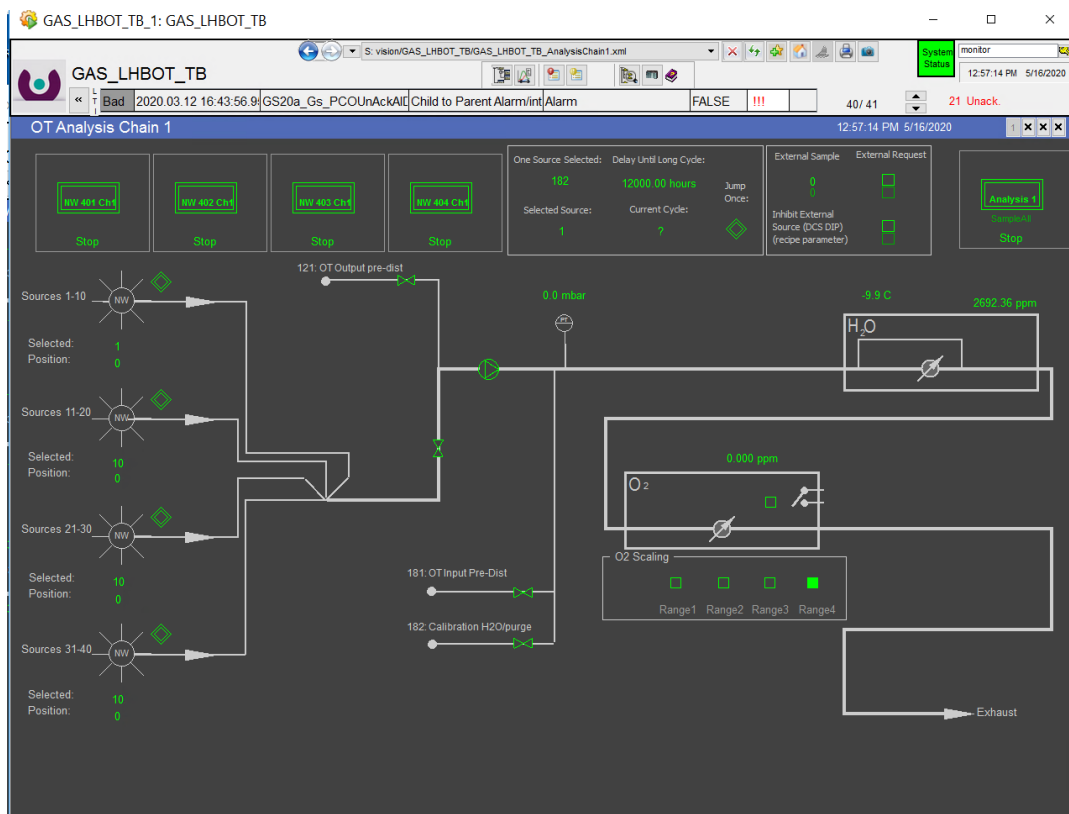


FIGURE 2.17: Analysis WinCC-OA overview

2.4.7 Humidifier Module

The purpose of the Humidifier modules is to add the appropriate quantity of water to the process gas. There are two types of Humidifier modules:

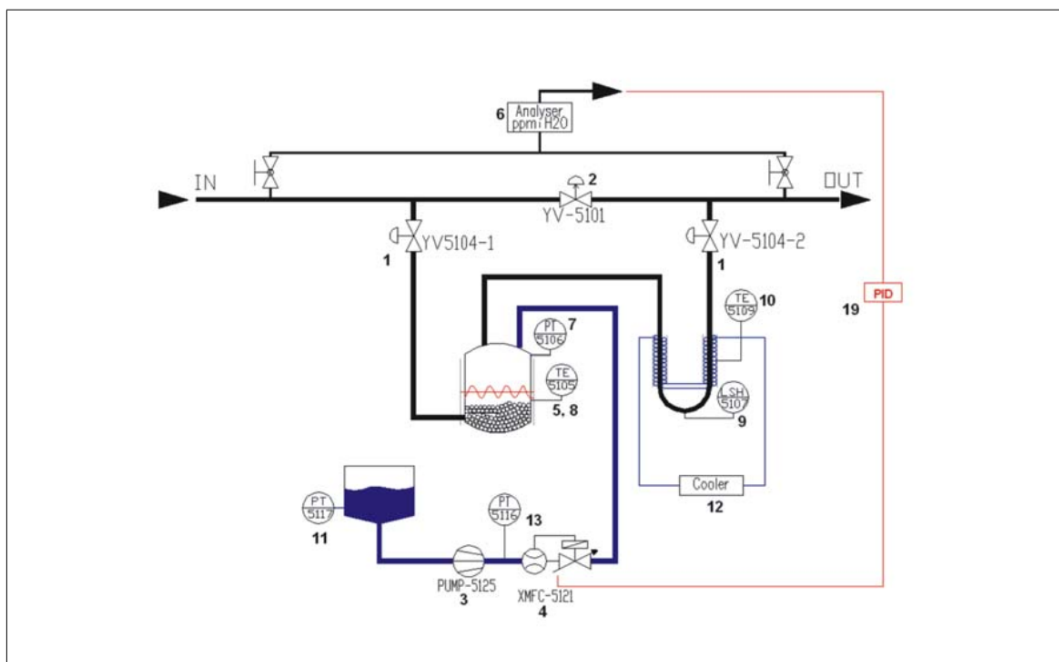


FIGURE 2.18: Humidifier module type A [2]

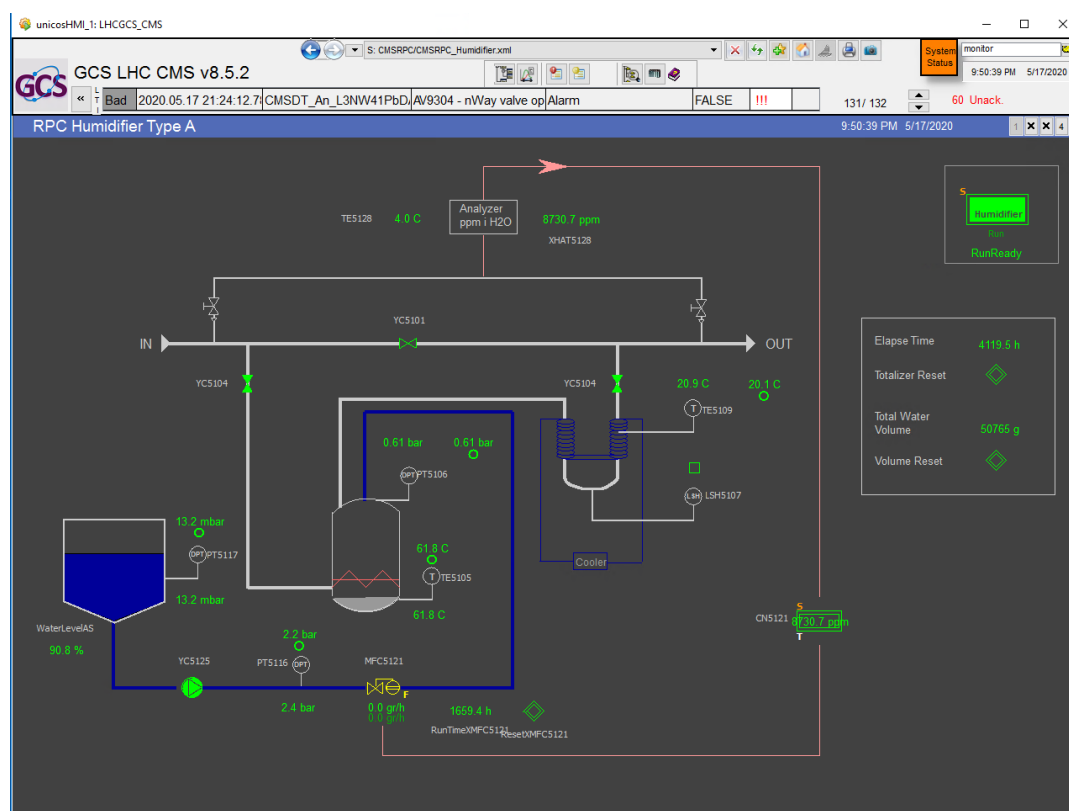


FIGURE 2.19: Humidifier type A

- The Humidifiers of type A (Fig. 2.18 and 2.19) are complex Humidifiers which control the moisture of the closed loop gas systems.
- The Humidifiers of type B (Fig. 2.20) are simpler, they have only a bubbler

which saturates the gas with water. The bubbler water temperature is monitored and the moisture is controlled.

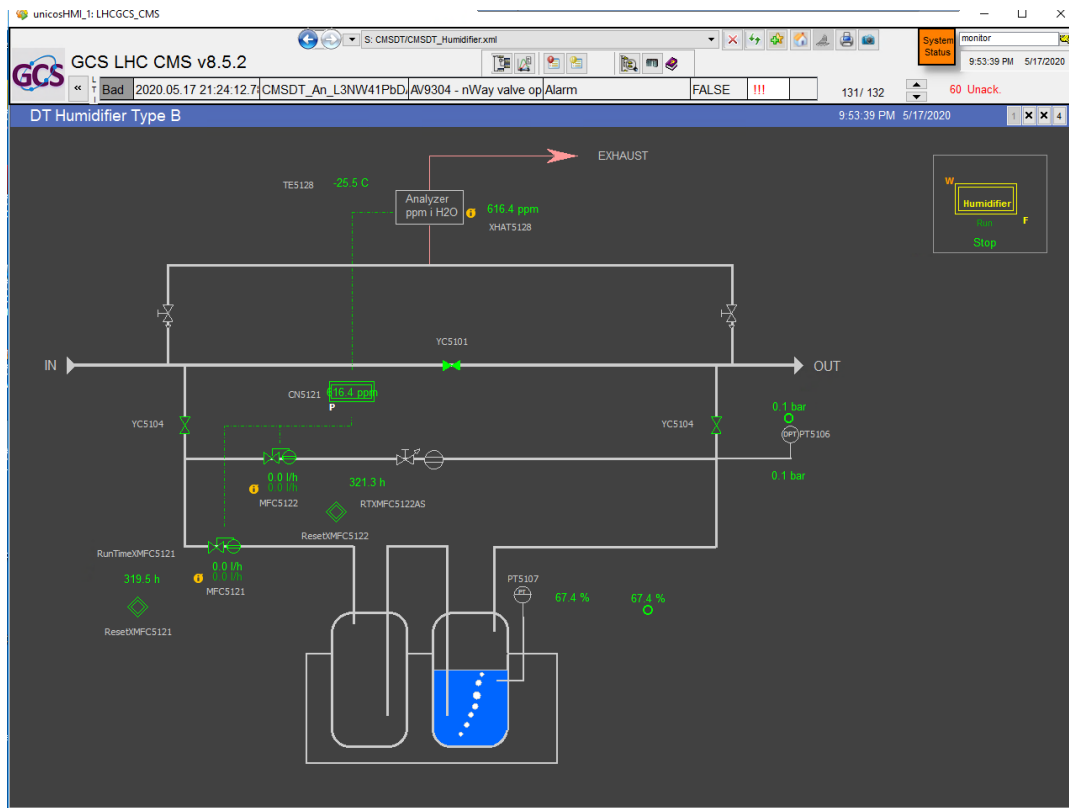


FIGURE 2.20: Humidifier type B

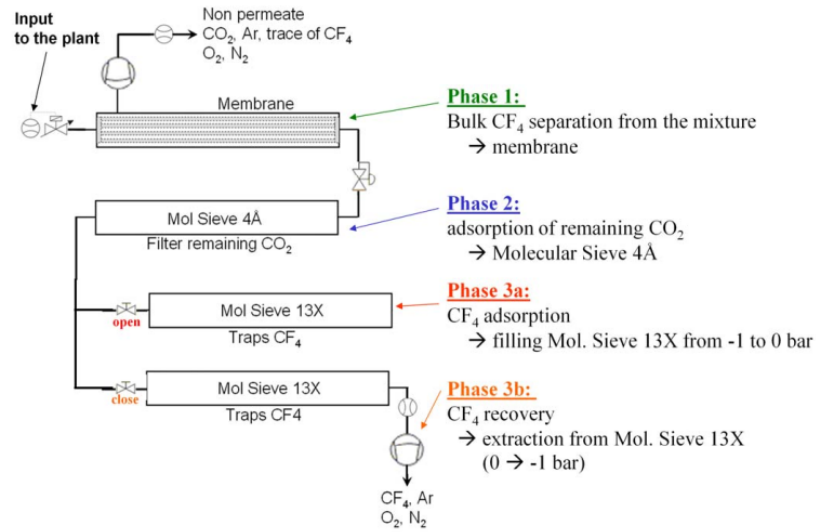
2.4.8 Gas Recuperation Systems

The gas circuits of a certain number of sub-detectors are equipped with a system to recuperate the used gas. Gas recuperation systems are used to minimize the operational costs of emptying the volumes of systems that are using expensive gases and to reduce the level of impurities without increasing the fresh mixture injection.

In most of the recuperation plants, the mixture returning from the detector is cooled down until the liquefaction point of the gas to recuperate. Then the liquid is recuperated and stored either in liquid or in gas phase. A different method is used for the CF_4 recuperation (Fig. 2.21): the plant makes use of gas separation membranes and selective adsorption in different molecular sieves in order to achieve good CF_4 recuperation efficiency [6]. All plants are fully automated and controlled by PLC.

Greenhouse Gas emissions

Greenhouse gases (GHG) are gases that absorb and emit radiation within the thermal infrared range and therefore they are responsible for the greenhouse effect, known for raising the average temperature of the earth's surface. Human activities, mainly the burning of fossil fuels and clearing of forests, have intensified the greenhouse effect and caused a phenomenon known as global warming. GHGs are

FIGURE 2.21: CF_4 recuperation working principle [6]

classified according to their Global Warming Potential (GWP) which is a relative measure of how much heat a GHG traps in the atmosphere with respect to the same mass of CO_2 in a fixed timespan. The GWP of a gas strongly depends both on its radiation-absorption in the infrared spectrum and on the atmospheric lifetime of the gas.

GHG emissions due to particle physics detector activities at CERN are mainly coming from the R134a Freon ($\text{C}_2\text{H}_2\text{F}_4$) and SF_6 used by the large ATLAS and CMS RPC systems and CF_4 used by other detectors. The GWPs for R134a and SF_6 are 1430 and 23900 respectively.

Their production and use are subject to a new European Union (EU) regulation as of January 2015. The EU regulation on fluorinated gases aims in limiting the total amount of F-gases that can be sold in EU from 2015 onwards with a reduction to one-fifth from 2014 to 2030, banning the use of F-gases where less harmful alternatives are available and preventing the emission from existing equipment [22]. The EU regulation might have a significant effect on availability and price, especially for R134a where other alternative gases are already available for refrigeration systems.

As already explained, in order to reduce operational costs and emissions, most of the LHC gas systems were already designed to operate in recirculation mode, with a recirculation fraction up to 90%. In some cases, it is however not possible to operate the detectors to higher recirculation fractions due to the presence of leaks at detector level. For this reason, the fresh gas mixture must be continuously injected into the system, leading to GHG emissions that account for 85% of the total CO_2 equivalent emission [5].

Short term approach is then making the leak search campaign as effective as possible⁶. Besides, for a longer-term approach, investigating new environmentally friendly gas mixtures with a lower GWP that can be used as an alternative to $\text{C}_2\text{H}_2\text{F}_4$, in order to reduce the emissions and contain the operational costs. Several gases with similar properties of the $\text{C}_2\text{H}_2\text{F}_4$ are already available on the market and used

⁶Unfortunately, these leaks in the detectors cannot be easily repaired.

for specific industrial application as replacements for the R134a; for example, gases in the family of the HydroFluoroOlefin (HFO) have already been identified by the refrigeration industry as a low GWP (4-6 over 100 years) alternatives and are used nowadays in refrigerating systems.

Studies on new eco-friendly mixtures are currently on-going [17].

2.4.9 Gas Supply Monitoring System

Each LHC experiment has its own Primary Gas Supplies module: it takes care of the monitoring of various parameters concerning the primary gases. The number and the nature of the supplied gases is experiment dependant. These gases are stored in gas bottles, gas batteries or dewars. The bottles and batteries are located in a surface building and (because of security, especially for flammable gases) separated from electronics or computers. Dewars are usually located in open air.

Two independent supply sources are available for each gas. While one is actually on-line and therefore used, the second is on stand-by and ready to automatically switch-over when the first source gets empty (Figures 2.22, 2.23 show typical WinnCC-OA interfaces for PGS monitoring).

The gas supply monitoring system aims in monitoring the availability and quality of each primary gas supply before it is put into operation. The idea is first to detect abnormal consumption or unavailability of a gas and, secondly, to avoid contamination of the gas mixture present in the detector with a potentially polluted source. The system monitors state of bottles and batteries (e.g. full, empty, in use, stand-by), the supply pressures, the weight of low vapour pressure liquid and the gas flow used by the experiment. Also more sophisticated apparatus for gas quality measurement (e.g. GC) can be installed.

For some gases heating of the bottles is necessary, monitoring and control is task of this module. The heating of gas lines (to avoid condensation, or to heat up the gas coming from a dewar), even when they do not transport primary gas (e.g. lines from the mixer to the distribution module) is also considered a part of the primary supplies module [2].

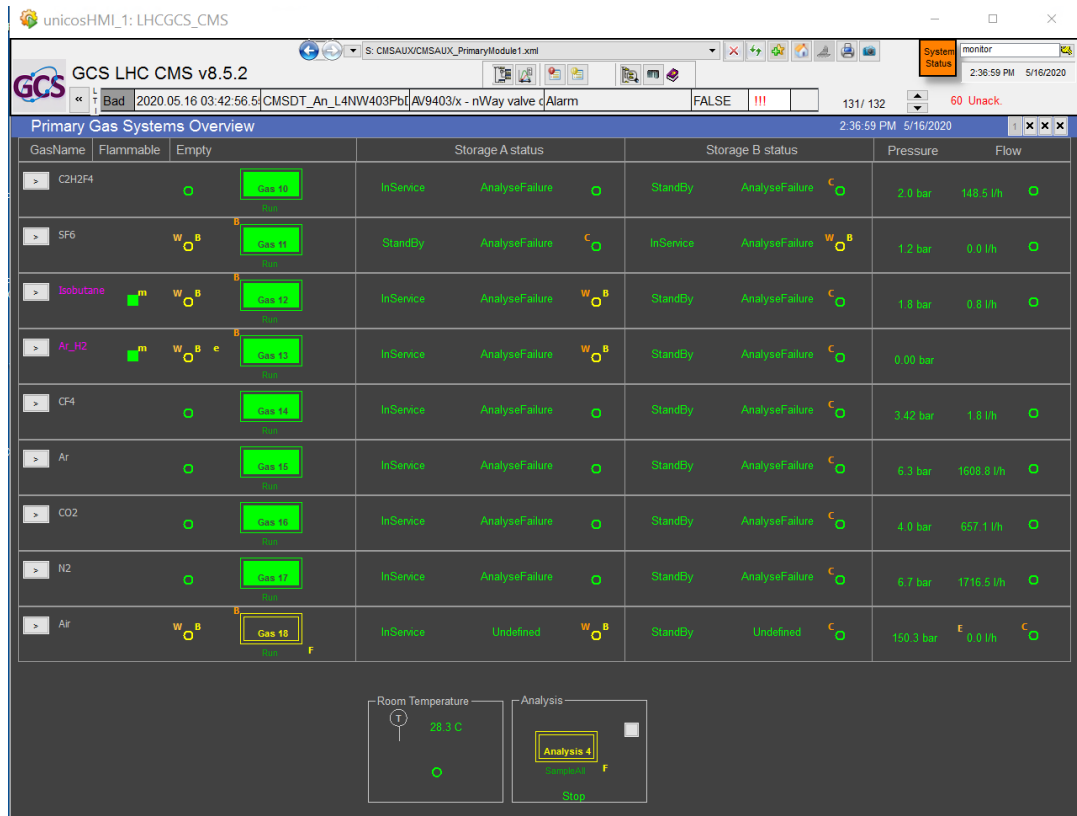


FIGURE 2.22: PGS WinCC-OA overview

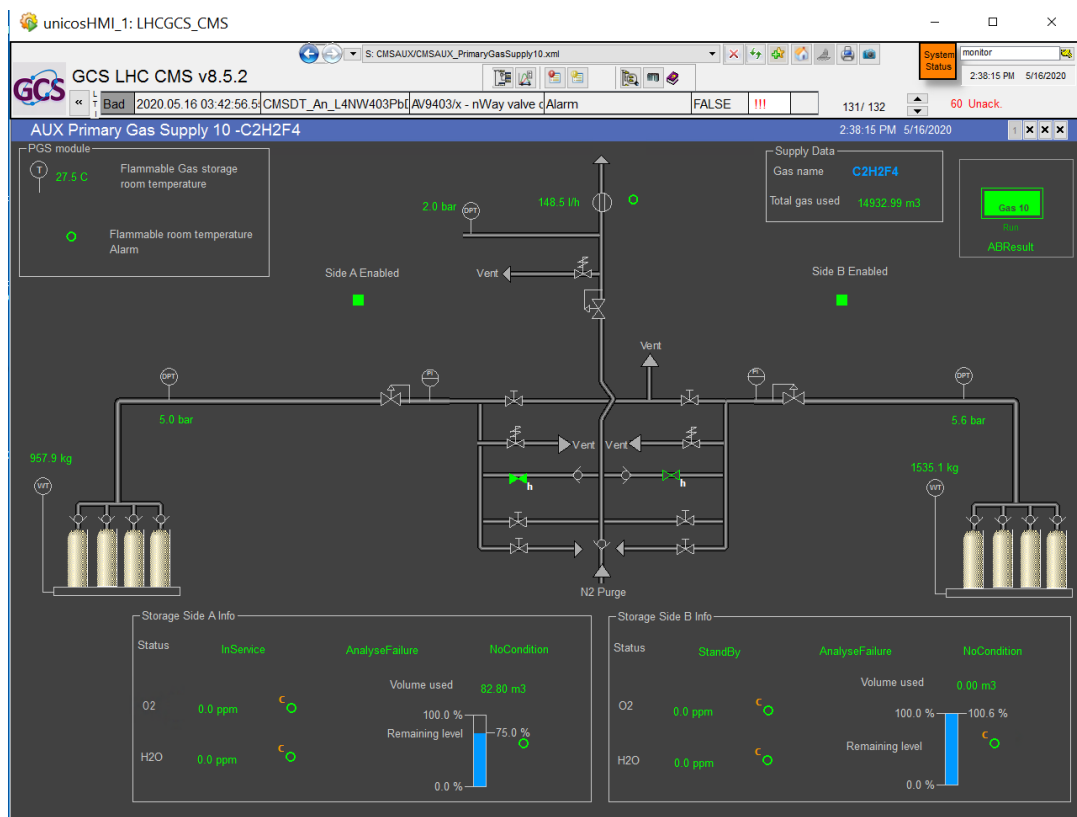


FIGURE 2.23: R134a monitoring

Finally, in Figures 2.24, 2.25 and 2.26 the typical gas system P&ID of respectively the SG, USC and UXC areas are shown, with all the characteristic components.

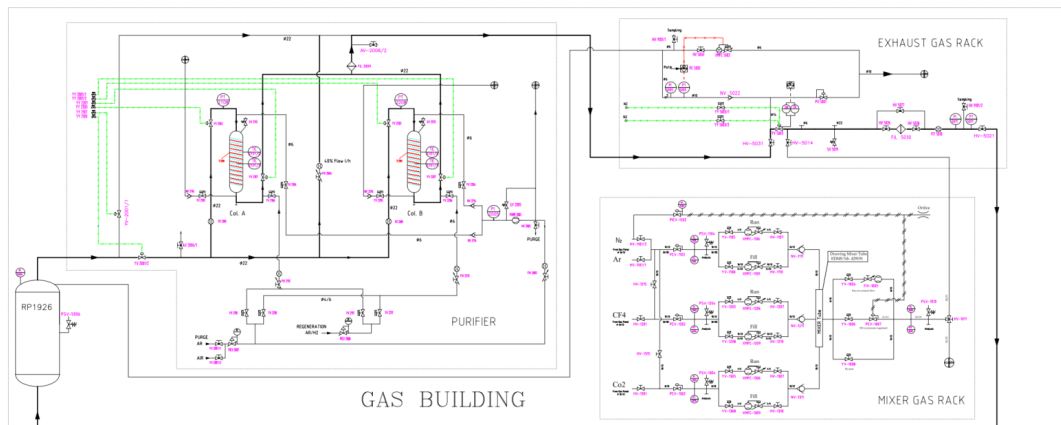


FIGURE 2.24: Surface Gas Building (SG) P&ID

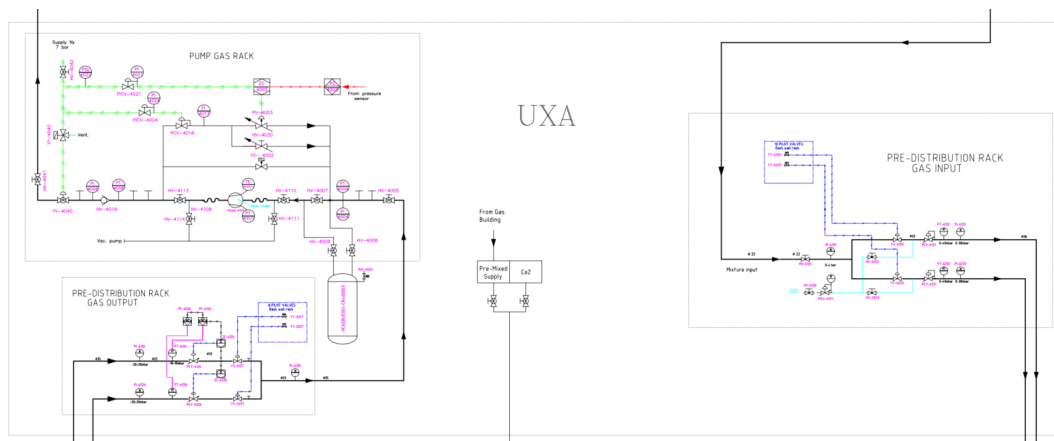


FIGURE 2.25: Underground Service room (USC) P&ID

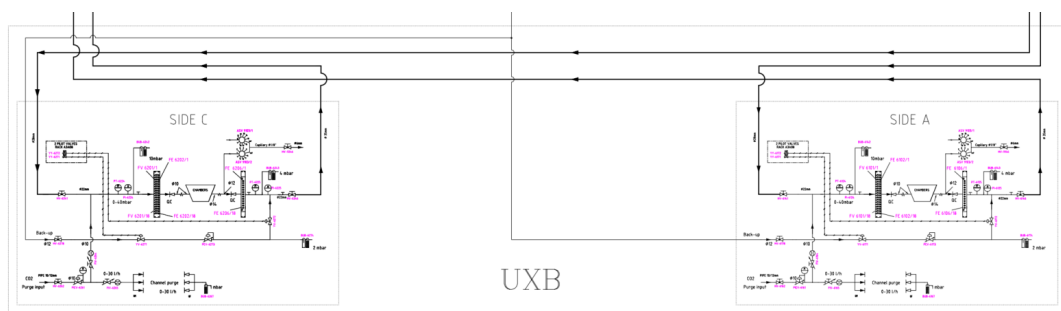


FIGURE 2.26: Underground Experimental Cavern (UXC) P&ID

Chapter 3

LHC-like Gas System test bench and Standard Maintenance Procedures

3.1 LHC-like Gas System Test Bench

3.1.1 Introduction: Why a system test bench

As shown in the previous chapter, a gas system is a huge, delicate and expensive system. It is composed of hundreds of components which operate together in different working conditions. The failure of the system can lead to severe damage of the fragile detectors chambers which are expensive and difficult to replace or even fix. Also, the dynamic response of the system is not always easy to control due to the many variables involved and simultaneously controlled.

Thus, the set up of an LHC-like gas system to simulate the operation of a real system is very useful. It can be used for training and will allow to test new or different components and software updates, performing characterization, optimisation, validation in a lab premise instead of on-site thus reducing time, costs and risks related to the operation. Similar to a race car or plane simulator, the test bench can be used to become acclimated to its behaviour, to get confidence with the machine and also to try new actions or operations. It can be used to "play" with the system and push it to its limits without occurring in big risks.

Also, it can be used as a reference for the development of maintenance standard procedures, first of all as a demo system then also to practically try and compare different procedures. It's really a great advantage to have available such a system instead of having to go on-site every time without effectively being able to touch anything in order to avoid any risk. Furthermore, it's not always obvious that some procedure you have thought about in office is practically doable or makes sense when you put hands on the system. So, not only the system test bench is a fundamental tool for newcomers, but it can be also useful for expert users to perform those operations that could be dangerous to be operated in real systems or when the systems are in RUN. To give an example, PID control parameters tuning is one of those delicate activities: the test bench is a perfect facility indeed to simulate the dynamic step response and get a first idea of the parameters to be set which can be later on tested and adjusted in the real systems.

3.1.2 Layout design and installation

After the general overview of an LHC gas system given in Chapter 2, in this section the setup of a gas system test bench will be discussed as well as its installation and

start-up.

As previously mentioned, the LHCb Outer Tracker system (OT) has been dismounted from the experiment in 2019 to be replaced by the SciFi tracker as part of the experiment's major upgrade during Long Shutdown 2 (LS2). So there it came the idea to recuperate the whole complex and expensive system as it is and re-use it as a lab test bench, obtaining a full system test bench, with all the modules, which is not a simplification of the real system but the system itself.

At this point, we should not forget to consider that LHCb is located at Access Point 8 of the LHC tunnel, whereas the room available for the LAB setup is located in the Meyrin site.

First of all, an inspection on the site where the OT gas systems racks were installed was necessary. In this occasion the overall dimensions were recorded as well as all the critic parts of the operation have been investigated (i.e. checklist of all modules, components, possible transportation difficulties, etc...). Like the majority of LHC gas systems, the OT system racks were indeed distributed over three levels (Figure 2.24, 2.25 and 2.26 show the OT system P&ID): the surface gas room (SGX), the underground service cavern (USC) and the experimental cavern (UXC). All the modules had to be taken and be carefully transported to the LAB room in Meyrin. A total of 10 gas racks were recuperated (4 from the SG, 6 from the underground areas) as well as two gas buffers. In Figure 3.1 recuperation of racks from the underground cavern is shown.



(A) Distribution rack in experimental cavern



(B) Buffer recuperation

FIGURE 3.1: Racks recuperation operations from the underground area

In Figure 3.2 the racks to be dismantled from the SGX room and to install in the laboratory.



FIGURE 3.2: Racks and high-pressure buffer to be recuperated from LHCb SG.

In parallel, a layout design for the installation in the lab room was executed. Various layout configurations were proposed because of the following constraints:

- number of racks to be installed and their dimensions
- functional constraints (e.g. modules that have to be installed next to each other for functional or practical reason, for instance reducing interconnecting pipes length or simplifying their distribution)
- space constraints (e.g.: actual size of available room; room inaccessible points and limitations like electrical non-coverable panels, doors, ventilation pipe; proper and enough space from the walls had to be taken into account to allow technical operations and access to the inside components of the rack)
- electrical, Ethernet and gas points available in the laboratory room

The final solution chosen as best layout was a double row configuration, with racks one in front of the other.

The four grey racks and the buffer that used to be installed in SG are re-installed the same way they were in LHCb in order to reuse exactly the same piping, while the orange underground racks are arranged in a way to reduce new pipes length and do not interfere with the quite huge ventilation pipe present in the middle of the room, that is now used as exhaust line to exhaust the gas when operating in open mode or



FIGURE 3.3: Laboratory empty available room

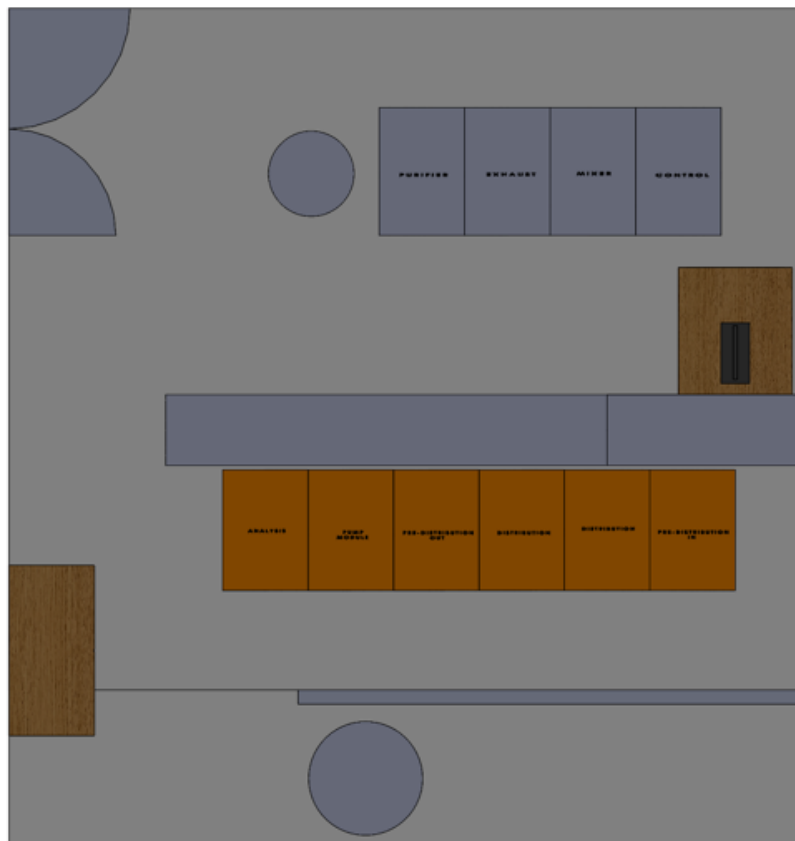


FIGURE 3.4: Final layout configuration: plant

for safety reasons. Of course, the system was fit in one single room in the lab, and not distributed over three levels like it was in the experiment: this condensation has introduces differences in terms of dynamical behaviour of the system (e.g. time of

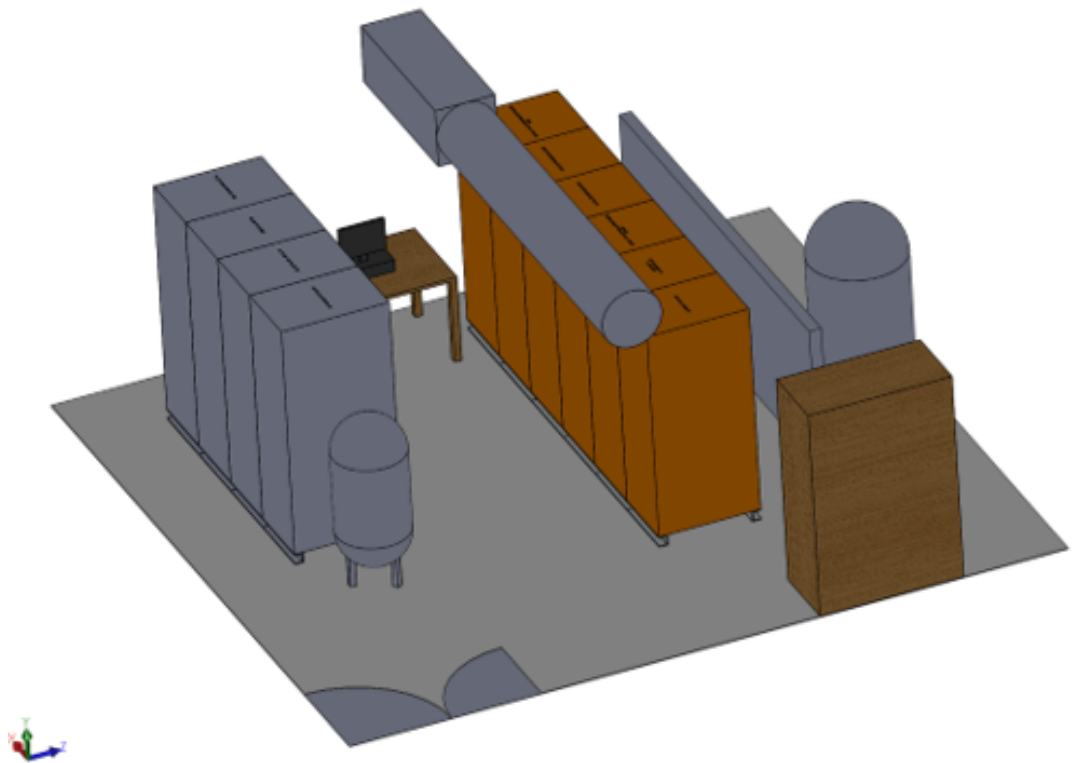


FIGURE 3.5: Final layout configuration: isometric view

reactions to changes, response time) and of pressure drops. There is no need of the spare pump, so only one pump is installed inside the pump module rack. A cupboard useful for some tools and other stuff storage (e.g. spare parts, documentation, etc) has been also placed as well as a desk for a laptop and some stationery. In figure and the final design layout is shown.



FIGURE 3.6: Final layout

Once the final layout had been defined, the racks have been arranged accordingly in the Laboratory room and the piping layout had to be made. The decision to reduce pipes diameter was taken since the pipes in laboratory are shorter than the real ones (especially the ones which go from SG to the underground areas). Furthermore, pneumatic lines for pneumatic components had to be installed as well as electrical and data transmission cables, like power supply and feedback signal cables, PROFIBUS and CANBUS data cables from and to the PLC. All the cables were arranged on cable trays. PLC migration was performed and communication was tested.



FIGURE 3.7: Dummy chambers volumes

Smaller volumes, called in the following dummy chambers, are used to simulate the gaseous detector chamber volumes. Hence, from the distribution modules the gas is sent to the dummy chambers: 8 lines are connected to the corresponding chambers, six with a 10L volume and two of 20L. See Figure 3.7. A great work has been done thanks to the coordination of all the different technicians. Once everything was in place a pressure test was performed and the high-pressure buffer was inspected and safety tested. P&ID old drawings were carefully checked and compared to the actual system, any difference spot was then noted.

Another big difference that occurs between the Lab test bench and the real system is the gas used: in the Lab the proper mixture of gas is not so far used, but dry Air is used. This is due to compressed air line availability in the room, and also to its simplicity and low cost. The air is supplied from N2 Mixer Purge line. For more accurate and realistic tests, other gases can be used and the desired mixture can still be created by the mixer module.

The system is now fully operational and remotely controllable via WinnCC-OA.

3.2 Standard Maintenance Procedures

3.2.1 Why a maintenance procedure

Data collected during past years RUN phases show that the average reliability of the gas systems is always greater than 99% corresponding to less than 1.5 hours of

down-time per year per system (power-cuts and external sources excluded). Some systems usually require a slightly higher number of interventions as they have more complex systems, like the ones for the RPC detectors. Anyway, the faults in the gas system modules account only for about 20% of the total down-time. Considering that gas systems construction was carried out in the years 2003-2007 and they that they started being operated in 2007, it is clear that a proper intensive maintenance and consolidation program is necessary in order to maintain and possibly improve this exceptional reliability in the years to come. As it is evident from the overall description of a gas system it might sound obvious that the maintenance operations for such complex systems is anything but easy.

The gas system is made of many components and devices:

- manometers,
- rotameters,
- data transfer, electrical, pneumatic and mechanical (pipes) connections,
- bubblers,
- filters,
- mass flow controllers and other flow meters,
- manual, electro, solenoid, non-return, safety and multi-way valves,
- pressure transducers and other sensors,
- pumps,
- purifier columns,
- flow cells, etc...

and each can face specific problems and requires different care. Maintenance consists of replacements, corrective actions, cleaning, etc...

According to the kind of system and part to maintain, different maintenance policies can be adopted:

- Corrective Maintenance (i.e. after failure)
- Scheduled Maintenance (based on statistical or hystorical data)
- Preventive on conditions (i.e. relying on sensors: e.g. differential pressure sensor on filter)
- Pro-active maintenance (i.e. new design or retrofit)

As well known, a good maintenance can lead to a longer life-time of systems components, reduce downtime and, in general, cost of operations both in terms of materials and time. Experience-based or sporadic maintenance can often be unreliable and difficult to manage, control and evaluate. Maintenance procedures are then needed to help the operations and make the system reliable. They have to be written in a way that any operator, even if not familiar with the gas system, can perform the maintenance following each step.

Therefore, the main advantages of having a standard maintenance procedure are here summarized:

- minimize errors introduced by operators who, while being really expert, can forget some details due to lack of attention or forgetfulness.
- minimize arbitrariness introduced by the different way-of-working of operators that can be unpredictable and could lead to different behaviour of the systems in run conditions.
- reduce the eventuality that every operator acts following his own perceptions without having the proper knowledge and awareness of what he is doing or whatever else his action, even well-intentioned, could affect.
- provide useful documentation for future technicians who are going to cope with the operation of these complex systems for the first time. The procedure has, therefore, the intention to give them guidelines, thus reducing the risks related to inexperience.

The development of maintenance procedure required the in-depth study of the working and operation of each module and taking into consideration each possible failure cause (a sort of Failure Mode and Effect Analysis). Using as starting and reference points the analysis of historical data and collecting the precious technicians' experience-based feedbacks a first procedure has been developed for each module.

3.2.2 Gas System Test-Bench Status

The ex-OT system test bench has been really useful in the development of the maintenance procedures: it helped to identify the critical parts and possible failures as well as the evident problems. At the end, it was also useful to test and validate the procedure itself and eventually to improve it. When the installation of the gas system was completed in the laboratory, some issues could be easily identified regarding the system status.

Here are some examples spotted at a first check of the gas racks:

- some manometers didn't read zero even if the system was open at the air: a check was needed to verify if the line was pressurised or they were broken and have to be replaced or may need recalibration of the zero.
- Documentation sometimes not present in the rack or not updated.
- P&ID were not up-to-date.
- Some part expected to be in place from the drawing were actually missing or, the other way around, physically present but not mentioned in the P&ID. This was due to several upgrades of the system since 2011. P&ID were unfortunately not always updated.
- Also, some components label was missing or it was wrong, making it difficult to identify the different parts in the different lines.
- For some missing parts, it is sometimes difficult to understand if spare ones are available and where (especially for old components that are not used anymore or components rarely used). Need to improve spare parts management (e.g. spare parts inventory and management).

Starting from this critical analysis of the status of the old OT system some key points of the eventual maintenance procedure have been highlighted and further in detail developed in order to fix some of the issues spotted.

3.2.3 Procedure development and key goals

A specific maintenance procedure has been developed per each module, taking into account all the different operating modes and criticalities. The procedure is defined as "standard", meaning that, given a certain module, it is meant to work for all the same kind of modules for the different systems (e.g. the Mixer Maintenance procedure is valid for all the Mixer Modules of the different Gas Systems around the LHC experiments). Of course, there are some special cases for which an exception must be done and a specific non-standard maintenance has to be performed.

The generic Module Maintenance procedure has been developed keeping in mind the different operational phases of the detectors and consequently of the gas systems. When the LHC is in RUN the feasible maintenance operations are limited indeed both because underground areas are not accessible due to radiation levels and because it is not possible to perform those actions which require a gas system stop. For the few doable ones, the design has been often done such a way that the system could keep running without affecting data acquisition and data quality. For example, some components, especially the most critical for operation, have been installed with redundancy: in this way, if one fails, the other comes into operation and in the meanwhile reparation or replacement might be possible for the one that has failed (e.g. more than one pumps in parallel). Other examples are filter installation with a bypass line: when the filter needs to be changed or cleaned it is possible to temporarily bypass its line and perform the operation.

Nevertheless, during the LHC RUN period, some Technical Stop are foreseen. During these stops, it is possible to intervene in a deeper way to eventually solve problems and perform corrective (on condition) maintenance. Anyway, the general and main maintenance should be performed in the long End of Year Technical Stop (EYTS) and in the Long Shutdown (LS) phase, the latest is the long period during which the accelerator is off and data acquisition is not ongoing and it usually lasts a couple of years. At these times it is, therefore, possible to carry out the periodic scheduled maintenance as well as corrective and especially predictive maintenance. It is also the moment to think about an eventual upgrade of the different systems components, may it be in terms of retrofit or partial or even complete re-design of the system.

Besides, system operation can be tested, simulating different operating conditions and observing different system responses when subjected to different inputs. For this last aspect, the new system test bench represents a big opportunity to make these tests possible not only in the LS time duration.

The generic procedure has been thought as divided into three parts, corresponding to the different phases and working conditions in which a generic system can be operating. A system is here intended as the whole gas system, composed of the different multiple modules. The three parts are:

- system ON with module under examination in RUN
- system ON or OFF with module under examination in STOP
- system ON or OFF, module to be restarted.

For each phase, an analysis of the required or feasible actions has been performed.

Specific attention has been paid to Leak tests, being the gas leaks one of the main and more insidious reasons of efficiency losses of the whole system as well as a

cost and, often, source of emission of harmful (with a high GWP), polluting or toxic gases.

A good and reliable maintenance procedure is one of the simple but relatively cheap and still effective tools which can be able to limit gas emissions and consumption. Along with leak tightness, other ways to reduce these losses are systems operating in recirculating mode (as explained in chapter 2, all CERN gas systems using expensive or polluting gases work in gas recirculation mode) or the use of gas recuperation and purification systems, which are however more difficult to design and implement, as well as more expensive. So, the maintenance has the important goal of ensuring that the system to be operated is, at the end of the procedure, leak-tight or leak proof. Assuring perfect tightness is unfortunately very difficult though, but what it is possible to do is to make sure that the leak rates are within some tolerance thresholds in terms of acceptable leak rates. In addition to the actual leaks, the intake of gaseous components from the outside must be limited as these may affect the purity of the mixture and, consequently, the behaviour and efficiency of the gaseous medium in the interaction with the charged particles and even the operation of the detector itself. Not only that, the intakes can alter the correct functioning of some components in the system, such as vacuum pumps, forcing them to process more gas than necessary and slowing down the whole process.

An effort has been made in trying to optimize and minimize the execution times of the procedures, so as not to be heavy and perceived as an unnecessary and pedantic waste of time by technicians and operators, and also to limit their cost.

Another characteristic of the developed procedures is the approach, typical of lean manufacturing, of trying to keep the systems clean and in order, with documentation that is always up to date, available and usable. As well known, a disorganised system is also often difficult to maintain, on the contrary, a clean and neat system, with each component well highlighted and in its place it is of easy status evaluation and makes the procedure more easily executable even for those who are less experienced.

The steps performed to develop a generic maintenance form were:

- Study and understand the working principle, regimes and phases of the module under examination.
- Identify the various functional parts of the module (e.g. flow meters, control valves, pumps)
- Identify for each component the possible failure modes
- Analyze the overall effects of eventual failure
- Identify the best maintenance technique accordingly.

So, for each module, a list of checks/actions is the result of all these steps, thus generating the procedure. Different attention must be paid if the module was situated in SG, USC or UXC. For example, in UXC a flammable or toxic gas cannot be vented in the cavern. In the next paragraph, one of the procedure will be described in detail.

3.2.4 Example of Maintenance procedure

An important requirement for maintenance procedure is to be user friendly and simple to read and understand. Furthermore, it has to be well organised and traceable,

therefore an interactive excel spreadsheet was chosen as solution. In figure 3.8 the initial part of the mixer maintenance procedure form is shown as an example.

MIXER MAINTENANCE PROCEDURE Complete the form and print it at the end						
SYSTEM:		START DATE:		END DATE:		OPERATOR:
Mixer in RUN system ON						
WHAT	DESCRIPTION	STATUS	RESULT	ACTION LIST		Notes
LEDs check	Press the button in the mixer chassis and check if the leds are ok	☐	To Be Done ☐ Ok ☐ Problem ☐ Solved			
Check Pressure Reducers	Check PI-1X03 reading and compare their value with the corresponding PT-1X03 reading on WinCCOA. Is error less than 20%?	☐	To Be Done ☐ Ok ☐ Problem ☐ Solved			
Lines pressure	Check if the pressure of each line is equal to the DMFC calibration pressure (indicated on the device).	☐	To Be Done ☐ Ok ☐ Problem ☐ Solved			
	Compare PCV Tescom gauge pressure with supply pressure on the wall panel for each line: regulator pressure should be 0.3-0.5 bar lower than network pressure	☐	To Be Done ☐ Ok ☐ Problem ☐ Solved			
	Check that pressure master MFC PI-1103 is lower than pressure slaves MFCs	☐	To Be Done ☐ Ok ☐ Problem ☐ Solved			
	Make sure that the smallest concentration line has the highest pressure	☐	To Be Done ☐ Ok ☐ Problem ☐ Solved			

FIGURE 3.8: Mixer maintenance procedure (to be filled) form

The sheet has been designed also keeping in mind some visual management tools. First, there is a space where the operator should indicate the system on which he performs the maintenance, then take note of the date and starting time. There is also a cell for the end time, but the whole procedure can sometimes take several days to be completed. The operator should always write down his name so that in case of problems it is clear who touched the system and it is possible to contact him to understand what can be wrong.

The three main parts of the procedure are highlighted. In each section, there are several columns:

- *What*: here is a general title for the test or check to be performed
- *Description*: a more detailed explanation regarding the test or check is given in terms of actions to be done and limits or thresholds to be checked
- *Status*: checkbox which indicates if the test has been done or still has to be done (visual check)
- *Result*: If the test is done, here's where you can indicate its outcome. Next to the multiple-choice group box, there is a blank cell. If the result is *Ok*, the blank cell will be filled in green colour. If you encountered a problem or couldn't do or finish the test, tick the *Problem* box and a red cell will be displayed. If there used to be a problem but you managed to solve it, tick the *Solved* box and the coloured cell will be displayed in blue. This is another visual tool which helps understanding, at first look, where and what were the problems, whether they were solved or are still unsolved. As it is clear the visual tools help understanding if the system was in a critical situation and required a lot of interventions.

MIXER MAINTENANCE PROCEDURE Complete the form and print it at the end						
SYSTEM:		START DATE:		END DATE:	OPERATOR:	
Mixer in RUN system ON						
WHAT	DESCRIPTION	STATUS		RESULT	ACTION LIST	Notes
LEDs check	Press the button in the mixer chassis and check if the leds are ok	☒	Done	☒ Ok ☐ Problem ☐ Solved	Ok, go ahead with next step	
Check Pressure Reducers	Check PI-1X03 reading and compare their value with the corresponding PT-1X03 reading on WinCCOA. Is error less than 20%?	☒	Done	☐ Ok ☒ Problem ☐ Solved	Take note of the two readings. If possible, set the corresponding PCV to zero and see which one doesn't read zero	
Lines pressure	Check if the pressure of each line is equal to the DMFC calibration pressure (indicated on the device).	☒	Done	☒ Ok ☐ Problem ☐ Solved	Great! Go Ahead with the procedure	
	Compare PCV Tescom gauge pressure with supply pressure on the wall panel for each line: regulator pressure should be 0.3-0.5 bar lower than network pressure	☒	Done	☐ Ok ☐ Problem ☒ Solved	Take note of the two values. Supply pressure has to be increased. Contact David Jailliet.	
	Check that pressure master MFC PI-1103 is lower than pressure slaves MFCs	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to adjust and set it 0.3-0.5 bar below master pressure	
	Make sure that the smallest concentration line has the highest pressure	☒	Done	☐ Ok ☒ Problem ☐ Solved	Please select only one option	

FIGURE 3.9: Example of filled Mixer Maintenance form

- **Action List:** accordingly to the result box ticked, it displays the actions to be taken. If the result is *Ok* it basically says to go ahead with the procedure; if there is a problem it suggests some actions to try and help to solve or fix the issue. Once the problem is solved the action displayed will not change and this is useful to see and compare if the actions taken were actually the same indicated in the action list or something different (this can also help in improving the procedure); it makes possible to record the problems and see what solved them.
- **Notes:** here is the space where the operator can take notes about different parameters or process values, add his comments, report the eventual issues and the actions he took to solve the problems. In this area he can also propose to add something on the procedure or improve some aspect.

The form is "interactive" meaning that it only displays the actions and colour cells as soon as the operator fills it and makes his choices ticking the appropriate boxes. For the interactive displaying some conditional formatting of the cells has been used as well as some simple Boolean conditions.

Here below the simple code used for each cell (being X the generic number of the row corresponding to the generic "what" check):

- for the *Status* cells DX:
=IF(LX,"Done","To Be Done"); where the LX cell is the one linked with the format control in CX status checkbox
- for the *Result* coloured cells FX:
conditional formatting rules formulas have been applied as follows:
-fill with green:
=AND(\$L\$X,\$M\$X=1)
-fill with red:
=AND(\$L\$X,\$M\$X=2)

-fill with blue:
 =AND(\$L\$X,\$M\$X=3)
 else, leave blank.

So, the formula checks at first if the status is done, then accordingly to the value of cell MX it chooses the filling colour. The value in MX is programmed to be respectively 1 if the result is *Ok*, 2 if it is *Problem*, and finally 3 if it is *Solved*. To make it possible, the check-boxes of the multiple-choice selection cells EX have been linked respectively to the cells NX, OX, PX. It means that, to give an example, the value of cell NX is TRUE (or 1) if the Ok checkbox is ticked in cell EX, FALSE (or 0) if not ticked. Logically combining these values, it's possible to have the desired behaviour of cell MX:

=IF(AND(NX, NOT(OX), NOT(PX)), 1, IF(AND(OX, NOT(NX), NOT(PX)), 2, IF(AND(PX, NOT(NX), NOT(OX)), 3, 0)))

- for the *Action List* cells:
 =IF(NOT(QX), IF(AND(LX, MX <> 0), IF(MX=1, "Ok, go ahead with next step", "Describe and record the problem."), ""), "Please select only one option")
 It also checks if more than one options are ticked with the value of the cell QX:
 =OR(AND(NX, OX), AND(NX, PX), AND(PX, OX))
 If FALSE only one option has been selected, if TRUE more than one check-boxes have the tick and the action asks to select only one.

A Macro has also been added to clear to form up once finished. The Macro runs pressing Ctrl+q.

For instance, having a look to the Mixer Module maintenance (Appendix A), a series of checks is reported in the "what" columns, following all the critical components present in the module:

- check electrical connections are working (LEDs check);
- check pressure sensors (i.e. indicators and transducers): they must read the same value if on the same line (within a certain tolerance), they must read zero if the module is open to atmosphere
- each line has to have the proper pressure according to the calibration pressure of the MFC: if not the case the pressure should be adjusted using the pressure regulator;
- before the module is restarted, when it is in stop, the MFCs calibration must be checked as well as their internal PID parameters settings;
- the position of certain valves or their setting must be checked and corrected in case; safety valves must be within their validation expiration date;
- leak test should be performed after the calibration of the MFC, when the module doesn't have to be reopened again. So if the test is passed, the module is leak tight.
- before the restarting of the module, all the hand valves position must be controlled to be in the right one, some stability checks are necessary until the run mode reaches a stable condition. Moreover, the deadband and archiving thresholds must be checked.

Obviously, each module requires a specific study depending on its components and working principle, but the logic of the maintenance always follows these general guidelines.

3.2.5 Leak test

The leak test is one of the most important tasks the maintenance procedure has to attempt to perform as well as possible. The required leak tightness for a gas system is mostly related to the following effects:

- Gas leaking out will also cause impurities (mostly Air) leaking into a system, which could deteriorate the detector performance. That is of particular importance for the parts of the circuit that can run under pressure.
- Even relatively small gas losses can be a critical cost factor for expensive gases, like *Xe*, *Ne*, *CF₄* or *C₂H₂F₄*.
- An uncontrolled gas loss in the experimental area can cause risks for personnel or detectors if flammable, toxic or strongly electronegative gases are released.
- If GHG are used, then it is a good practice to reduce emissions.

At the end of the maintenance list there is a hyperlink to a leak test procedure for the module in STOP phase. Basically, a leak test consists of filling with some gas the lines of the module (after having isolated the module from the rest of the systems i.e. closing the interconnecting lines valves) up to a certain pressure and then perform some checks or inspection.

One simple method to check the leak tightness is the "*pressure decay method*": once the lines are under pressure, the gas supply is closed and you have to wait for a certain time. Recording the relative pressures and the temperatures at the beginning and the end of the test, and knowing the volume of the filled closed module, it is possible to calculate an approximation of the actual leak rate. You can easily get these pressure and temperature parameters from the PLC archiving. It is necessary to take into account temperature changes as they influence the closed system pressure (Figure 3.11). This leak testing method is also described in the Standard BS EN 13184: 2001 Non-Destructive Testing - Leak Testing – Pressure Change Method. It can be used for leak rate measurements bigger than $1 \cdot 10^{-4}$ STD cc/s and it is considered the best to quantify a total leakage on a device.

Gas leak rates are usually given in a density-independent unit, i.e. either mass flow or volume flow at constant density. Here, leak flows are given in STD cc/s (standard cm^3 per second at atmospheric pressure 1,013 bar and 0°C) or $bar \cdot cm^3/s$. To compare leak rates of different test conditions, all rejection leak limits shall be based onto the same reference condition, i.e. a Δp of 1 bar.

A leak tightness limit for a sub-unit of a gas system is to be specified individually for each entity and system as it depends on the number of such modules, the operating pressure, and other system-specific parameters. However, for most gas system modules (or rack) a leak flow smaller than $1 \cdot 10^{-3}$ STD cc/s at an over-pressure of 1 bar is considered satisfactory. The sensitivity of this method can be down to $1 \cdot 10^{-4}$ STD cc/s, but it strongly depends on the measurement conditions, i.e. the volume of the device, the accuracy of the pressure measurements and the temperature stability.

If the pressure reading is relative to atmosphere conditions, the barometric pressure must be recorded to calculate the total pressure of the device. Before the leak test,

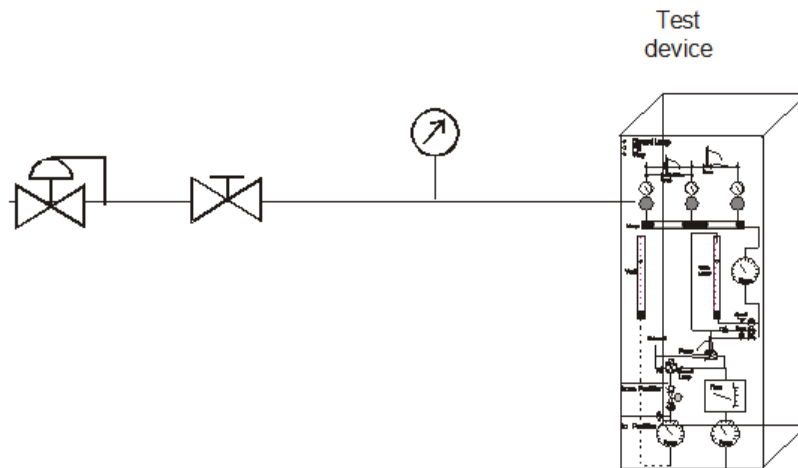


FIGURE 3.10: Pressure decay method test scheme [19]

5						
6	General Information					
7	Experiment			Target Leak flow		STD
8	Sub-detector			at reference conditions	1.00E-03	cc/s
9	Module	MIXER				
10	Rack	Mixer				
11	Test Method:	Pressure decay method				
12	Persons performing test:					
13	Location of Test					
14						
15						
16	Leak test parameter					
17		Start		End		Difference
18	Time	10/2/19 2:16 PM		10/3/19 3:35 PM		91181 sec
19						
20	Pressure Inside	3	bara	2.8	bara	0.2 bara
21	Pressure outside	0.976	bara	0.976	bara	0 bara
22	Delta P	2.024	bara	1.824	bara	0.2 bara
23	Temperature	293.3	K	293.3	K	0 K
24	Volume	900	cm ³			
25						
26						
27	Results					
28	Leak at test conditions	1.84E-03	Std cc/s	Leak rate conform to specification YES		
29	Leak flow at reference conditions	7.01E-04	Std cc/s			
30						

FIGURE 3.11: Leak test form for pressure decay method

the free gas volume of the test device needs to be measured or calculated. For a gas rack, for example, this can be done by summing up the volumes of all individual pipes and other free volumes that are in the rack.

For example, considering the free volumes of valves bodies, buffers, etc,

$$V_{tot} = \sum_{i=1}^n V_{pipe_i} + V_{free} = \sum_{i=1}^n \frac{\pi}{4} r_i^2 L_i + \sum_{j=1}^m V_{free_j}$$

Some attention must be given to the possible aspects that can interfere with the test:

1. Temperature variations (day-night effects, direct sunlight on the device) should be minimized. For large systems, several temperature transducers might be necessary.
2. If the pressure reading is relative, the barometric pressure needs to be recorded too.
3. Permeation of gases through porous walls can influence the measured leak rate, e.g. long Rilsan (FESTO) tubes must be avoided for high precision leak tests.
4. Deformations of the device under pressure should be excluded.
5. Condensation of gas (humidity) during the test is to be avoided or needs to be measured and corrected for.
6. Trapped or poorly accessible volumes as, for example, wrongly isolated pipe, that is not part of the test device, can behave like (or cover) external leaks or can cause longer stabilisation time.

The leak flow can be calculated using Equation 3.1:

$$Q_{leak} = \frac{T_s \cdot V_{tot}}{\Delta t} \left(\frac{p_0}{T_0} - \frac{p_1}{T_1} \right) \quad (3.1)$$

where:

- V_{tot} : free volume of the module
- T_s : temperature at STP conditions (273 K)
- Δt : time interval
- p_0 : absolute pressure at the start (after stabilization time)
- p_1 : absolute pressure after Δt
- T_0 : temperature at the start (in K)
- T_1 : temperature after Δt (in K)

For the acceptance test, it is important to calculate a minimal time during which no pressure drop is observed before a device can be certified leak-tight up to a level specified. The minimal test period can then be calculated using Equation 3.2.

$$\Delta t = \frac{T_s \cdot V_{tot}}{T_0 \cdot Q_{adm}} \frac{\Delta p}{3600} \quad (3.2)$$

where:

- Q_{adm} : leak flow rejection limit for the overpressure used in the test
- Δp : smallest observable pressure change

The leak rejection limit at reference conditions, e.g. $1 \cdot 10^{-3}$ STD cc/s (at Δp of 1 bar) should be translated into a rejection limit at the test conditions using Equation 3.3 (for small leaks one can assume the leak flow to be laminar, and the pressure dependents can be calculated using the Hagen-Poiseuille formula):

$$Q_{new} = Q_{old} \cdot \frac{p_{IN_{new}}^2 - p_{OUT_{new}}^2}{p_{IN_{old}}^2 - p_{OUT_{old}}^2} \quad (3.3)$$

with:

- Q_{new} : New leak flow rate in $bar \cdot cm^3/s$
- Q_{old} : Old leak flow rate in $bar \cdot cm^3/s$
- $p_{IN_{new}}$: New pressure inside the module
- $p_{OUT_{new}}$: New pressure outside the module
- $p_{IN_{old}}$: Old pressure inside the device
- $p_{OUT_{old}}$: Old pressure outside the module

After the test pressure is reached and the gas supply is isolated (or disconnected), a certain stabilisation time is recommended for temperature stabilisation, to be added to the minimum time.

A numerical example is reported here below. A Mixer Module shall be certified for a reference leak rate of $< 10^{-3}$ STD cc/s. The test parameters are as follows:

- The internal free gas volume of the part of the rack tested is 900 cm^3 ;
- For the test, the rack will be pressurized to 2 barg;
- The pressure reading has an accuracy of 20 mbar;
- At the start of the test the atmospheric pressure is 970 mbar and the temperature in the laboratory is 22°C ;
- The leak test is stopped after 14 h (next morning), at this moment the temperature in the laboratory is 20°C , the barometric pressure is 968 mbar and the recorded pressure in the test device 1.78 barg.

Step I

The reference leak rate (for $\Delta p = 1$ bar) is translated into a leak rejection limit at test conditions ($\Delta p = 2$ bar) using Equation 3.3.

$$Q_{adm} = 10^{-3} \text{ bar} \cdot \text{cm}^3/\text{s} \cdot \frac{(2 + 0.970)^2 - 0.970^2}{2^2 - 1^2} = 2.63 \cdot 10^{-3} \text{ bar} \cdot \text{cm}^3/\text{s}$$

Step II

Equation 3.2 is used to estimate the time needed for the test, if temperature and barometric pressure are unaltered.

$$\Delta t \geq \frac{273\text{K} \cdot 900\text{cm}^3}{295\text{K} \cdot 2.63 \cdot 10^{-3} \text{ bar} \cdot \text{cm}^3/\text{s}} \cdot \frac{0.020\text{bar}}{3600} \approx 1.76\text{h}$$

Step III

At the end of the test, it is possible to calculate the effective leak rate under the given experimental conditions using Equation 3.1:

$$Q_{leak} = \frac{273K \cdot 900cm^3}{14h \cdot 3600} \cdot \left(\frac{2.970bar}{295K} - \frac{(1.78 + 0.968)bar}{293K} \right) = 3.36bar \cdot cm^3/s$$

which is bigger than the rejection limit, and the rack is therefore not accepted.

Step IV

It is also possible to translate the measured leak rate into a leak rate at reference conditions using again Equation 3.3:

$$Q_{adm,ref} = 3.36bar \cdot cm^3/s \cdot 10^{-3} \cdot \frac{2^2 - 1^2}{2.970^2 - 0.970^2} = 1.29 \cdot 10^{-3}bar \cdot cm^3/s$$

The main advantage of this method is that it actually quantifies the leak and it can be performed with whatever clean gas, for example, a non-expensive one, like Nitrogen or Argon. On the other hand, it has some not negligible pitfalls: first of all, the pressure decay method can tell you there is a leak but you don't know where it is located. You can then think of splitting the module in sub-parts, if possible, in order to at least identify the line which is leaking. But this is not always feasible as often you don't have pressure transducers on each line, so it is impossible to read the pressure. One limitation of this method is indeed that you need to rely on pressure readings, meaning that you need to have physically installed sensors in the system. Also, you could wait a lot of time (depending on the pressure used to pressurise, the volume of the module and the sensitivity of the pressure sensor) and at the end, the only info you get is whether there's a leak or not without having clue where to intervene. One possible method that can be thought is to use leak detection sprays which can identify the potential leaking spots (e.g. connections) and see if the liquid product starts bubbling.

However, this simple and effective technique cannot be used for the CERN gas systems because these products can contain chemical substances that, if entering inside the system, could irreversibly damage the detectors or affect their performance.

On the contrary, the use of leak detectors can be a good choice. These devices can be a thermal conductivity leak detector or they can use infrared absorption sensing cell that is extremely sensitive to all refrigerants—and only refrigerants.

The method only allows an approximate quantification of the leak flow and should be used in particular to locate leaks that were measured with the pressure drop method. This method can also be used for quality control tests on individual connectors or components, but it should normally not be used for the final acceptance test of a gas module.

The main drawback of this method is that it requires the use of a traceable gas, but it allows to identify the leaking spots as soon as the system is under pressure. Besides, the majority of gas systems at CERN make use of detectable gases in their standard mixture, so it doesn't represent a big deal. To increase the sensitivity of the leak measurement, the applied over-pressure should be as high as possible, but at least as big as the future operating pressure. The over-pressure must be measured and recorded. Nitrogen and air, unfortunately, are not detectable, but Carbon Dioxide, Argon, Helium and many refrigerant gases are examples of detectable ones.

By the way, some are easier and better detectable than others or residuals are less

dangerous for the gas systems and detectors: for example, CO_2 is always preferable to Ar because more easily and accurately traceable, because present in many of the systems and especially because residuals of Argon in the mixture can alter the behaviour of the detector chamber resulting in too many discharges and streamers with the risk of damage. Thermal conductivity detectors are sensitive to all gases that have a thermal conductivity different from Air; background gases in the test area can therefore significantly alter the test result. A zero correction of the detector must be done regularly. The test surfaces should be clean, dry and oil-free; contaminants drawn into the leak detector may clog the probe or alter the signal. Normally, the detector shall be moved in front of the orifice leak in a distance of not more than 1 mm and moved not faster than 20mm/s.

The procedure states to combine the two methods: once the system is under pressure, filled using the most convenient gas among the available ones in the mixer lines (if present, CO_2 is preferable) you perform a first Leak identification using a sniffer in every line. If any leak is spotted, try to fix it. Then you wait some time, take note of pressure and temperature values and calculate the eventual residual leak rate: if the results are within the tolerances the system can be declared leak-tight, otherwise the leak identification with the sniffer must be performed again and more accurately. Leak identification then consists of:

1. The device to be tested must be filled homogeneously with a tracer gas different than air or nitrogen.
2. For racks with tricky and lengthy pipe-circuits the operator must ensure uniform distribution of the tracer gas by either flushing through the pipes or by several subsequent pressurisation of the module.
3. Sniffer carefully every single spot of the system. Mark the eventual leak detected with a marker and take note of the points for future reference (dangerous leak spots "blacklist");
4. According to the type of leaking spot (connection, pipe, valve, reducer...) perform the best appropriate reasonable action to try to eliminate the leak (e.g. for a connection at first attempt, if possible, gently tighten the threads, but not too much to not damage the gaskets). Once done perform again the test;
5. Wait the minimum amount of time and check pressure decay;
6. If no more leaks detected, great! Otherwise, a deeper investigation is needed (e.g. maybe the connections or the seals must be replaced because damaged. A list of possible causes can be done based on technicians experience);
7. The tracer gas vent should be outdoors or far away from the test area.

Why to combine the two methods? Because even if your sniffer doesn't spot any leak you can still have a pressure decay in time. These leaks through the components of the module (e.g. shut off valves) need to be replaced.

Once there are no more leaks the detectable gas can be vented to the exhaust. The leakage rate on a pressurised and sealed device, determines the total change of pressure over a given period of time and the observed pressure decay can be used to quantify the total leak flow of the device. The pressure decay method should be then still used for all final acceptance tests of the gas modules.

LEAK TEST PROCEDURE - MIXER

Leak test inside the rack: Put **Mixer Module in Forced Mode**.

For open mode systems HV-5014 is replaced by HV-6131 or HV6123
In case dedicated Analysis Modules are present for the mixer check if other valves have to be closed (e.g. IR).

- o **Detectable Gas Leak test** (after having re-mounted the DMFCs): use the most convenient gas among the available ones in the mixer lines. If present, CO₂ is preferable
 - a) Close supply valves inside the rack (HV-1X01)
 - b) Turn HV -1011 to System and close HV-5014
 - c) Open the valves:
 - HV-1X15
 - YV-1X05, YV-1X08
 - HV-1X07 and HV-1X10
 - YV-1004, YV-1006, YV-1008
 - (FIV-1005 and PCV-1007)
 - d) Send selected detectable gas to each line from the correspondent supply valve inside the rack (e.g. if only CO₂: open the CO₂ valve)
 - e) Set PCV-1X02 to ~0.5bar less then relief pressure of PSV-1010
 - f) Open the DMFCs (manual mode → regulated, set a set point flow)
 - g) When the system reaches everywhere the set pressure, close the supply valve and close again the valves HV-1X15 to isolate each line
 - h) Take note of PT-1X03 and PT-1009 reading (Check dead-band is less or equal to 0.1 bar)
 - i) Perform a first **Leak identification** using a sniffer in every line. If any leak is spotted, try to fix it.
 - j) Wait at least 6h.
 - k) Then compare the PI readings to the previous ones:
 - If the values did NOT change → No leak, turn the HV-1101 to Vent and go ahead with the procedure
 - If they did change → Fill the [excel table](#) for leak test:
 - If the result is ok, go ahead with the procedure
 - If not acceptable perform again **Leak Identification** using a Sniffer and fix the leaks. Then perform again the leak test and check if there are no more leaks

[Check drawing for final configuration](#)

Once all the leaks are fixed, empty the system from the detectable gas turning the HV-1101 to Vent.

FIGURE 3.12: Mixer Module Leak test procedure

An iterative process, making a leaking system leak-tight, can take a lot of time: similarly to management problems, a typical PDCA approach is here recommended, having in mind a continuous improvement target (kaizen).

Once the module is proven to be leak-tight, it should not be opened anymore until its next restart. If it is not possible, the leak test procedure must be performed again.

Once the procedure is completed and the form is entirely filled, it is also possible to print the filled form and eventually share the experience with other operators to constantly improve the maintenance effectiveness.

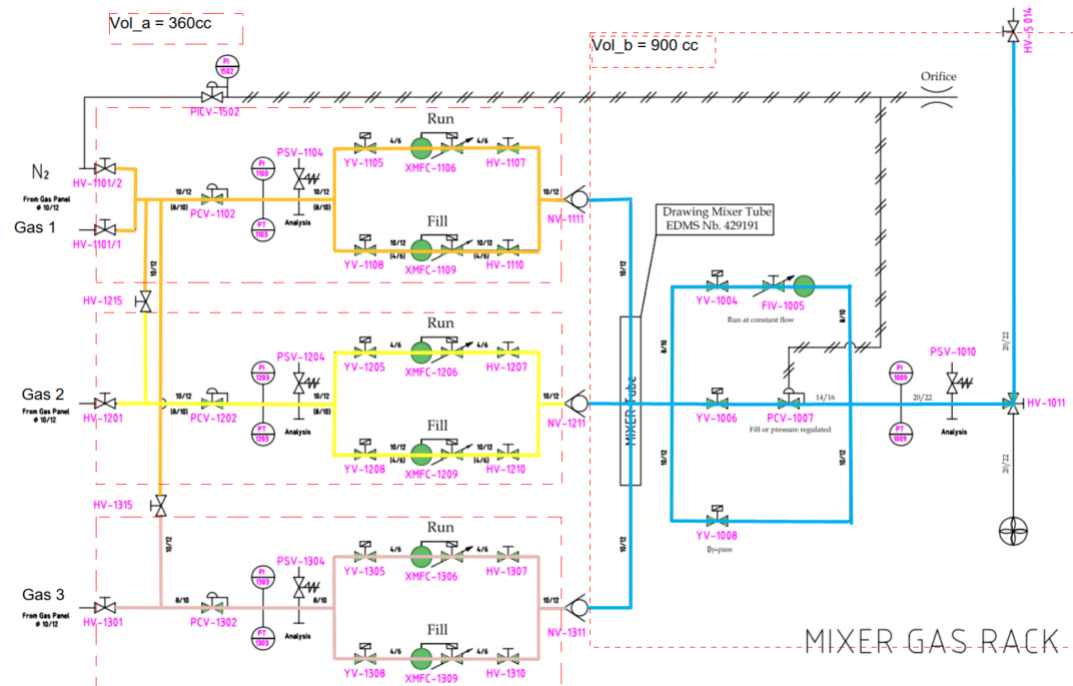


FIGURE 3.13: Mixer P&ID. Valves to be opened for the leak test are highlighted. Different isolated volumes are indicated as well.

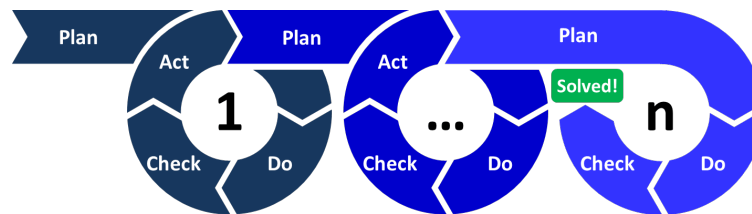


FIGURE 3.14: Multiple iterative loops of a PDCA (plan, do, check act) cycle, also known as Deming Cycle. The loops are repeated until the problem is solved. [23]

All the maintenance and leak test procedures can be found in the Appendices from A to D .

3.2.6 Conclusions and future possible developments

Maintenance and related leak test procedures have been developed for the modules Mixer, Exhaust, Pump, Purifier and Pre-distribution of the gas systems. The module Distribution is missing and will be developed soon.

These procedures match the needs of standard modules, with a standard design, but there are also some special systems: a more specific maintenance procedure for each gas system might be needed, especially for the ones with peculiar characteristics. Some future developments might be the implementation of a QR code to be attached on each module of each gas system linking to all the documentation and the information related to the module. Further good developments regarding the spare parts management could be the implementation of a Spare Parts Inventory. In general, as a good practice, the direction should aim to 5S implementation, towards a lean manufacturing and Industry 4.0 approach.

Chapter 4

New regulation valves for CMS RPC Gas System

4.1 Introduction

The Compact Muon Solenoid experiment

The CMS experiment is 21 m long, 15m wide and 15 m high, and sits in a huge experimental cavern, a hundred of meters underground.

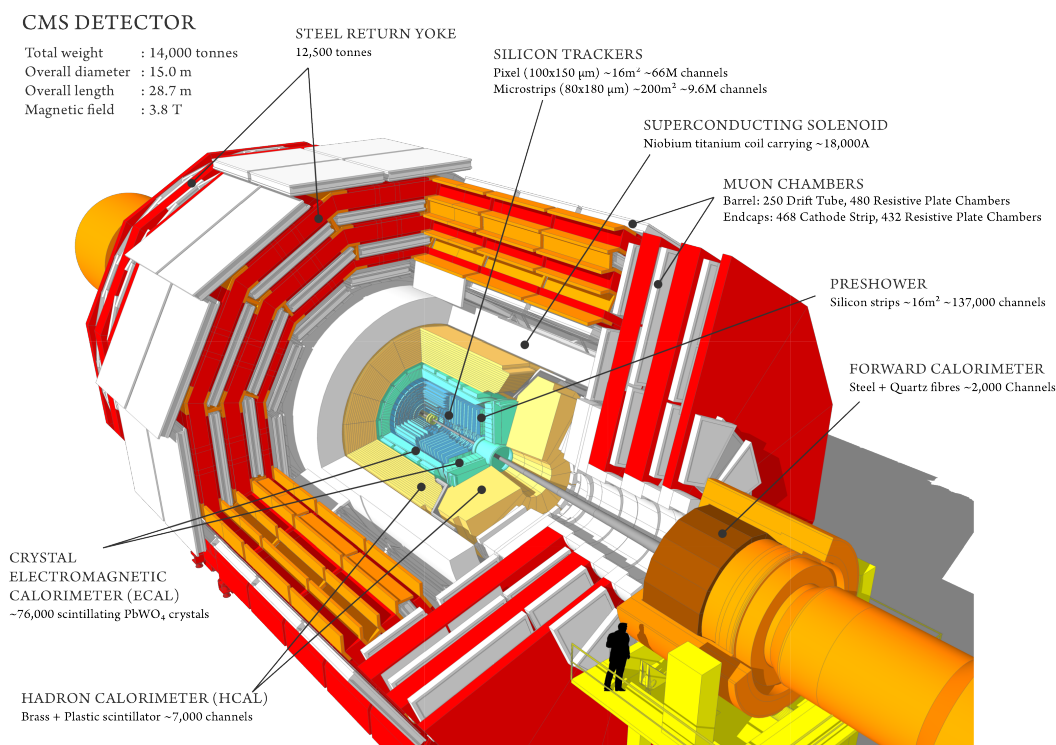


FIGURE 4.1: The Compact Muon Solenoid experiment [26]

The detector is built around a huge solenoid magnet. This takes the form of a cylindrical coil of superconducting cable, cooled to -268.5°C , that generates a magnetic field of 4 Tesla, about 100,000 times that of the Earth. The detector is like a giant filter, where each layer is designed to stop, track or measure a different type of particle emerging from proton-proton or heavy ion collisions. Finding the energy and momentum of a particle gives clues to its identity, and particular patterns of particles or “signatures” could be indications of new physics.

Particles emerging from collisions first meet a tracker, made entirely of silicon detectors, that chart their positions as they move through the detector, allowing to measure their momentum. Outside the tracker there are calorimeters that measure the energy of particles. In measuring the momentum, the tracker should interfere with the particles as little as possible, whereas the calorimeters are specifically designed to stop the particles in their tracks. The outer part of the detector, the iron magnet “return yoke”, confines the magnetic field and stops all remaining particles except for muons and neutrinos. The muon tracks are measured by four layers of muon detectors that are interleaved with the iron yoke. Because muons can penetrate several metres of iron without interacting, unlike most particles they are not stopped by any of CMS’s calorimeters. Therefore, chambers to detect muons are placed at the very edge of the experiment where they are the only particles likely to register a signal. A particle trajectory is measured by fitting a curve to hits among the four muon stations, which sit outside the magnet coil and are interleaved with iron “return yoke” plates (shown in red below in Fig. 4.2, for the barrel region).

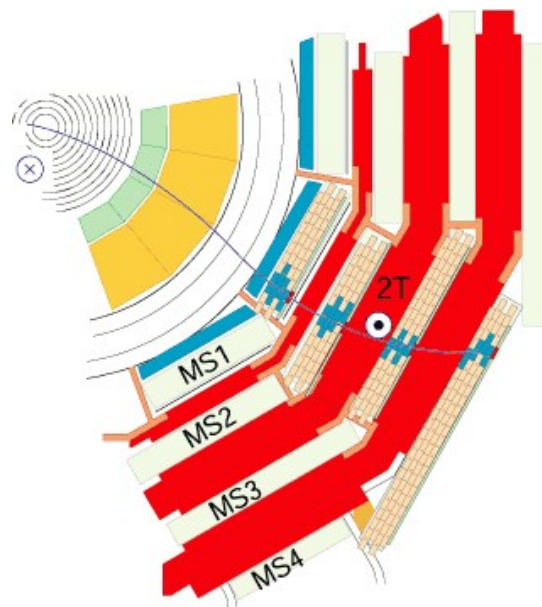


FIGURE 4.2: A muon, in the plane perpendicular to the LHC beams, leaves a curved trajectory in four layers of muon detectors ("stations") [26].

By tracking its position through the multiple layers of each station, combined with tracker measurements the detectors precisely trace a particle’s path. This gives a measurement of its momentum: the CMS magnet is very powerful so it’s possible to bend even the paths of very high-energy muons and calculate their momenta.

Muon chambers are arranged in such a way that every muon, with enough energy to cross the full detector, should traverse at least three of these stations. A longitudinal view of one quadrant of the CMS detector is shown in Fig. 1.3b. The muon system makes use of three kind of detectors: : the Drift Tubes (DTs) and Cathode Strip Chambers (CSCs) track the particles’ positions and provide a trigger, while Resistive Plate Chambers (RPCs) form a redundant trigger system, which quickly decides to keep the acquired muon data or not. Because of the many layers of detector and different specialties of each type, the system is naturally robust and able to filter out background noise. DTs and RPCs are arranged in concentric cylinders around

the beam line (“the barrel region”) whilst CSCs and RPCs, make up the “endcaps” disks that cover the ends of the barrel.

CMS Resistive Plate Chambers

Resistive Plate Chambers (RPCs) are gaseous parallel-plate detectors extensively employed at the Large Hadron Collider (LHC) experiments as a part of their muon trigger systems. RPCs basically consist of two parallel plates (see fig. 4.3, a positively-charged anode and a negatively-charged cathode, both made of a very high resistivity plastic material and separated by a gas volume.



FIGURE 4.3: Resistive plate chamber (RPC) [26].

As explained in section 1.4, when a particle passes through the chamber, electrons are knocked out of gas atoms. These electrons in turn hit other atoms causing an avalanche of electrons. The electrodes are transparent to the signal (the electrons), which is instead induced on external metallic strips. The pattern of hit strips gives a quick measure of the muon momentum, which is then used by the trigger to make immediate decisions about whether the data are worth keeping. RPCs combine a good spatial resolution ($\approx 1\text{cm}$) with a time resolution of just few nanoseconds. At CMS, RPCs are widely used: 480 of them are installed in the barrel, 432 in the endcaps (Figure 4.1, [26]).

RPC gas distribution system

Due to its large volume (18 m^3) the RPC detector system of the CMS experiment employs a gas re-circulation system. Since the mixture composition and quality are crucial issues for the detector operation, CMS-RPC uses an online gas analysis and monitoring system. RPCs are operated with a three component non-flammable standard mixture: 95.2% of R134a ($\text{C}_2\text{H}_2\text{F}_4$), 4.5 % of $i\text{C}_4\text{H}_{10}$ and 0.3% of SF_6 . Water vapor should be added to the gas mixture in order to maintain a relative humidity of about 45% and avoid any changes of the bakelite resistivity. Moreover, the large detector volume and the use of a GHG and relatively expensive gas mixture make a closed-loop circulation system unavoidable.

In Fig. 4.4 a scheme of the RPC gas system is reported.

As shown in the scheme, the gas flow leaves the SG from Humidifier module and reaches the USC55 in Pre-Distribution Input modules of endcap+, endcap- and barrel. From there each line is split in different numbers, accordingly to the number of racks in the distribution. From USC then pipes go to experimental cavern UXC55 to the respective Distribution racks. As previously mentioned before, Distribution racks are spread over the detector cavern, distributed in three main regions: barrel

TABLE 4.1: CMS RPC gas system

Total volume of the CMS-RPC	18 m ³
Gas mixture composition	95.2 % R134a, 4.5 % iC4H10 and 0.3 % SF6
Mixture relative humidity	40 - 50 %
Number of channels	360
Nominal gas flow	8 m ³ /h
Maximum gas flow	18 m ³ /h
Gas re-circulation factor	95%
Fresh gas replenishing rate	5 %

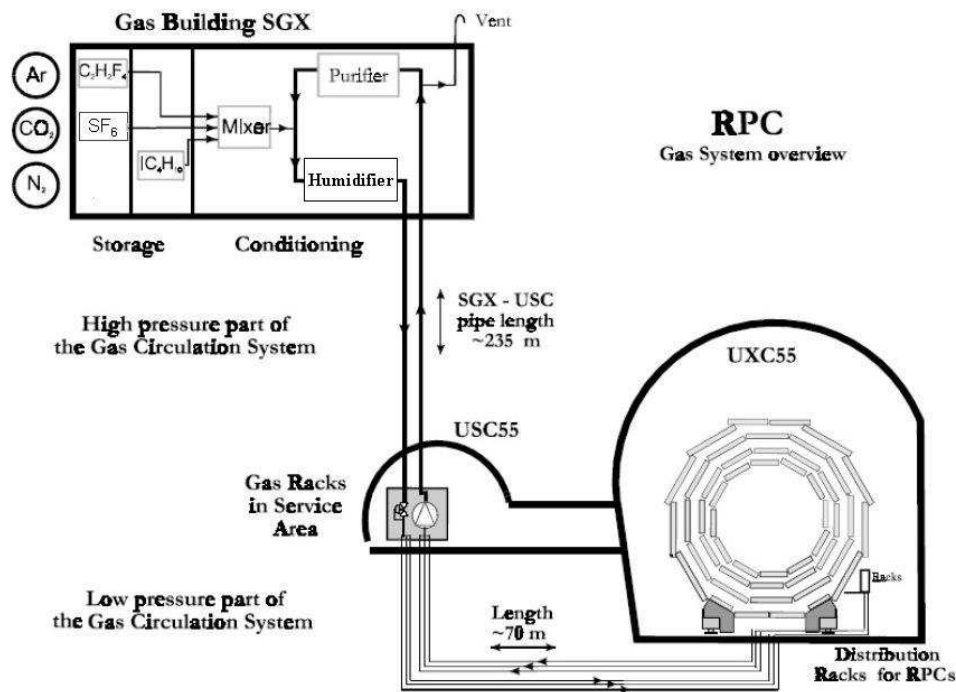


FIGURE 4.4: CMS RPC gas system scheme [1].

(RB), positive endcap (RE+) and negative endcap (RE-). From the distribution racks many channels, corresponding to the RPC chambers to feed, start and go in the different zones of the detector. The barrel region is then divided into top and bottom parts, whereas endcaps regions are divided into two concentric regions, called inner and outer. Return pipes from the chambers are then collected again in the Distribution racks and the gas is pumped up to USC in Pre-Distribution Output racks by the pump module and sent back to SG for purification. P&ID of pre-distribution and distribution are shown in the following figures.

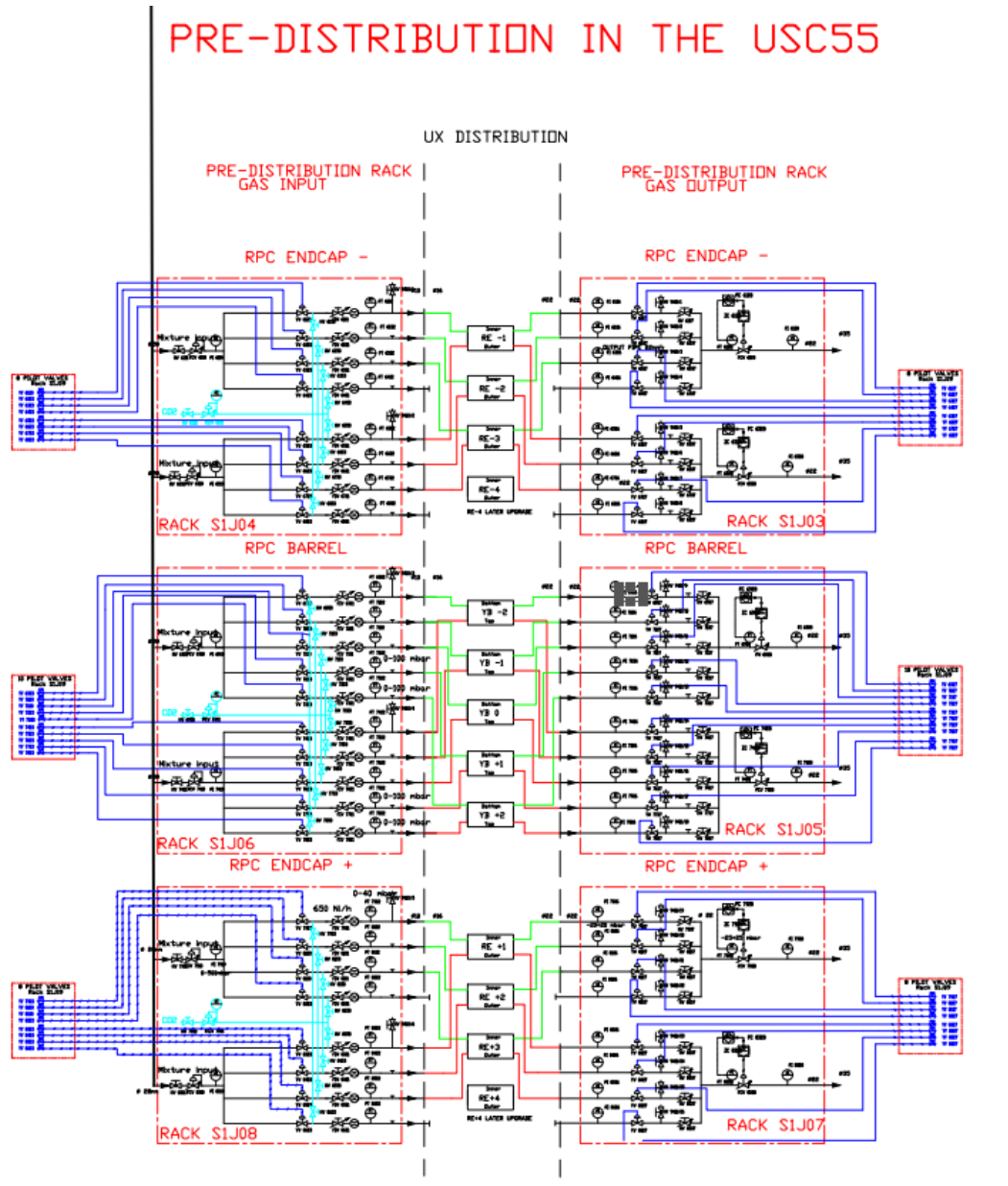


FIGURE 4.5: CMS RPC Pre-Distribution P&ID

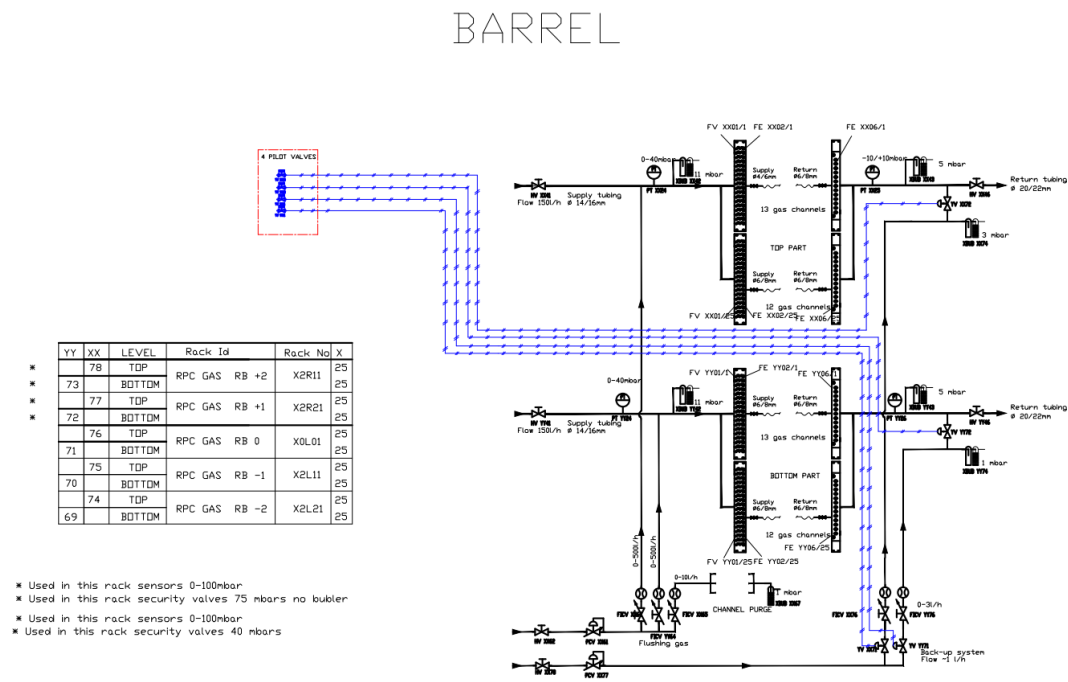


FIGURE 4.6: CMS RPC barrel distribution P&ID

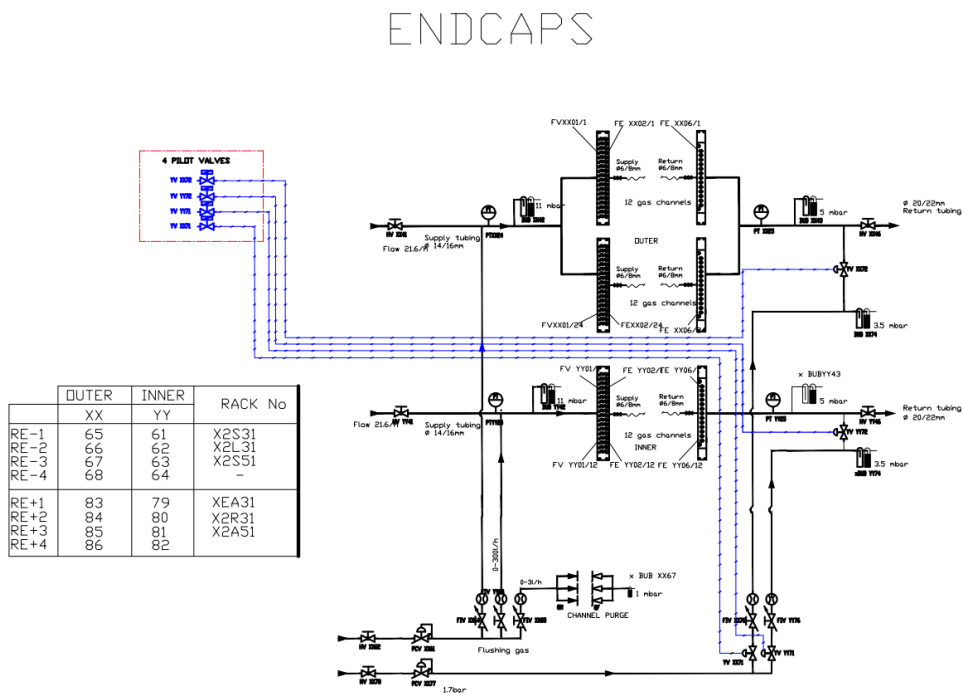


FIGURE 4.7: CMS RPC endcap distribution P&ID

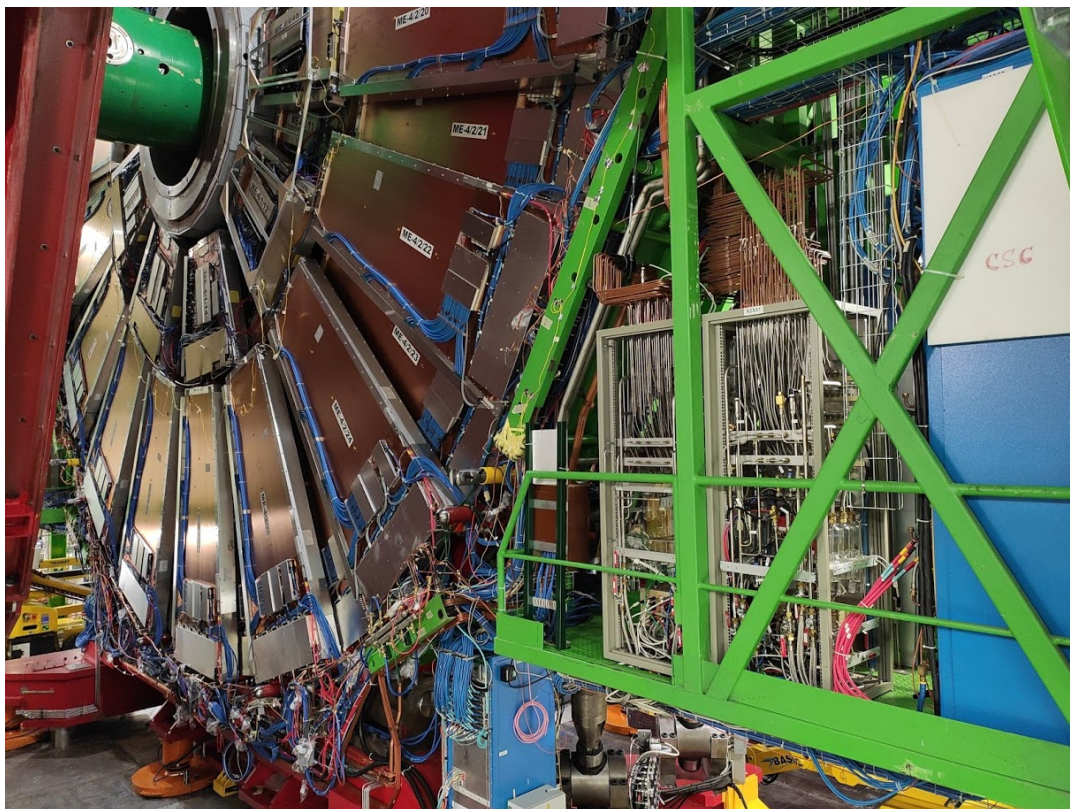


FIGURE 4.8: CMS RPC endcap in UXC55



FIGURE 4.9: CMS RPC barrel distribution rack in UXC

4.2 New regulation valves: problem definition and technical specs

To regulate chamber pressure and equalize the pressure between different detector zones to make the return possible, manual regulation valves are installed in the pre-distribution racks. These manual valves are installed in Pre-Distribution Output racks in USC, mentioned in the P&ID as HV-6X37 (see Figures 4.10 and 4.11) and visible in fig. 4.12. The valves are installed in USC for practical reasons: space constraints in UXC racks and, especially, impossibility access and regulate during RUN phase. After regulation, the return lines are arranged in different groups and additional group pressure regulation is done by a mechanical back pressure regulator (PV-XY28, Fig. 4.10 and 4.11) to make the flows from different groups mix again.

Detector pressure regulation is done basing on pressure sensors PT-XY04 at rack level (XY rack number, e.g. 70). The regulation is particularly critical during the gas filling and emptying phase, or when gas mixture is changed, so pressure can either change due to dynamic or static effects or because of hydrostatic weight change. Operating with the manual valve is a very delicate, time consuming and unstable operation during these phases. Moreover, given that detector connections are really fragile and it has been proved they easily break due to vibrations or oscillations (if broken, these connectors are often not accessible, so not fixable nor replaceable, leading to chambers leakage), a manual regulation might not be effective enough to avoid pressure fluctuations or peaks and keeping the chamber pressure constant.

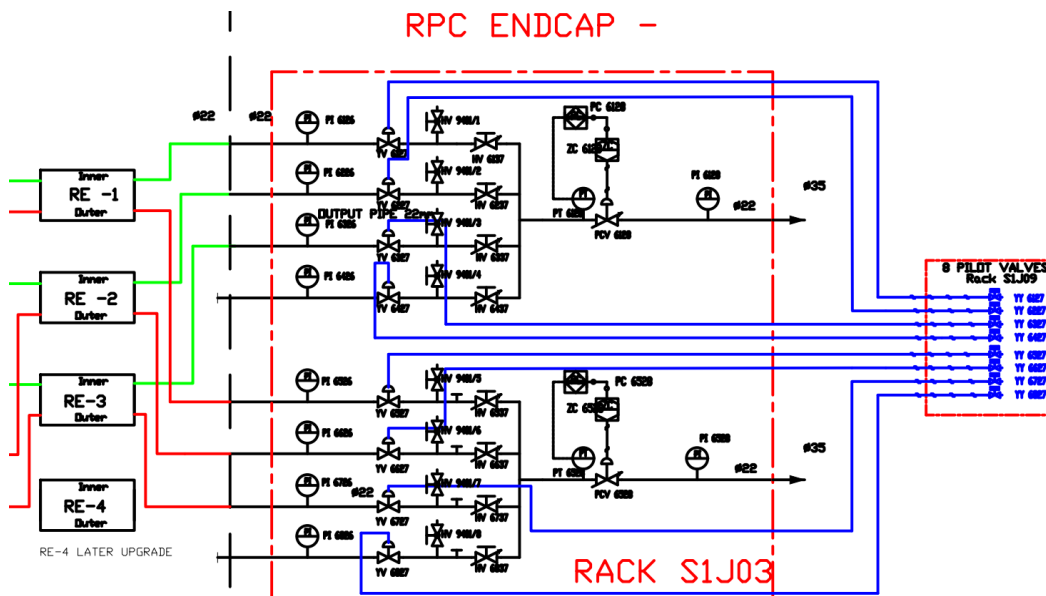


FIGURE 4.10: CMS RPC endcap pre-distribution output P&ID

The replacement of manual is therefore fundamental for a better and automated regulation, also safer because there would be no need to go in place to perform regulation if a sudden change happen, reducing time of action if a regulation is needed and keeping safe the detectors at the constant desired pressure.

Surely an automated regulation valve would be a more expensive solution, but it might be a worth upgrade considering its benefits on operational time and risk reduction.

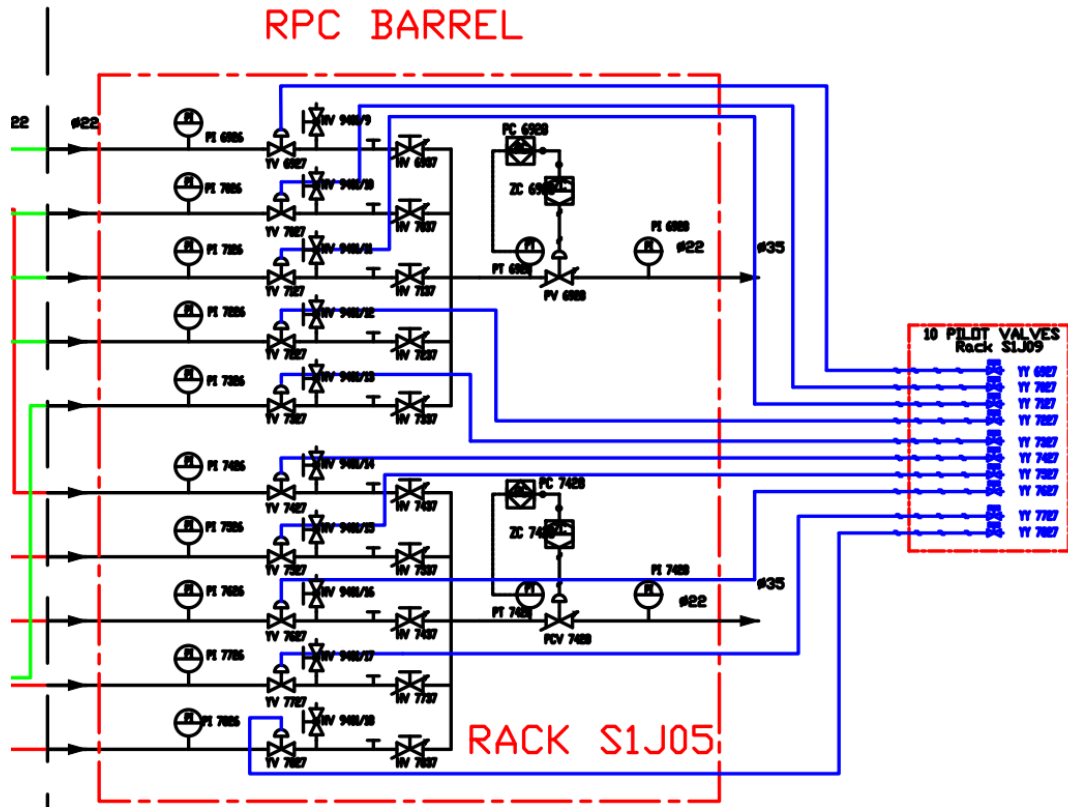


FIGURE 4.11: CMS RPC barrel pre-distribution output P&ID

What makes the search for the valve challenging is the application and requirements: very low pressure and precision required, space constraints, presence of magnetic field, particularity of the gas media and budget constrains (30 valves will be needed). To summarize, the technical specifications and requirements for the application are:

- Process gas: standard mixture 95.2% of R134a ($C_2H_2F_4$), 4.5% of iC_4H_{10} and 0.3% of SF_6
- Valve silicon free
- Normal flow rate: $\approx 600NL/h$ in the barrel, $\approx 300NL/h$ in the endcap
- Input pressure around 0mbarg
- Maximum Δp allowable on the valve 10mbarg
- Pipe OD 22mm
- Connection requirements: G 1/2"-1" ISO 228-1 (DIN 259, BSPP)
- chamber pressure to be controlled around 0-5 mbarg with a precision required within tenths of mbar.



(A) Pre-Distribution Output positive endcap rack

(B) CMS USC55 racks view

FIGURE 4.12: CMS RPC gas system in the underground service cavern

Calculation of K_v flow coefficient value is then possible [24], considering for gas properties the ones of R134a, being the one in highest percentage and denser.

- If $\Delta p < \frac{p_1}{2}$, sub-critical conditions occur, so:

$$K_v = \frac{Q_N}{514} \sqrt{\frac{\rho_N \cdot T_1}{\Delta p \cdot p_2}} \quad (4.1)$$

- If instead $\Delta p \geq \frac{p_1}{2}$, the flow is chocked and the formula is:

$$K_v = \frac{Q_N}{257 \cdot p_1} \sqrt{\rho_N \cdot T_1} \quad (4.2)$$

where:

- Q_N : NTP flow rate [$\frac{Nm^3}{h}$]
- ρ_N : NTP density [$\frac{kg}{Nm^3}$]
- p_1 : absolute inlet pressure [bar]
- p_2 : absolute outlet pressure [bar]
- Δp : pressure differential [bar]
- T_1 : inlet gas temperature [K]

Substituting the numerical values, in particular at the maximum flow rate, a $K_v = 0.39m^3/h$ is obtained. An increment of 30% can be added to obtain the minimum required design K_v of the valve:

$$K_{v,d} = 1,3 \cdot K_v = 0.51 \frac{m^3}{h}$$

This design value, together with all the application specifications, has been provided to various valves producers and re seller companies in order to find the best suitable product.

Regarding electrical and control specifications, a 4 - 20 mA control signal with feed-back is preferred, being simple to implement with the PLC and more stable than voltage control with long cables. No ATEX application is required and a IP65 (EN60529) electrical enclosure protection is sufficient.

Different kind of valves and working principles were investigated. Among these: solenoid valves, pneumatic and electrical actuated, pinch valves, etc.

As result of the search, some considerations could be done:

- not many valves could suit the application needs
- the low-pressure application often implied a big sized valve, especially if pneumatic
- mechanical back pressure regulators are not suitable because the pressure to control is far away ($\approx 100m$) from the valve itself and, again, due to low pressure the regulator would be really big and not fit
- solenoid valves often showed hysteresis and they might not work properly in presence of an external magnetic field, so they need to be tested also in presence of magnetic field
- expensive solutions due to the low-pressure range to be controlled and the fine regulation required

A list of the tested valves is shown in Tab. 4.4.

In the following a quick overview of the valves investigated.

ASCO

Among the solenoid valves, some [ASCO Series 290](#) proportional motorised valves were tested, with different orifice sizes.

TABLE 4.2: ASCO proportional valves tested

VALVE	$K_v [\frac{m^3}{h}]$
ASCO DN4	0.42
ASCO DN15	3.8
ASCO DN20	6

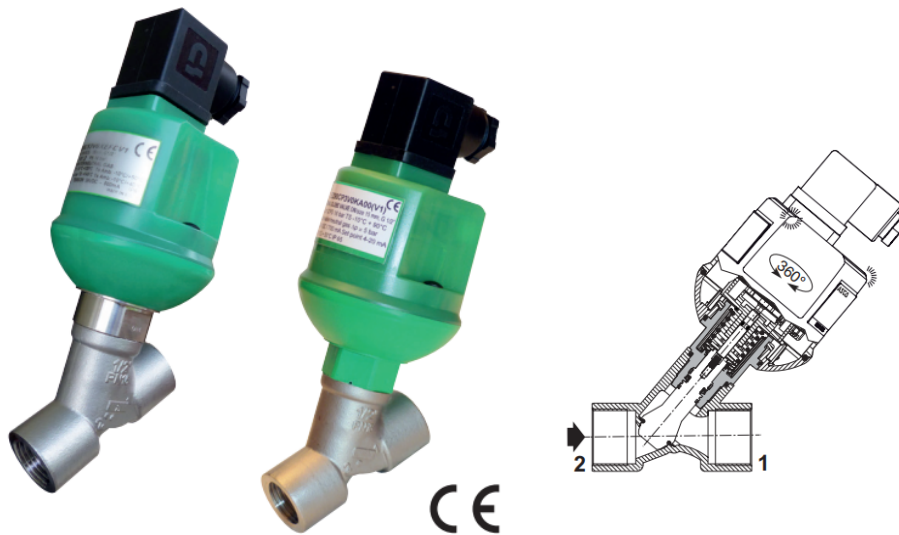


FIGURE 4.13: ASCO proportional motorised valve

All the valves are 2/2 way, fail closed or NC (closing of the valves in case of power failure). These valves are designed to have a flow proportional to the input signal, which is a DC current with setpoint in the range 4-20mA. Power supply 24VDC and they also have feedback signal for the control of the position. Flow regulation characteristics: linearity $\pm 5\%$; hysteresis $< 5\%$; accuracy $< 3\%$; sensitivity $< 3\%$; repeatability $< 3\%$. In Tab. 4.2 the K_v values of the ASCO valves tested.

BURKERT

Then [Type 2875](#) direct-acting 2 way standard solenoid control valves from BURKERT with different orifice sizes were tested. In Tab. 4.3 the K_v values of the Burkert valves tested.

TABLE 4.3: BURKERT proportional valves tested

VALVE	$K_v [\frac{m^3}{h}]$
BURKERT 8mm	1.5
BURKERT 9.5mm	1.4
BURKERT 12mm	2.5
BURKERT 12S	2.5

They are also controlled by a 4-20mA signal, but it is sent to a electronic control unit which converts the current signal in a PWM signal for the valve. They do not

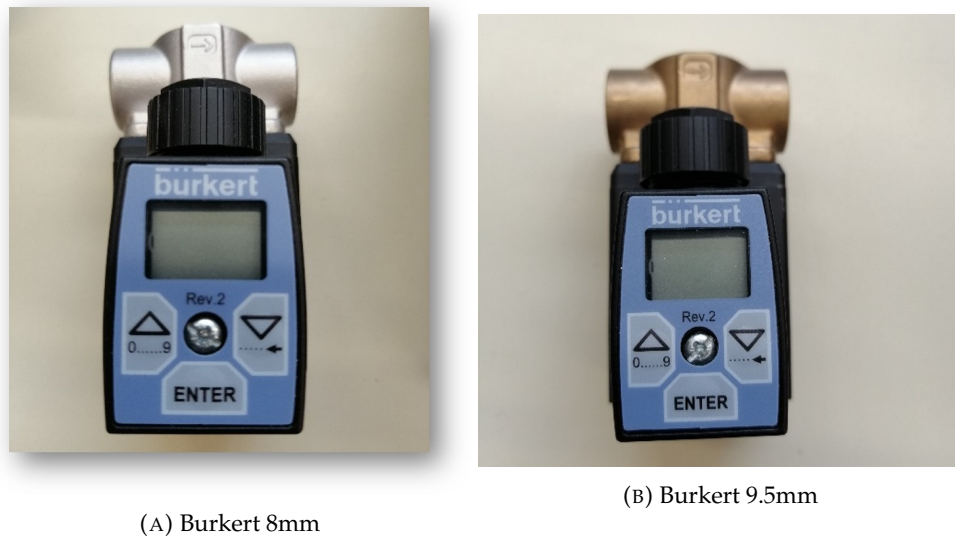


FIGURE 4.14: Burkert valves

have feedback signal. Regarding the control data at PWM-control, maximum values are: hysteresis < 5%, repeatability < 0.5% FS (by flow measurement), sensitivity < 0.25% FS, span 1:200, response time (10-90%) 25ms. These valves are very compact.

Bronkhorst

A solenoid valve from BRONKHORST was also characterized, [model F-004AC](#). It is a control bellow valve with pressure compensation for Low Pressure Drop applications. It is closed by spring force, but bellows compensates the closing force acting on the plunger to such a degree that only a very small magnetic force is required and, in this way, large orifices can be opened, without causing oscillation. The bellows pressure compensated design enables to smoothly control large flows at extremely low pressures. The control input current is not the classic 4-20mA, but in the range 60 - 190 mA. This valve is also very compact, but quite expensive.

Von Rohr

In addition to solenoid valves, some other of different technologies were also tested, starting from a pneumatic actuated valve from VON ROHR ([series 8B](#)), controlled by an electropneumatic 4-20mA positioner. Air pressure for the pneumatic actuator should be in the range 3-6 bar; the K_{vs} of the valve is 1, with equal percentage characteristic. The issue with this valve is that it is cumbersome and quite expensive.

Festo

Other pneumatic solutions were offered by FESTO. A first one is composed of a simple ball regulation valve ([model VZBA](#)) on which is mounted a pneumatic quarter turn actuator ([model DFPD](#)) actuated by an electropneumatic position regulator ([model CMSX](#)). The air pressure for the actuator should be in the range 3-8bar, then regulated by the reducer with a 4-20mA signal. Different spherical bodies with different shapes and K_v were tested.

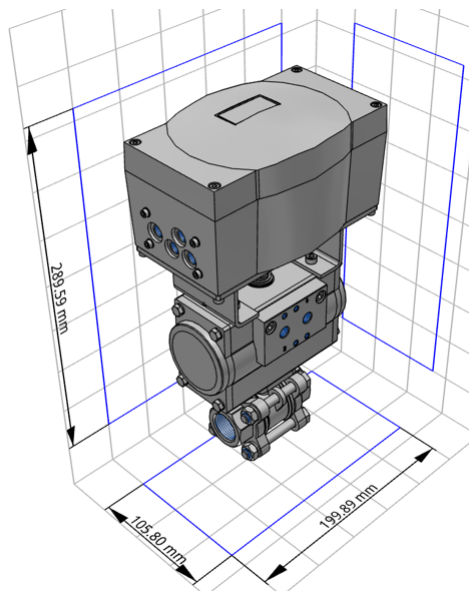


(A) Bronkhorst F004AC valve



(B) Von Rohr pneumatic valve

FIGURE 4.15: Bronkhorst and Von Rohr valves



(A) FESTO pneumatic actuator on spherical valve

Vanne à pincement



(B) Burkert 9.5mm

FIGURE 4.16: FESTO pneumatic valves

A second solution is a pneumatically actuated pinch valve ([model VZQA](#)), controlled by an electropneumatic proportional pressure regulator ([model VPPM](#)). Service compressed air pressure should be within 3.5-6bar; linearity error < 2%, repeatability 0.5% FS. The K_v of this valve is 5 m³/h, bigger than needed, but the solution was compact so considered worth to try.

ResolutionAir

Combining the characteristics of pinch valve fluid separation and proportional valve control, the Hybrid Proportional Pinch Valve ([HPPV-12](#)) pinches a fluid-filled, low durometer (50-65 Shore A) hose effectively varying the orifice size to regulate the flow of the fluid (liquid or gas) through the tube. The design incorporates a step-per linear actuator (stepper motor and lead screw) and a custom piston in a miniature aluminium valve body (see fig. 4.17). The bi-polar stepper motors used in the Miniature Proportional Pinch Valve require two input control signals, a Pulse Width Modulated (PWM) step signal and a digital binary signal which determines the clockwise/anti-clockwise motor rotation. The two signals must be generated by the PLC and then amplified by a bi-polar chopper driver ([DRV-1 Step Motor drive](#)).

Despite the many advantages this solution can offer, the valve is quite expensive and the control of the valve is not classical and requires quite a lot of work from software side, being necessary to program the PLC fixing PWM frequency, motor velocity, and other parameters. For the test a simple code was written using EcoStruxureTMControl Expert by Schneider.



FIGURE 4.17: ResolutionAir pinch valve

Gulex

Among the more mechanical actuated solutions the simplest seemed to install an electrical motor on the stem of the same manual valve currently installed. For this purpose, the [N802/P7 model](#) valve actuator from GULEX was tested. The motor is controlled with a 4-20 mA positioning signal and it has a position hysteresis < 3 deg and position accuracy of 0.25%. The motor rotations were adjusted accordingly to the manual valve ones. Of course, the pressure-opening curve exactly follows the manual valve, but the motor shows the possibility of a really fine regulation. The

drawbacks of GULEX motor are the cost and its dimensions (see fig. 4.18).



FIGURE 4.18: GULEX motor

Econex

The [MPV series control valve](#) from ECONEX are actuated by a unipolar and bidirectional electric motor. Its position is proportional to an analogic 4-20mA current input control signal. A cylindrical plug, linear featured, regulates the flow rate of the valve. By cylinder rotation, the orifice size of the plug changes with, adjusting the flow linearly. The K_v of the tested valve is $1.5\text{m}^3/\text{h}$. This mechanical solution is cheaper than the previous one. Only problem of this valve is that it is quite bulky and it might be difficult to fit many of those valves in the existing system.



FIGURE 4.19: ECONEX MPV valve

In total, twenty-eight valves are needed: the perfect valve is then the one which best satisfies the trade-off between technical behaviour, cost and dimensions.

TABLE 4.4: List of valves tested in Lab and characterised

	VALVE	Type	Cost [CHF]
1	ROTAREX	manual	100
2	GULEX motor	electrical actuator for manual valve	1400
3	ASCO DN4	solenoid	440
4	ASCO DN15	solenoid	320
5	ASCO DN20	solenoid	315
6	BURKERT 8mm	solenoid	420
7	BURKERT 9.5mm	solenoid	340
8	BURKERT 12	solenoid	780
9	BURKERT 12S	solenoid	500
10	RESOLUTIONAIR	pinch valve - stepper motor	1300
11	BRONKHORST F004	solenoid	1460
12	FESTO PINCH	electropneumatic	710
13	FESTO SPHERICAL	electropneumatic	620
14	ECONEX	electro actuated	500
15	VON ROHR	electropneumatic	3300

4.3 Tests

A series of tests were performed in laboratory to characterise and see the behaviour of the different valves. On the basis of these tests' result, few regulation valves were installed in the experiment for the final test the final decision will be taken.

In the next paragraphs each test will be described in details and their results shown and commented. The characterization of each valve is performed with the following test:

1. Laboratory characterization
2. Ageing test
3. Test in USC in real conditions
4. Magnetic field test

4.3.1 Characterization of the valves in laboratory

The first test performed is a test with a simple laboratory setup in order to characterize each valve in terms of pressure versus opening of the valve. As shown in Fig. 4.20 the setup is composed of:

1. Thermal flow meter
2. Pressure Transducer
3. Valve under test
4. Pressure reading
5. Valve position controller

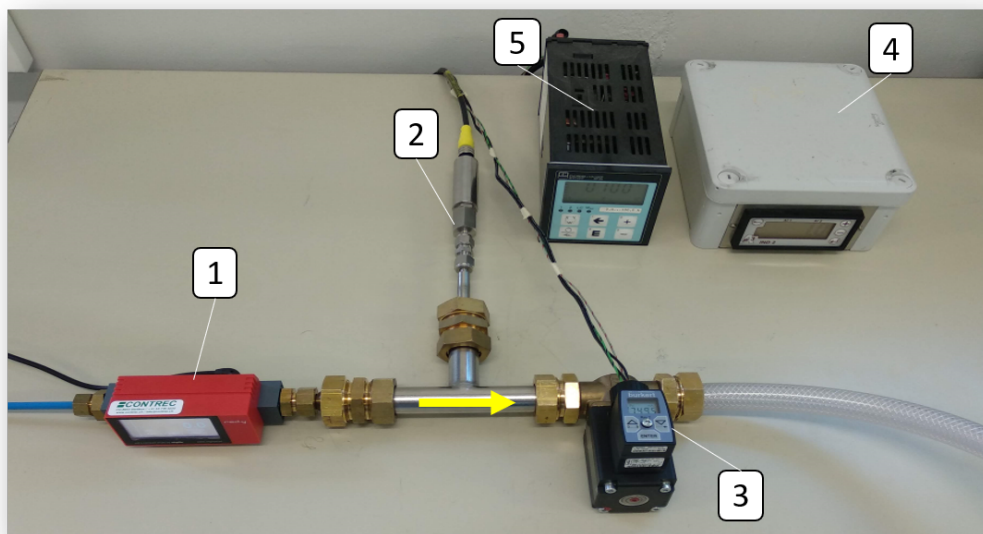


FIGURE 4.20: Lab test setup

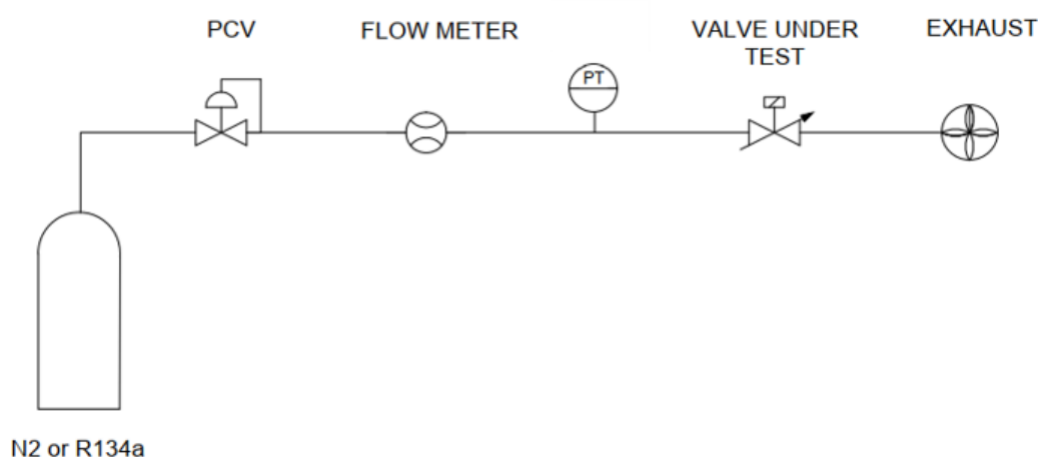


FIGURE 4.21: Lab setup scheme

In Fig. 4.21 a P&ID scheme of the setup is reported as well.

At starting position, the valve under test was fully open (100%). The gas was supplied from gas bottles and the flow was set and kept constant adjusting a pressure regulator installed in the line: the valve was then closed in little steps, the increased pressure value was read by the pressure transducer and recorded, paying attention to open the pressure regulator accordingly to closing of the valve to keep the flow constant.

The pressure monitored is the one upstream the valve, like the one to control in the experiment. As clearly shown, the setup was in open line: the gas was then vented to exhaust.

Each test was performed for two values of flow rates, simulating the two different flow conditions for barrel and endcap: the flow rate of the standard mixture at run regime conditions is about 570 L/h for the barrel distribution lines, while for the endcap the flow rate is about 300 L/h. The goal is to find a similar behaviour with a good and stable regulation, having the manual one as a target or desired curve as in Fig. 4.23.

It is necessary to specify now that these values express the normal flow rate for R134a flow. Some conversion factors can be calculated to have equivalent flows in Nitrogen, based on different thermal properties of the two gases. This problem arose because the thermal flow meter is calibrated for nitrogen, so we had to calculate what is the value we should read on the device when we are sending the correct flow rate value of Freon and what is the value of nitrogen flow rate which is equivalent to the freon one.

Using *FLUIDAT[®]ontheNet* from Bronkhorst (fig. 4.22), we can calculate the conversion factor between Nitrogen and R134a flows.

The conversion factor from Nitrogen to Freon is $CF_v = 3.402$, meaning that 1 Ln/min of freon is equivalent to 3.402 Ln/min of Nitrogen. This conversion factor is the division factor that is used to calculate the normal mass flow quantity of a certain reference fluid that should be applied to a thermal mass flow instrument in order to obtain the same output signal as it would read when applying the final operation

	Fluid from		Fluid to	
Fluid:	N2 ("Nitrogen")		C2H2F4 ("1,1,1,2-Tetraflu...")	
Phase:	Gas		Gas	
Flow:	1	In/min	0.2940	In/min
	0.00 °C and 1013.25 hPa (a)		0.00 °C and 1013.25 hPa (a)	
Pressure:	1	bar (a)	1	bar (a)
Temperature:	20	°C	20	°C
Density (n):	1.250	kg/m ³	4.694	kg/m ³
Heat capacity (cal):	1043	J/kg.K	945.0	J/kg.K
Viscosity:	1.747E-05	Pa.s	1.250E-05	Pa.s
Thermal cond. (cal):	0.02939	W/m.K	0.01672	W/m.K
Instrument model ¹⁾ :	UNIVERSAL			

FIGURE 4.22: Gas conversion factor calculation on FLUIDAT

fluid for the target instrument.

In principle the conversion factor between two fluids is a multiplying flow factor of which the value depends on the flow measuring principle. At Bronkhorst the conversion factor applies only to thermal mass flow instruments using volume flow units referenced to normal conditions of 0 °C and 1013.25 hPa(a). For a thermal mass flow meter the conversion factor is proportional to the Heat Capacity C_p and the Normal density ρ_n of the fluids for which the flow factor is calculated and thus related to volume flow units referenced to normal conditions only.

In formula, the conversion factor CF_v is:

$$CF_v = \frac{C_{p,1} \cdot \rho_{n,1}}{C_{p,2} \cdot \rho_{n,2}}$$

In which:

C_p : heat capacity at constant pressure in [J/kg.K]

ρ_n : normal density in [kg/m³], at 0 °C and 1013.25 hPa(a)

The indices apply to the operation fluid (Fluid1) and the calibration fluid (Fluid2). As the mass flow for a thermal mass flow meter is directly proportional to $C_p \cdot \rho_n$, the formula for the converted flow shows like:

$$Q_2 = \frac{Q_1}{CF_v}$$

In which:

Q_1 = instrument flow using Fluid1 in normal volume flow units (f.i. l/min)

Q_2 = calibration flow using Fluid2 in normal volume flow units (f.i. l/min)

So, the 285L/h freon flow corresponds to a nitrogen flow of $285\text{L/h} \cdot CF_v = 969.57\text{L/h} \approx 16\text{L/min}$, whereas, similarly, the 570L/h freon flow to a nitrogen flow of 32L/min.

These values were set and kept constant during the tests: in particular, when using Nitrogen, flow rates of 16 and 32L/min were used because different gas from Freon was used and in this way we had the equivalent flow; when using Freon, still 16 and 32L/min were set because, even if the gas was the correct one, the reading device is calibrated for Nitrogen, so we have to correct the reading to the equivalent

Nitrogen flow.

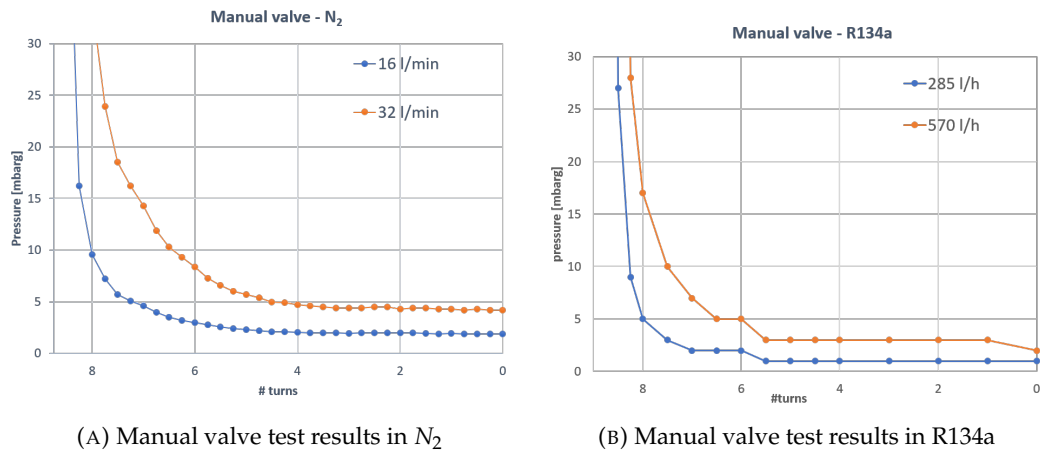


FIGURE 4.23: Manual valve characterization

The test is performed using first the equivalent flow in N_2 , to have a first idea of the behaviour of the valve, avoiding to waste the more expensive and toxic R134a. For the valves which showed an interesting behaviour, a second and more accurate test was done using the real Freon flow.

In the following pages, some of the results are reported, showing the characteristic curves of some tested valves, with the two different flow rates and different gases.

Only results for Burkert 9.5 are shown, being the behaviour of Burkert 8mm very similar. The hysteresis of the valve has been noticed during the test (Fig ??). Burker's seem to have a limited regulation range, that is, the pressure starts increasing quite soon during the closing of the valve (around 50% the pressure is already above the requirements). By the way, if we compare the shape of the curve and the amplitude of the effective working range, we notice that it is not so different from the manual one. If the Burkert curves would be shifted, they would be very similar to the manual one (Fig. 4.25a). In Fig. 4.25b indeed, the curves have been shifted and the Burkert is following the manual one, meaning that it is able to perform the same pressure regulation but in a different working position range.

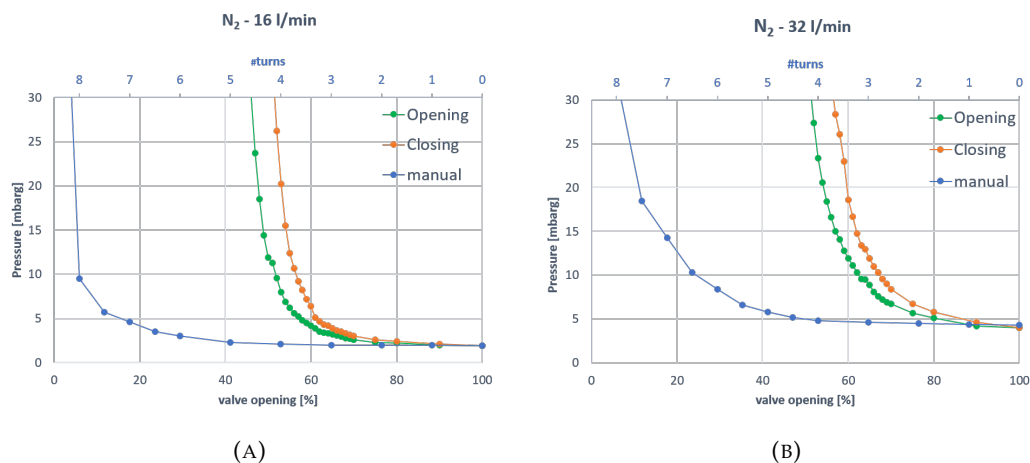


FIGURE 4.24: Burkert 9.5mm N_2 characterization curves

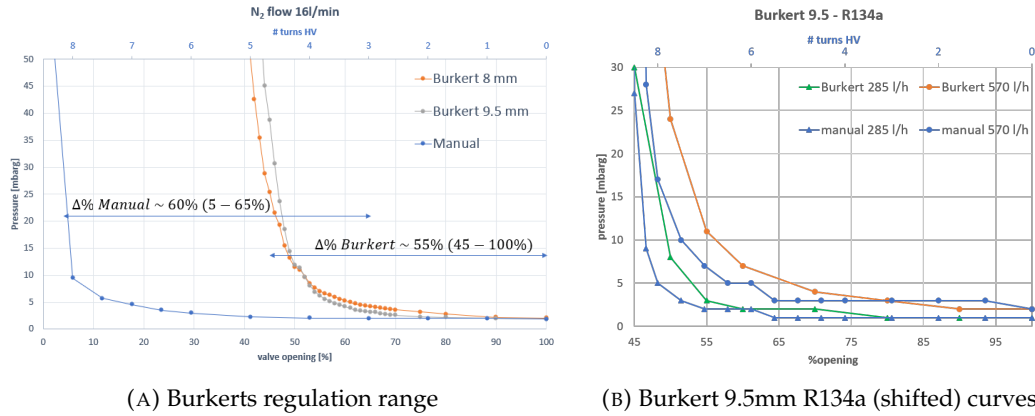


FIGURE 4.25: Burkert characterization

Comparison between ASCO DN15 and DN20 with N_2 shows they basically have same behaviour. At low pressures and for a quite wide range of valve position, it has a very similar curve to the manual valve, until 15-20% of opening. But when a position around these values is reached, the pressure suddenly rapidly increases (See Figures 4.26 and 4.27).

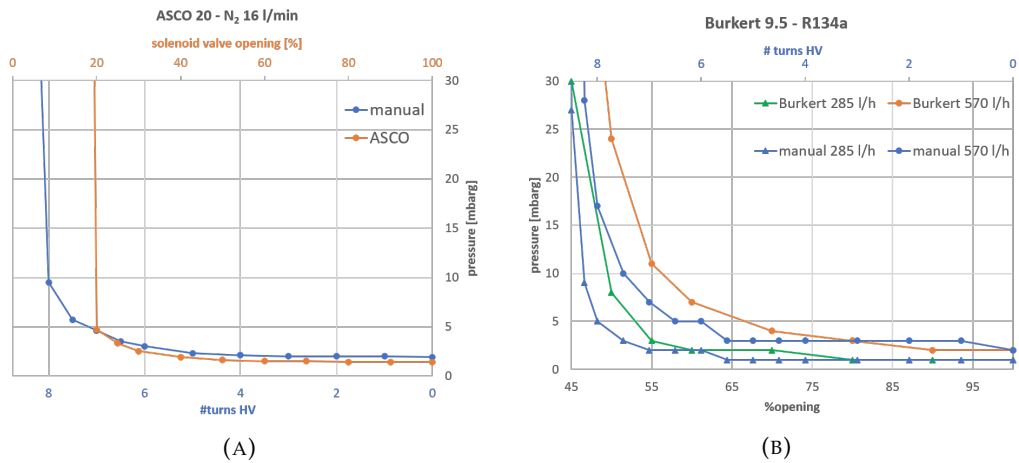
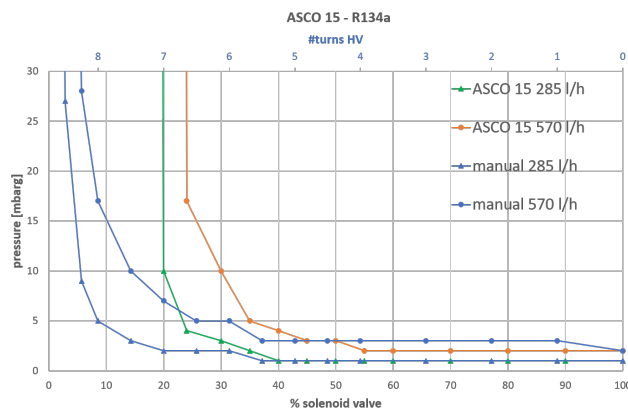
FIGURE 4.26: ASCO DN20 characterization curves with N_2 

FIGURE 4.27: ASCO DN15 characterization curves with R134a

The pinch valve from FESTO shows (Fig 4.28) instead an unacceptable behaviour: it basically behaves as a shut-off valve, that is, whatever change in position doesn't affect the pressure, until the reaching of a certain opening position (i.e. in this case around 20%), when the pressure increases vertically, suggesting that the valve is not allowing anymore the gas to flow. The several ball valves actuated by the FESTO pneumatic positioner give not bad regulation curves (Fig. 4.29), but not so accurate as other similar solutions and the curve is not as good as the other manual valve currently installed (smaller regulation range).

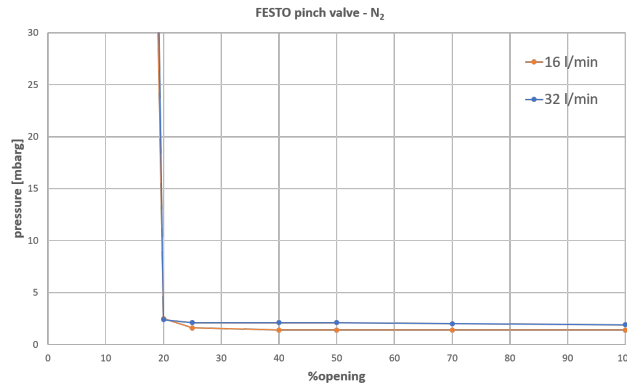


FIGURE 4.28: FESTO pinch valve characterization curves with N_2

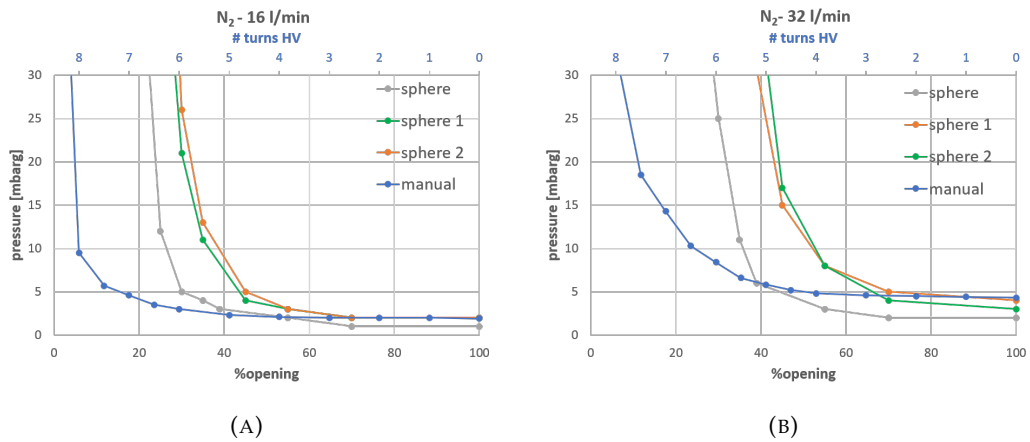


FIGURE 4.29: FESTO ball valves characterization curves with N_2

As expected, the Gulex motor actuates the manual valve exactly following the characteristic curve of the ROTAREX valve manually turned. It allows indeed a very fine and precise regulation, with high resolution and no hysteresis (Fig. 4.30).

Bronkhorst shows a smooth regulation but pressure reaches too high values, a bigger K_v is maybe needed (Fig. 4.31).

Econex MPV has also a very smooth curve, offering a good compromise of fine regulation and other involved factors (Fig. 4.33) Bronkhorst shows a smooth regulation but pressure reaches too high values, a bigger K_v is maybe needed (Fig. 4.31).

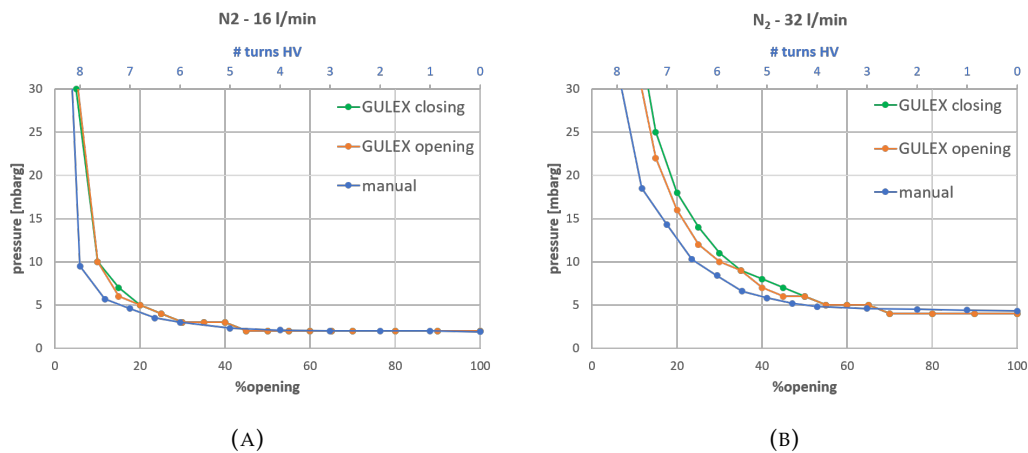
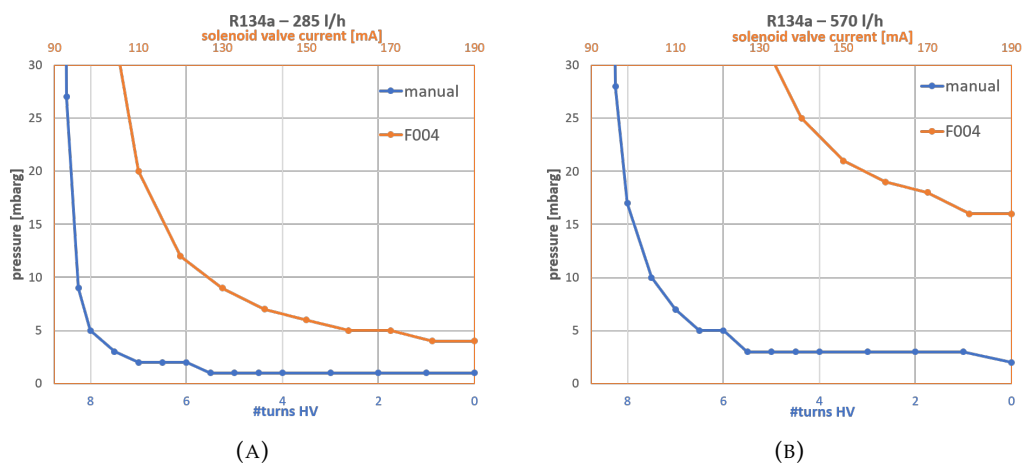
FIGURE 4.30: GULEX motor characterization curves with N_2 

FIGURE 4.31: BRONKHORST F004AC characterization curves with R134a

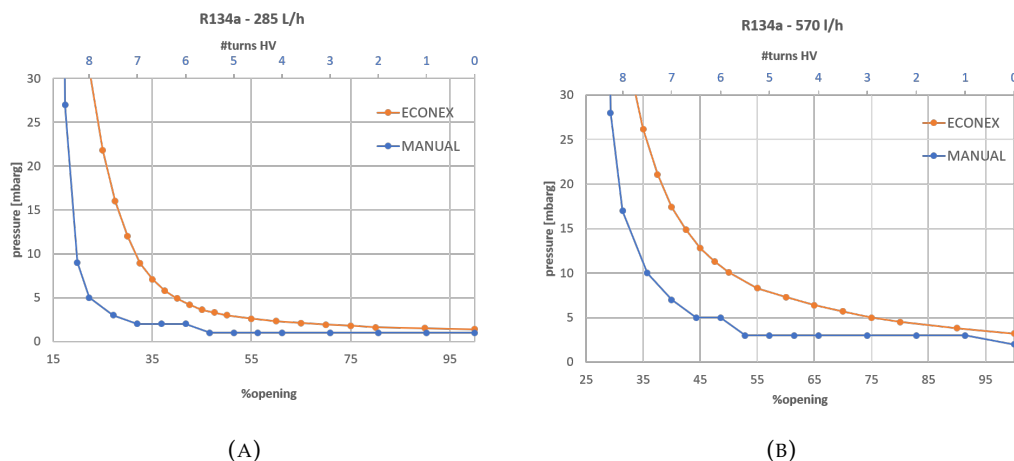
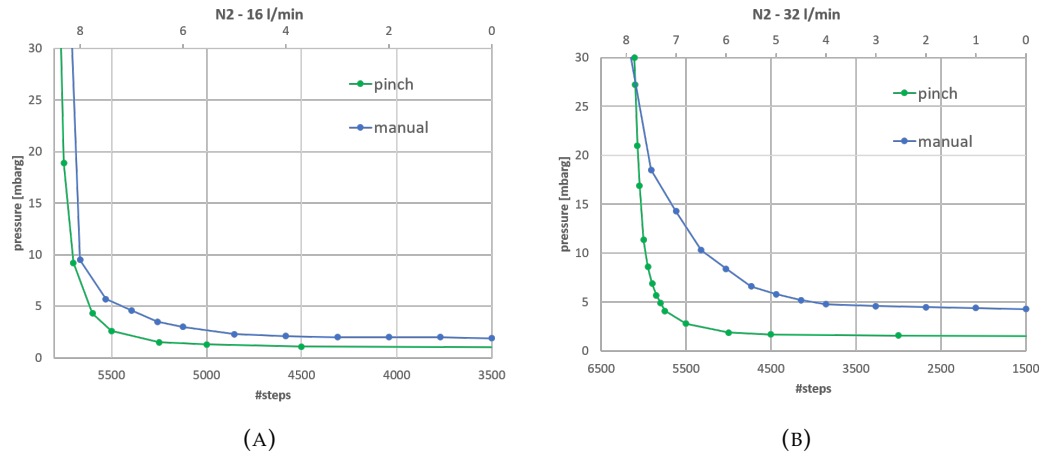


FIGURE 4.32: ECONEX MPV characterization curves with R134a

The result curve of the ResolutionAir pinch valve is really similar to the target one with a really smooth and fine regulation. The resolution of this valve is incredibly high, being able to control the single step of the stepper motor (Fig. 4.33).

FIGURE 4.33: ResolutionAir HPPV characterization curves with N_2

Von Rohr maybe shows the best curve among all the others: it has a wide regulation range and the curve is smooth and not steep in within the pressure range of our interest (Fig. 4.34).

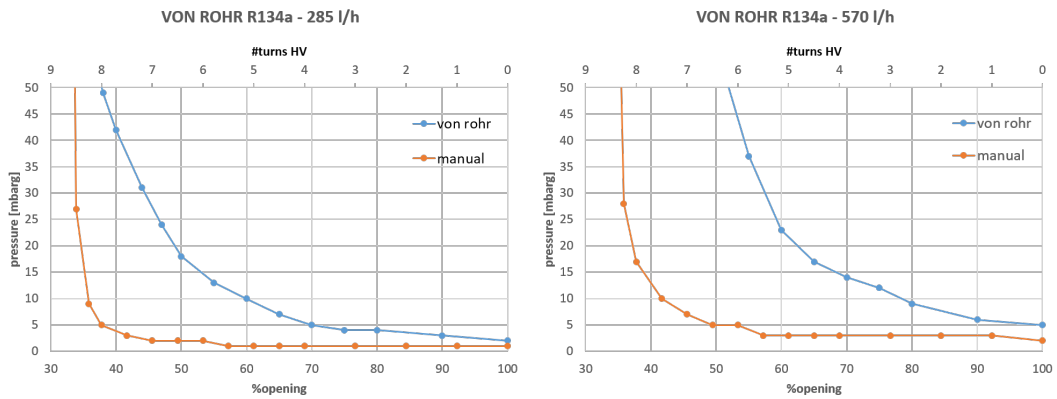
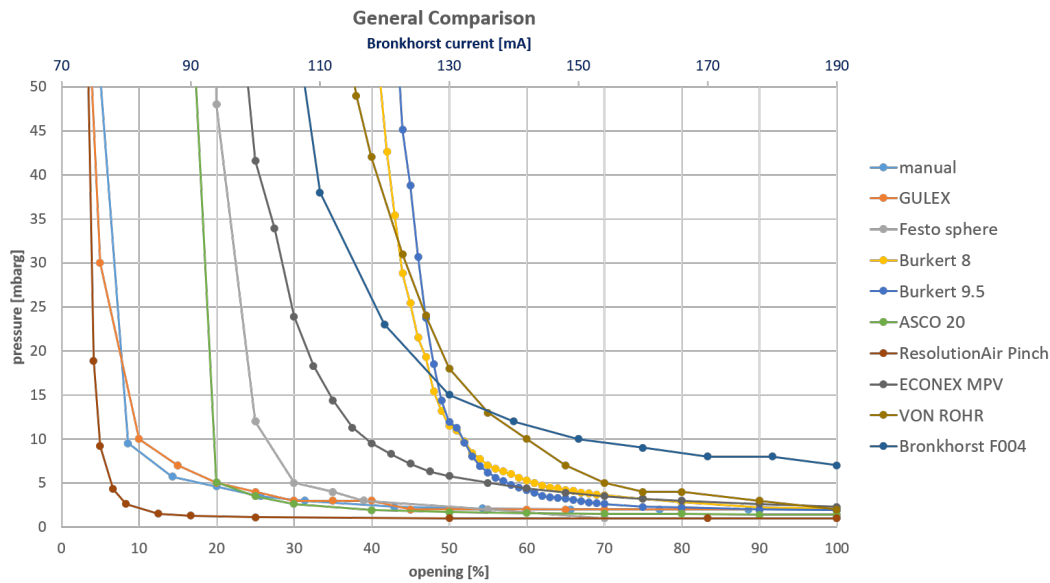


FIGURE 4.34: Von Rohr characterization curves with R134a

In Fig. 4.35 a general comparison of all the tested valves is reported.

FIGURE 4.35: Curves comparison with 16L/min N_2 flow

4.3.2 Ageing test

Ageing phenomena constitute one of the most complex and serious potential problems which could limit, or severely damage, the use of gaseous detectors in unprecedented harsh radiation environments. Long-term operation in high-intensity experiments of the LHC-era not only demands extraordinary radiation hardness of construction materials and gas mixtures but also very specific and appropriate assembly procedures and quality checks during detector construction and testing [4] [7] [25].

To protect the detectors chambers, ageing tests have to be performed on every component which has to be installed in the gas systems, valves included. The valves have been asked to be silicon free, but some organic material may be present and be potentially dangerous for ageing phenomena. A specific aging test set-up is used to check gas system components by measuring the gas gain drop of an irradiated wire chamber in which the gas coming from the device under test is flushed. Below an example of report for the validation of one of the valves tested.

Most of the valves passed ageing test, meaning that no organic greases or silicon based were actually present. In some of the valves some ageing was noticed. As an example, the ASCO case is reported in Figures 4.36 and 4.37. After the first test noted as not passed, the valve has been flushed with a nitrogen flow of 400 l/h for at least 8 hours and a second test was performed whose result was this time positive.

S.Doronin 1 November 2019

For: Sabino Zagaria

Sabino ASCO valve: received 24.10.2019 for test

Sample ID No. 2019-047

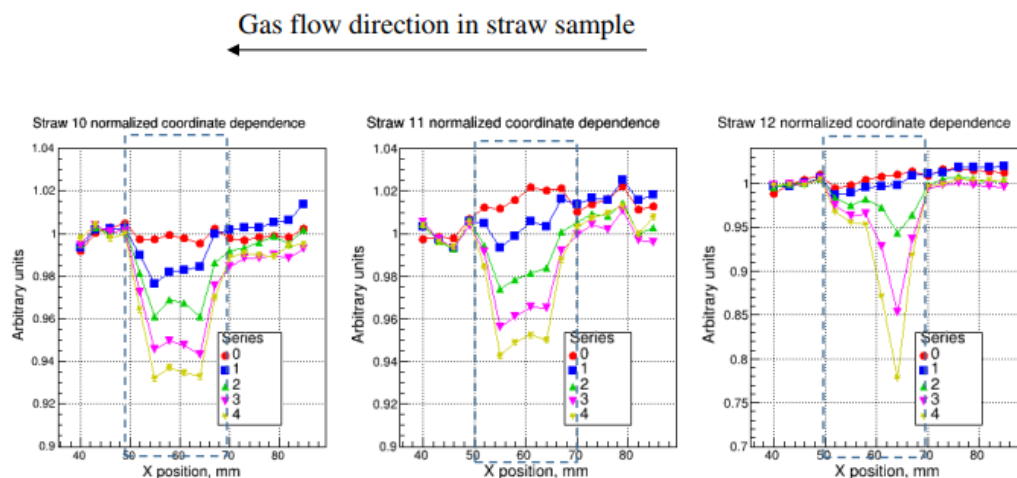


Measurement conditions:

1. Gas: Ar-CO₂ (70%-30%)
2. Gas flow 2 cm³/min.
3. Current density: 100nA/cm
4. Irradiation area 1 cm
5. 3 straws in parallel

FIGURE 4.36: Ageing tests on ASCO valve: test conditions

S.Doronin 1 November 2019

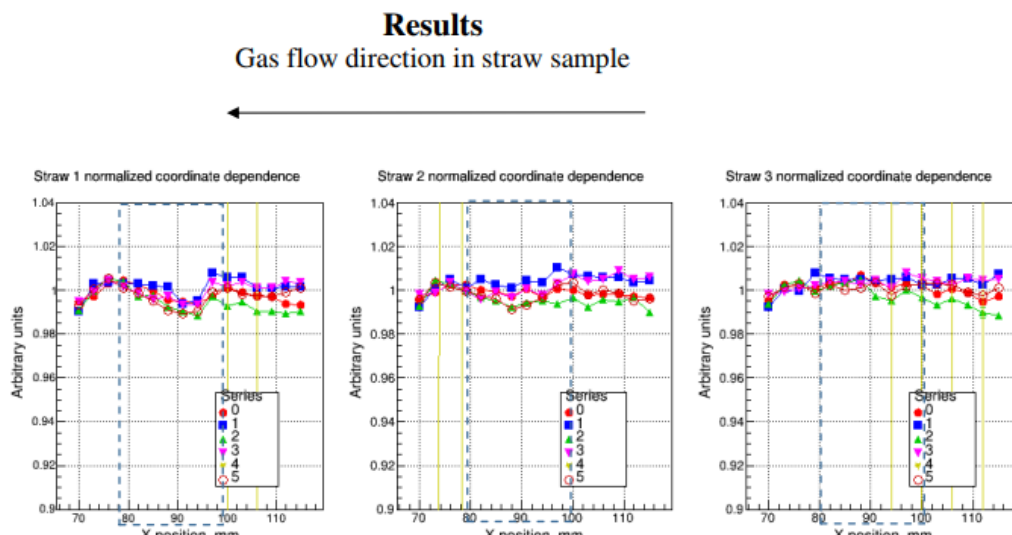


After 160h of X-ray exposure the maximum 23% of ageing is seen.
Validation is continued, now we can conclude that

Sample 2019-047 Sabino ASCO valve is considered as **NOT VALID** and can't be used in gas systems.

(A) First test results

S.Doronin 25 November 2019



No ageing after 200 hours of irradiation. 10mm gap for X-ray (12kV, 120mA).

Sample 2019-051 ASCO valve can be considered as **VALID**.

(B) Final test results, after flushing

FIGURE 4.37: Ageing tests results on ASCO valve

4.3.3 Test in the RPC Gas System

After the laboratory characterisation and the ageing test, five of the valves considered as potentially the best solution, or the ones showing better behaviour, were installed in the RPC gas. In Tab. 4.5 a detailed list of the valves installed and where.

TABLE 4.5: List of valves installed in USC

VALVE	RACK	WHERE
BURKERT 8mm	74	BARREL RB-2 top
BURKERT 9mm	69	BARREL RB-2 bottom
GULEX motor	70	BARREL RB-1 bottom
ASCO DN20	83	ENDCAP
ECONEX	74	BARREL RB-2 top

In Fig. 4.38 the comparison between the chosen valves to be installed in the real system and be tested in real conditions. These valves have been preferred over the others because they seemed to have not only a quite good behaviour but also acceptable features in terms of cost and size.

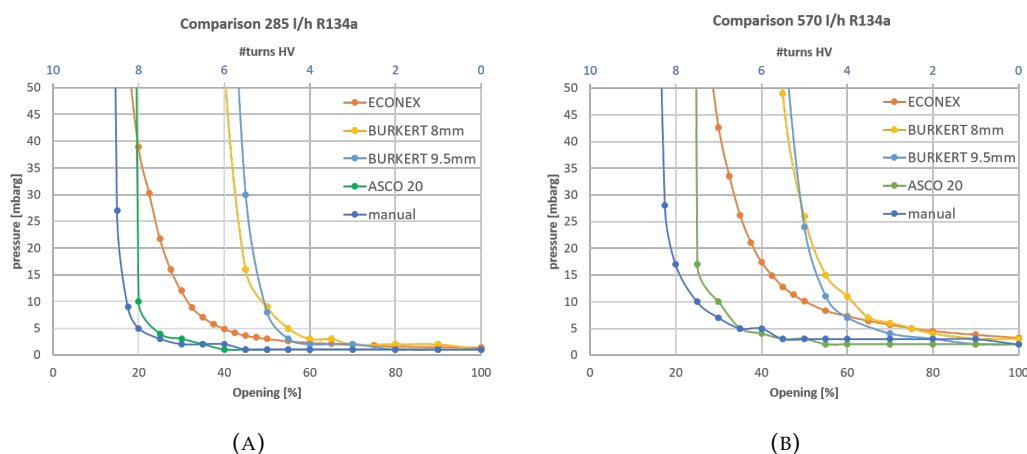


FIGURE 4.38: Comparison among the chosen valves

Given the results in laboratory, some low limits on the closing of the valves have been set for safety reasons, in order to avoid too high pressure peaks in the chambers due to the closing of the automatic valves. The limits were necessary because of the steep pressure increasing showed in the characteristic curves, as reported in Fig. 4.39 as example. The limit was then set at the valve percentage opening corresponding to the lab pressure of 30 mbarg. For the GULEX motor mounted on the manual valve also an high limit was set to make the valve not work where it basically doesn't regulate. The limits were set at software level, limiting the current input sent to the valve.

The new regulation valves are installed in series to the already present manual valves. Where possible, a bypass line was added and the valve was installed in this line, so it was possible to install the new valve without having to stop the distribution module.

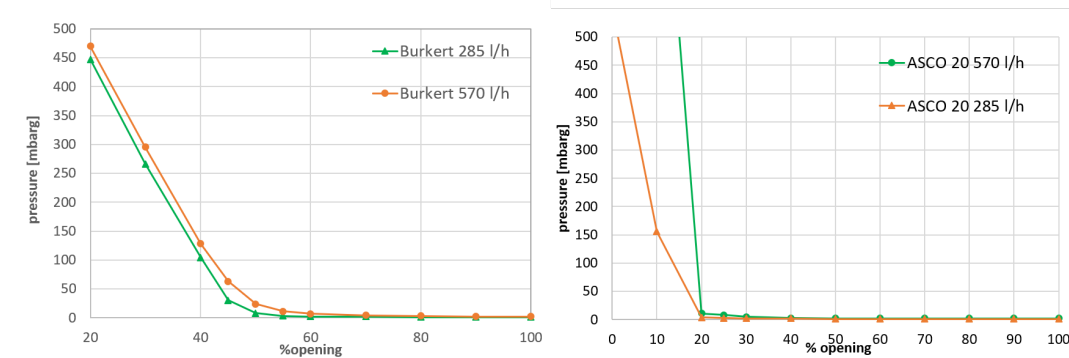


FIGURE 4.39: Fast pressure increments at low opening positions: limits necessary

TABLE 4.6: Limits set on the installed valves

VALVE	Operating Range [%]	Input current [mA]	$\Delta\%$
BUKERT 8mm	53-100	12.48-20	47
BURKERT 9.5mm	50-100	12-20	50
ASCO DN20	25-100	8-20	75
GULEX motor	15-70	6.4-15.2	55
ECONEX	0-100	4-20	100

In addition to the mechanical installation all the electrical connections to the control rack were done. Each valve was so remotely controllable via WinCC-OA, as shown in Fig. 4.40.

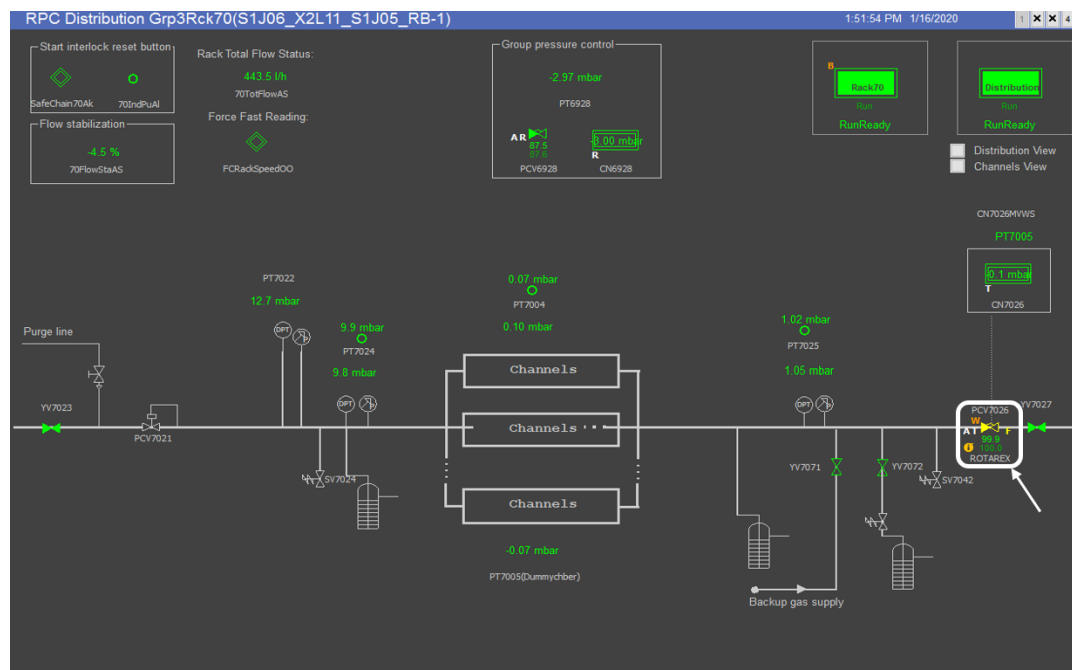


FIGURE 4.40: Automatic installed valve, WinCC-OA view

In test conditions, the regulation was done basing on the read value of the PT-XY05 sensor, placed on some dummy chambers. These dummy chambers are volumes (similar to the ones added in the gas system test bench) to simulate the detector chambers. This makes possible to be more cautious of the real chambers and exclude the effect of some leaking ones. Even if the regulation was done controlling the dummy chamber pressure, the valve affected also the real chamber pressure, so care was still needed and the value read by PT-XY04 was also monitored. Dummy chambers are still not present on every line of CMS RPC distribution, as this is an upgrade on-going and it will be completed in 2020: the valves were installed only where they were in place. In principle, the dummy chamber has more or less the same pressure of the real chamber since it is located at the same height: hydro-static pressure at least and flow are very similar.

In Fig. 4.41 some pictures of the installation in the CMS USC, at the top of pre-distribution output racks.



(A) Gulex motor, rack 70



(B) Burkerts, racks 69 and 74



(C) ASCO, rack 83



(D) ECONEX MPV, rack 74

FIGURE 4.41: Installation in USC

Different tests have been carried out with the new valves in USC. In the next paragraphs a more detailed explanation of each of these tests is given, as well as the tests results.

Forced steps test

The aim of this test is to reproduce in the experiment a similar test to the one performed in laboratory and check if the valve shows a similar behaviour in the bigger and closed loop real system.

First, the manual valve was gently turned to make the chamber pressure reach a value around 0 mbarg. Then, the idea is to keep the manual valve position fixed as well as the flow rate constant, and close (in forced mode via PLC) the new regulation valve in small steps, monitoring how the pressure in the chambers (real and dummy one) increases accordingly to the closing of the valve.

Some results are shown below. Pressure increments corresponding to valve forced steps are listed in the tables below: this info make us understand how and how much the valve is able to affect the regulated pressure. When pressure was increasing too much, manual valves were opened: that is the explanation for the regions in the plots where auto valve is still closing and pressure decreasing.

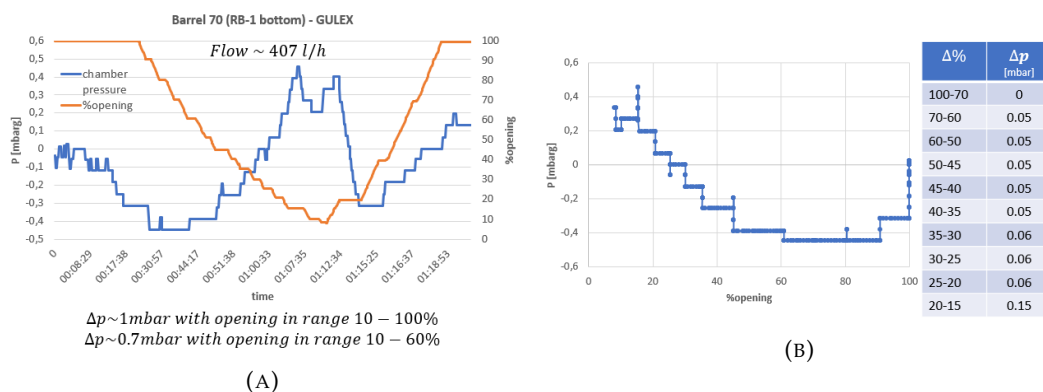


FIGURE 4.42: Gulex motor forced mode steps test

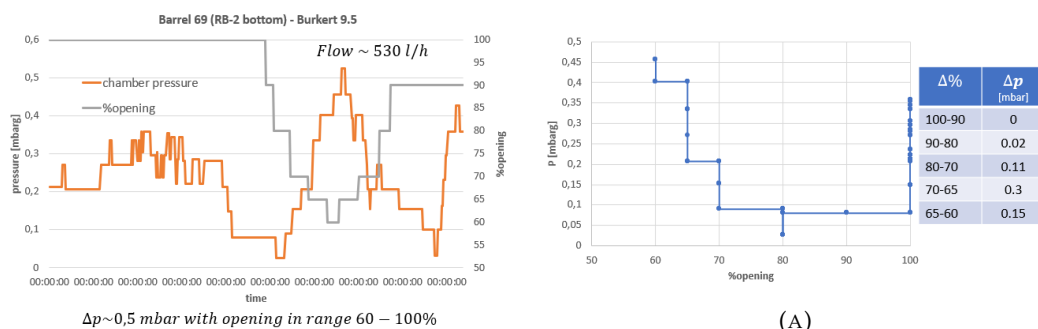


FIGURE 4.43: BURKERT 9.5mm forced mode steps test

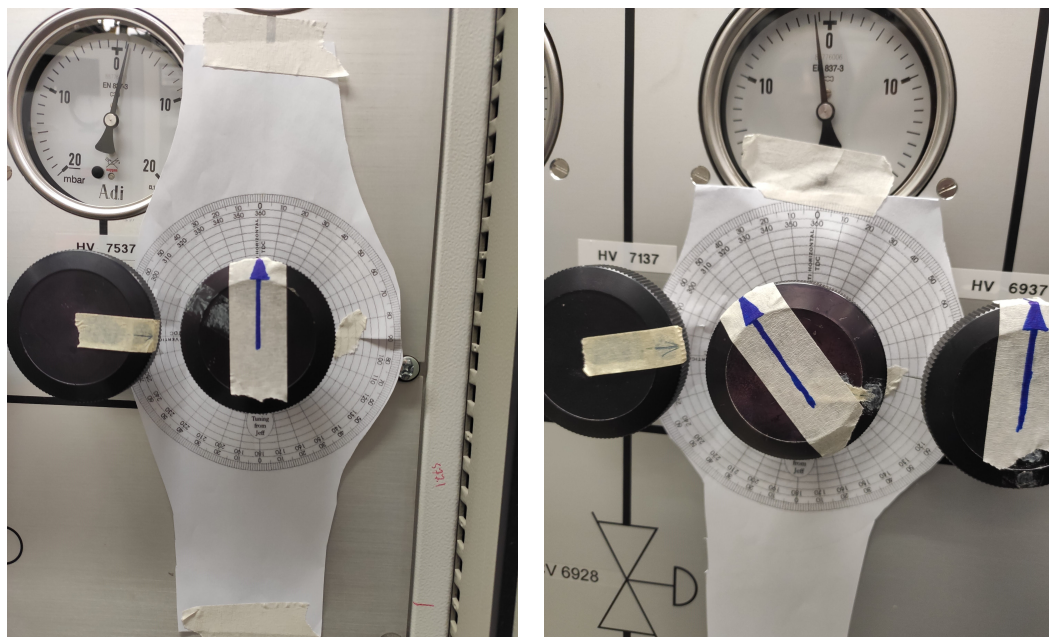
At the end of the test, the initial configuration was restored: automatic valve forced to 100% and manual valve in such a position to have about 0mbarg in the chambers. From these tests it is possible to notice the regulation ranges of the valves in the real conditions and compare them with the results obtained in the laboratory. As examples, the valve actuated by the Gulex motor gives no increment of pressure while closing till it reaches 70% (Fig. 4.42). In particular, in the range 10-60% of

opening the DP in the chamber is about 0.7 mbar. For the Burkert 9.5mm instead, the regulation starts before, around 90% (Fig. 4.43). Here the chamber pressure Δp is about 0.5 mbar in the valve position range 60-100%.

Auto mode

The aim of this test is duplex: to see how the valve reacts to external disturbs (i.e. change of the working point of the manual valve) and see if and how well the pressure setpoint is reached and kept.

So, starting from the automated valve fully open (100%), the initial 'zero' position of the manual valve is recorded using a goniometer, as shown in Fig. 4.44a. Sometimes the pressure setpoint was set to the current value of dummy chamber pressure (so the automation valve doesn't make sudden movements when put in auto mode), some other time a higher value was set as setpoint so as soon as the valve was put in auto mode it reacted to reach that value.



(A) Manual valve zero position marking

(B) Opening manual valve

FIGURE 4.44: Goniometer used for the test to record the manual valve position

Then the new valve is put from forced in auto mode: the setpoint should be reached and the pressure value should be kept constant. At this point any change of the pressure should be corrected by a consequent movement of the auto valve: if the pressure in the dummy chamber is for any reason increasing, overtaking the setpoint, then the regulation valve should open accordingly, while, if the dummy chamber pressure decreases below the setpoint, the regulation valve closes accordingly. How fast and intense this corrective action made by the valve is set with the PID control parameters. In this way, the manual valve has been opened in steps of rotation and the consequent position variation of the auto valve is recorded (Fig. 4.44b, as well as the dynamic response of the measured value of pressure (e.g. time response, oscillations, overshoot, steady state error, etc).

When the manual valve has reached its fully open position, the automatic valve is regulating alone in the line and how the regime is reached and kept is monitored. For instance, how big the steady state error was, how big the pressure oscillations

around the set-point as well as the amplitude of the excursions of the valve to keep the pressure constant.

In the following some results for the tested valve are shown.

Gulex motor - rack 70

Being the Gulex motor actuating the same ROTAREX manual valve installed, a quite stable behaviour was expected. The valve was therefore put in auto mode with a setpoint pressure slightly higher the current pressure in the dummy chamber. As shown in Fig. 4.46, the valve then gradually reached the setpoint moving from fully open to a stable position around 53%.

PID Settings		Flow rack [l/h]	Pressures [mbar]	
Kc	2.5	470	Dummy chamber	0.1
Ti	5	Flow dummy [l/h]	Setpoint	
Td	0	30	Group pressure	-3
Dummy chamber volume		Dummy chamber volumes per hour	Avg Channels flow [l/h]	
20l		1.5	17.6	

FIGURE 4.45: Gulex motor auto test conditions

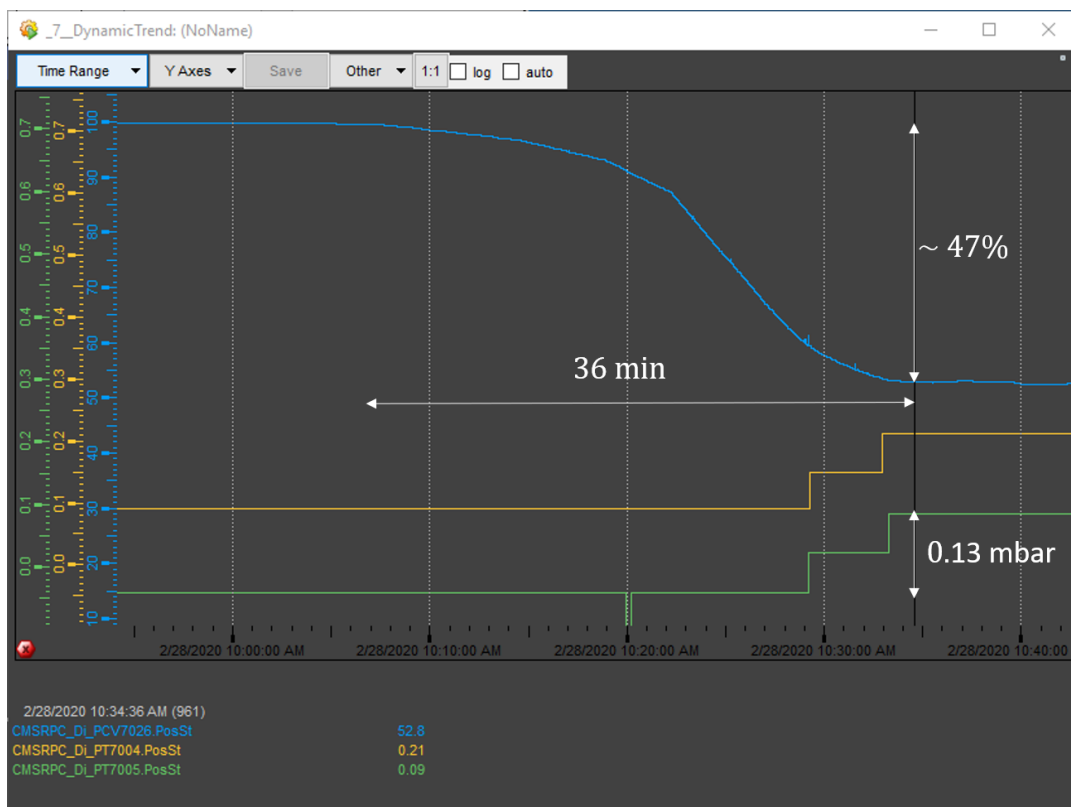


FIGURE 4.46: Gulex motor in auto mode reaching the pressure set-point

Once the setpoint was reached, the manual valve in series was gradually opened in small rotational steps and the motor reacted accordingly to the step disturb, as

shown in Fig. 4.47.

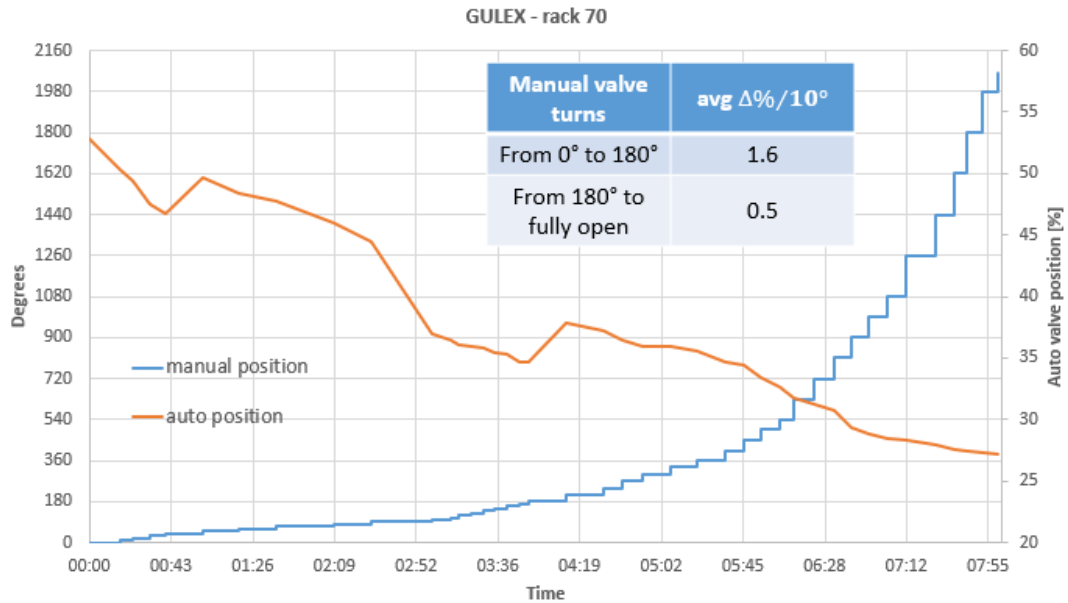


FIGURE 4.47: Gulex motor in auto mode while manual valve opening

Regarding the keeping of the setpoint, the valve is pretty stable (Fig. 4.48): only some strange spikes were noticed in the valve position and pressure signals, but not related to the group pressure regulation nor to rack flow oscillations. These spikes were spotted in other racks of the same group too.

TABLE 4.7: Gulex auto regulation performances in terms of average fluctuations

Valve position	Pressure
0.5-1%	0.05-0.1 mbar

So, generally speaking, having also a look to its performances in terms of average pressure and valve position fluctuations (Tab. 4.7), the regulation is quite good. Only there are some strange spikes and, as already mentioned, it is overall quite expensive.

ASCO DN20 - rack 83

ASCO valve shows an unacceptable behaviour: sudden jumps in pressure with small changes in valve position, working at limit of regulation. Some tests results are shown in Fig. 4.50: the valve is put in auto mode with low limit position at 25%. It doesn't regulate (doesn't reach the SP) until around 15%. Then, when started to gradually open manual valve, big oscillations of pressure were caused because of the oscillation of the valve. Reached a certain opening of the manual valve, it showed a sudden peak in pressure, similarly to behaviour spotted in the laboratory test (Fig. 4.51). It shows hysteresis and it does not regulate anymore reached 20%. In tab.4.8 the regulation performances are summarised.

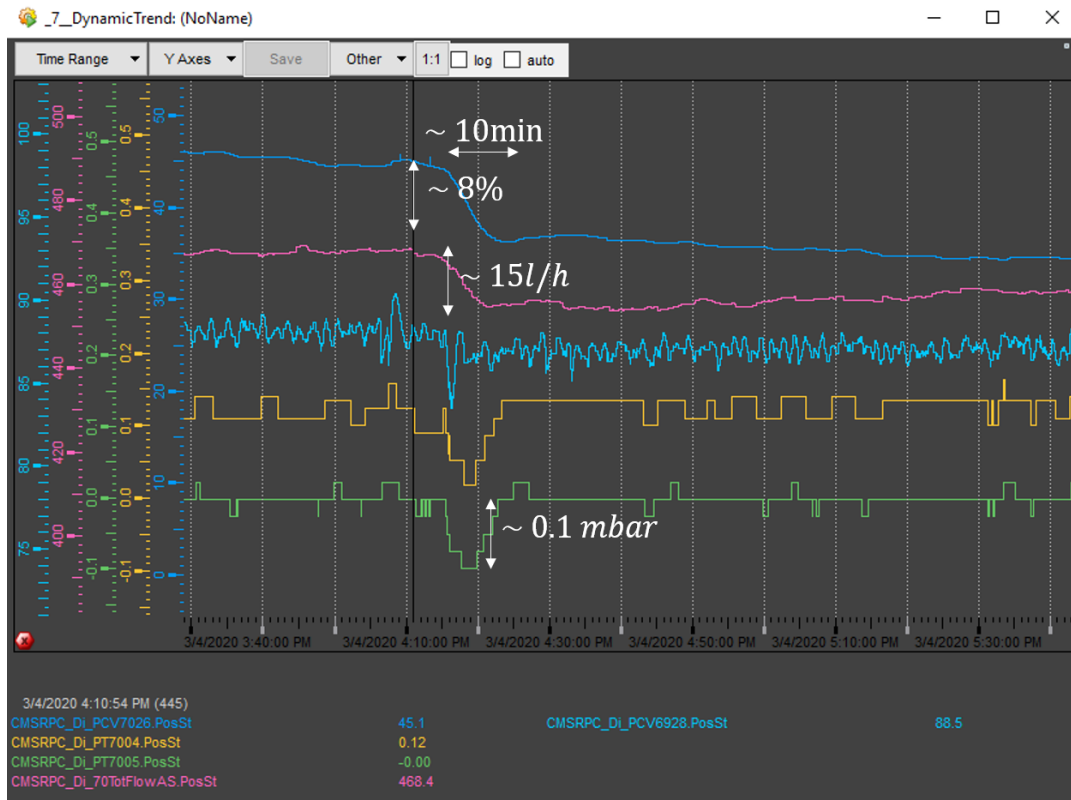


FIGURE 4.48: Gulex motor in auto mode keeping the setpoint

Flow rack [l/h]		Pressures [mbar]	
90	Dummy chamber	0.1	
Flow dummy	<u>Setpoint</u>		
10	Group pressure	0	
Dummy chamber volume	Dummy chamber volumes per hour	Avg Channels flow	
10l	1	6.7	

FIGURE 4.49: ASCO auto test conditions

TABLE 4.8: ASCO auto regulation performances in terms of average fluctuations

Valve position	Pressure
2-3%	0.2 mbar

BURKERT 9.5mm - rack 69

Some tests results are shown in Fig. 4.53 and 4.55. The valve was put in auto mode and the manual one was gradually opened up to 30°. Then, restored the manual valve initial configuration, it was left in auto for the night. We notice periodic oscillation of auto valve, with a poor regulation and some oscillation in pressures: The valve start closing in order to reach the pressure setpoint until there is steep increase



FIGURE 4.50: ASCO DN20 valve in auto mode (1)

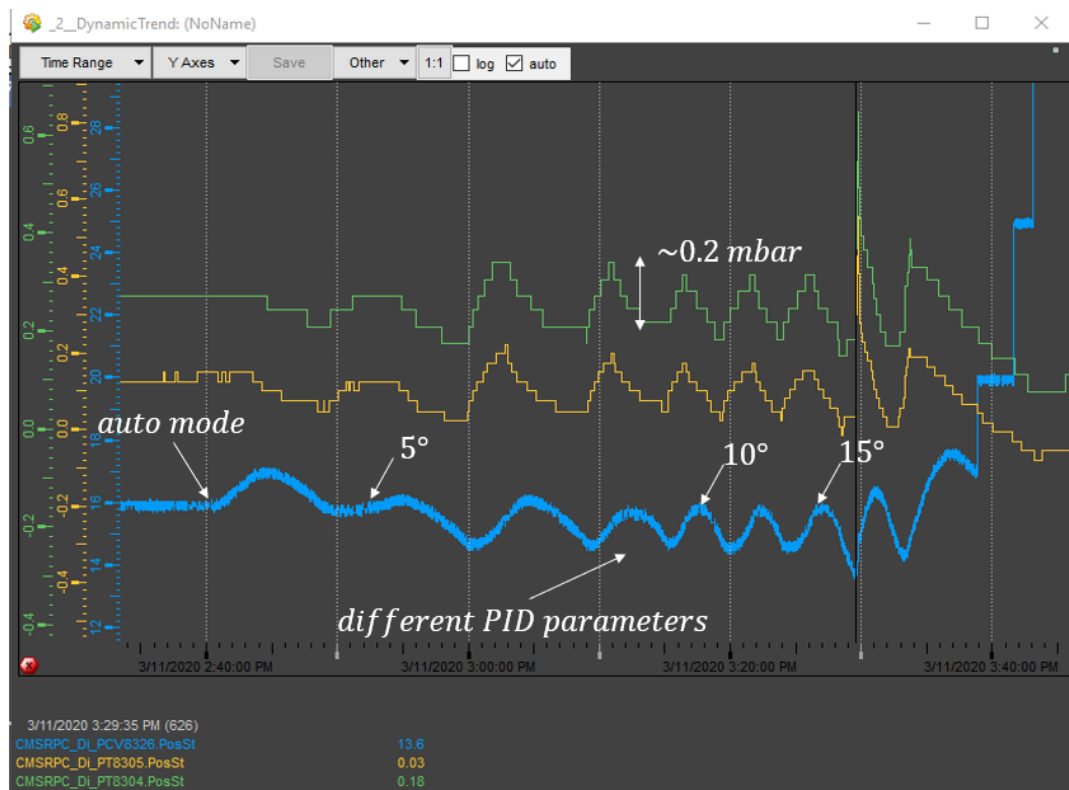


FIGURE 4.51: ASCO DN20 valve in auto mode (2)

in pressure. So the valve starts opening again and this cycle is repeated. This behaviour might be related to the hysteresis of the valve. In Tab.4.9 the regulation performances are summarised.

Flow rack [l/h]	Pressures [mbar]	
480	Dummy chamber	-0.3
Flow dummy	<u>Setpoint</u>	
30	Group pressure	-3
Dummy chamber volume	Dummy chamber volumes per hour	<u>Avg</u> Channels flow
20l	1.5	17.5

FIGURE 4.52: BURKERT 9.5mm auto test conditions

TABLE 4.9: BURKERT 9.5mm auto regulation performances in terms of average fluctuations

Valve position	Pressure
10%	0.15 mbar

Flow rack [l/h]	Pressures [mbar]	
480	Dummy chamber	-0.3
Flow dummy	<u>Setpoint</u>	
30	Group pressure	-3
Dummy chamber volume	Dummy chamber volumes per hour	<u>Avg</u> Channels flow
20l	1.5	17.5

FIGURE 4.53: BURKERT 9.5mm auto test conditions (1)

BURKERT 8mm - rack 74

Tests results for Burkert 8mm are similar to the ones of other Burkert. In tab.4.10 the regulation performances are summarised.

TABLE 4.10: BURKERT 8mm auto regulation performances in terms of average fluctuations

Valve position	Pressure
20%	0.15 mbar

Generally speaking, Burkert valves show periodic oscillations with big excursions of valve position but relatively small chamber pressure changes, thus poor regulation and unacceptable behaviour. Different PID parameters set without having significant changes in their behaviour.

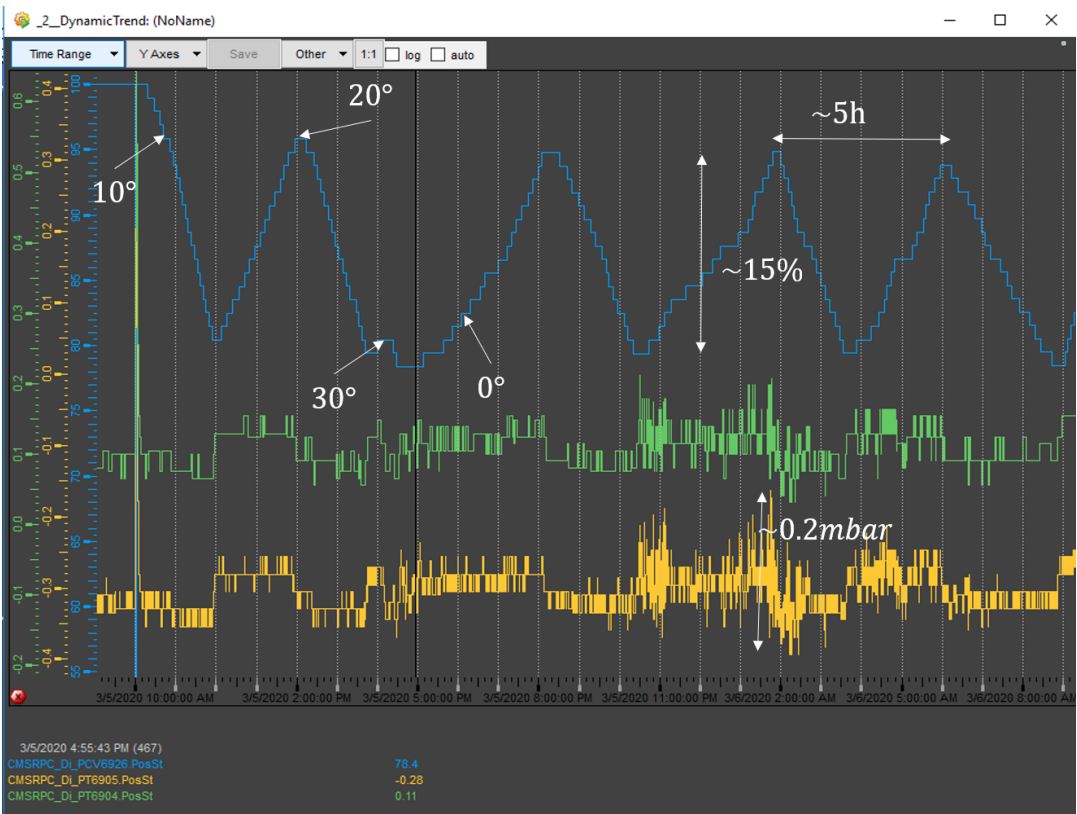


FIGURE 4.54: BURKERT 9.5mm valve in auto mode

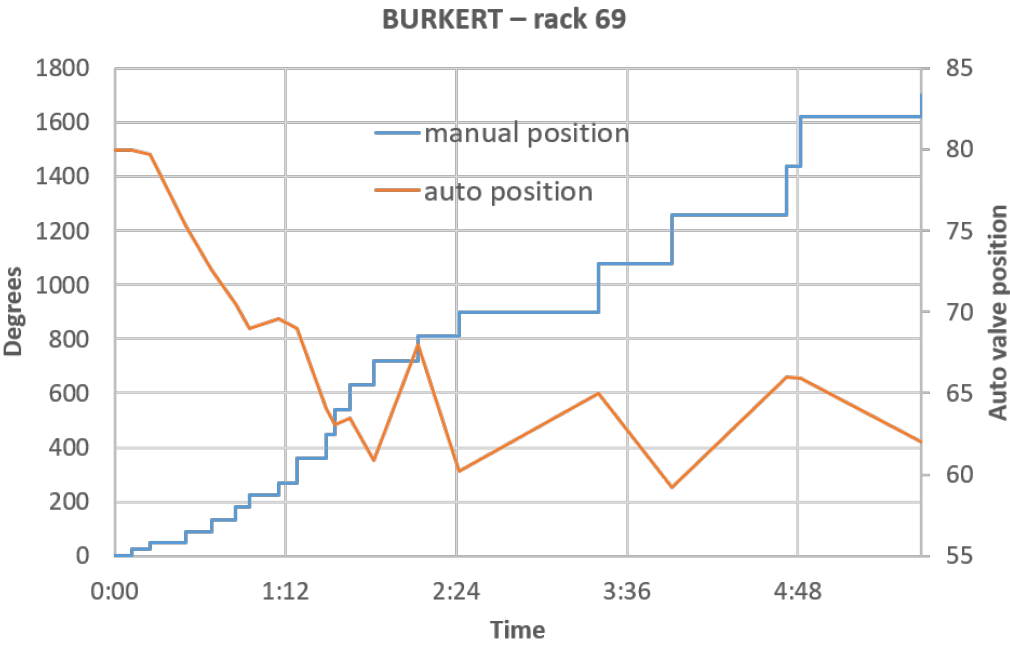


FIGURE 4.55: BURKERT 9.5mm valve in auto mode while manual valve opening

ECONEX MPV - rack 74

Some tests results are shown below. In tab.4.11 the regulation performances are summarised. The valve was put in auto mode, it reaches the pressure set point, then the manual valve was gradually opened in steps until its fully open position (Fig. 4.57 and 4.58). After that, it was left in auto regulation, showing a quite good regulation and a stable behaviour (Fig. 4.59). Only there are some flow oscillations. Oscillations in pressure generally don't seem to be related to group regulation valve, which has higher frequency oscillations.

Flow rack [l/h]	Pressures [mbar]	
470	Dummy chamber	0
Flow dummy	<u>Setpoint</u>	
30	Group pressure	-0.6
Dummy chamber volume	Dummy chamber volumes per hour	<u>Avg</u> Channels volumes per hour
20l	1.5	17.6

FIGURE 4.56: ECONEX MPV auto test conditions

TABLE 4.11: ECONEX MPV auto regulation performances in terms of average fluctuations

Valve position	Pressure
0.5-1%	0.05 mbar

So far, the ECONEX is the one showing best regulation features in terms of smoothness and reactions. PID fine tuning is necessary. Only issue with this valve, as already mentioned, is its quite huge size.

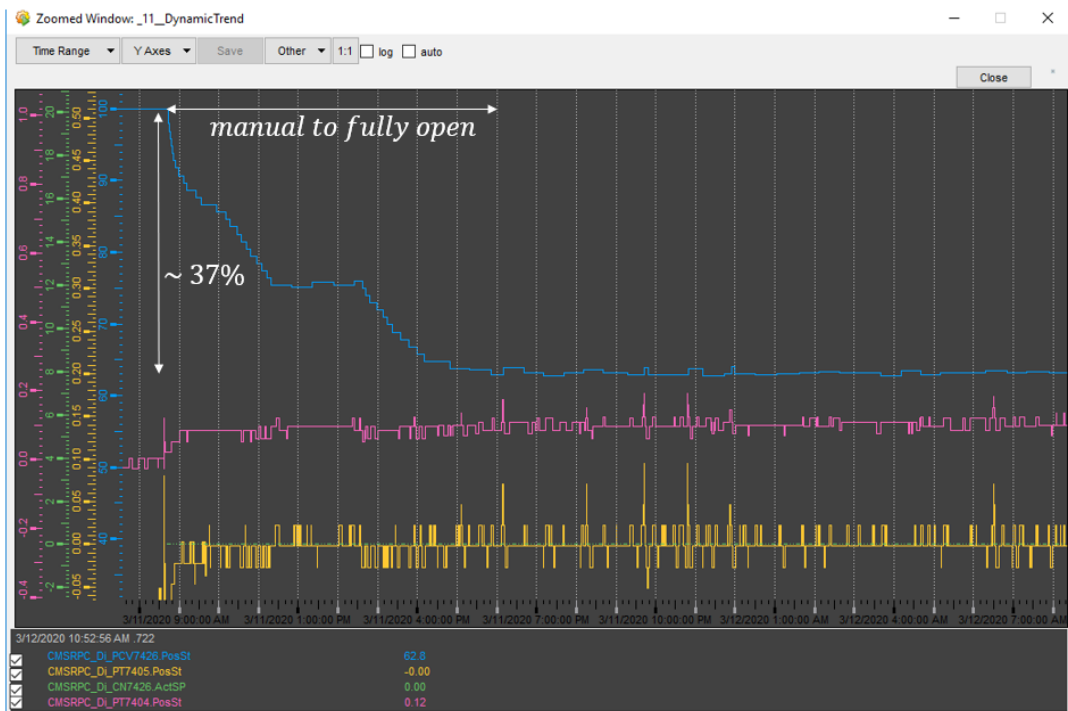


FIGURE 4.57: ECONEX MPV valve in auto mode

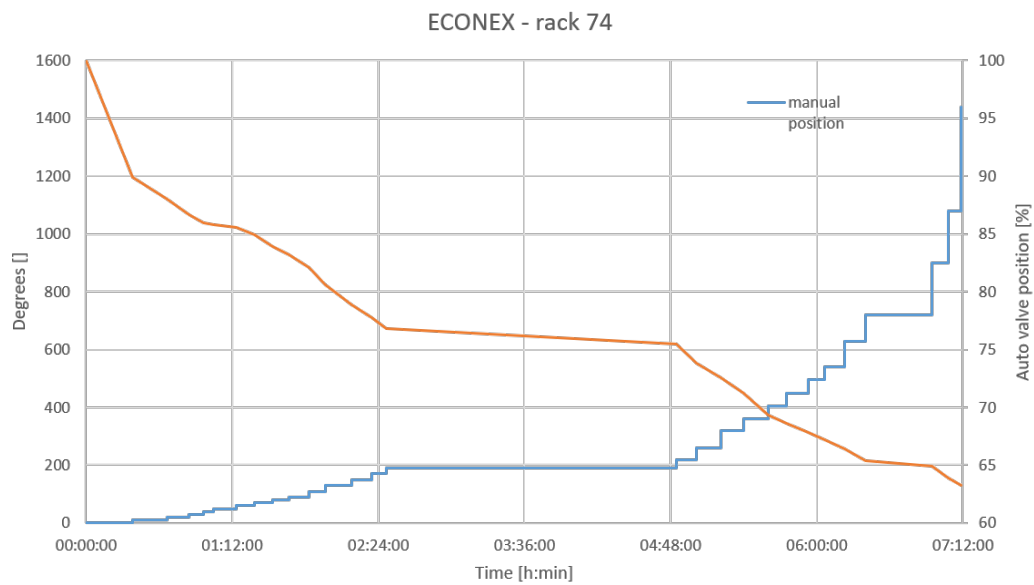


FIGURE 4.58: ECONEX MPV valve in auto mode



(A)



(B)

FIGURE 4.59: ECONEX MPV valve in auto mode while manual valve opening

PID tuning

As previously mentioned, the dynamic response behaviour is strongly affected by the set of PID parameters. As it is often the case for industrial applications, the PID control was indeed a PI one without a derivative term.

Obtained the Time constant T , the Process gain K and the Time Delay τ , assuming that $\tau \ll T$ and fixing a desired closed loop speed T_{cl} , a classical PI control suits the control, with the control parameters

$$K_p = \frac{1}{K} \frac{T}{(T_{cl} + \tau)}$$

$$T_i = \min(T, 4(T_{cl} + \tau))$$

And to control law would look like:

$$u = K_p e(t) + \frac{K_p}{T_i} \int_0^t e(\tau) d\tau + K_p T_d \frac{de(t)}{dt} \quad (4.3)$$

It was not possible to perform an open loop step test to calculate the process parameter, a trial and error approach was instead used for the PID parameters tuning. When the behaviour showed undesirable features, several sets of PID parameters have been tested, in order to find the best control in terms of rapid response, but not too nervous, in terms of cancelling the steady state error and minimizing overshoot as well as oscillations.

Some considerations about the tuning of PID parameters were possible and shown below, but further test are necessary to perform a fine tuning of those parameters. Some open loop step response test could be done in the gas system test bench in order to get a first hint on the direction the parameters should follow. Anyway, some results are shown and commented below.

For the Burkerts (Fig. 4.60), for examples, to reduce the periodic oscillations one parameter per time has been changed, noticing that high $T_i (3 \div 5)$ and medium $K_c (\sim 1)$ seem to provide better response.

The ASCO as well shows overshoots and steady state error is never zero (Fig. 4.61). It keeps oscillating changing the parameters, maybe a damper K_d term is needed in this case. Anyway, we notice that decreasing the T_i the amplitude oscillations is more or less constant but the frequency increases, hence, T_i must be bigger.

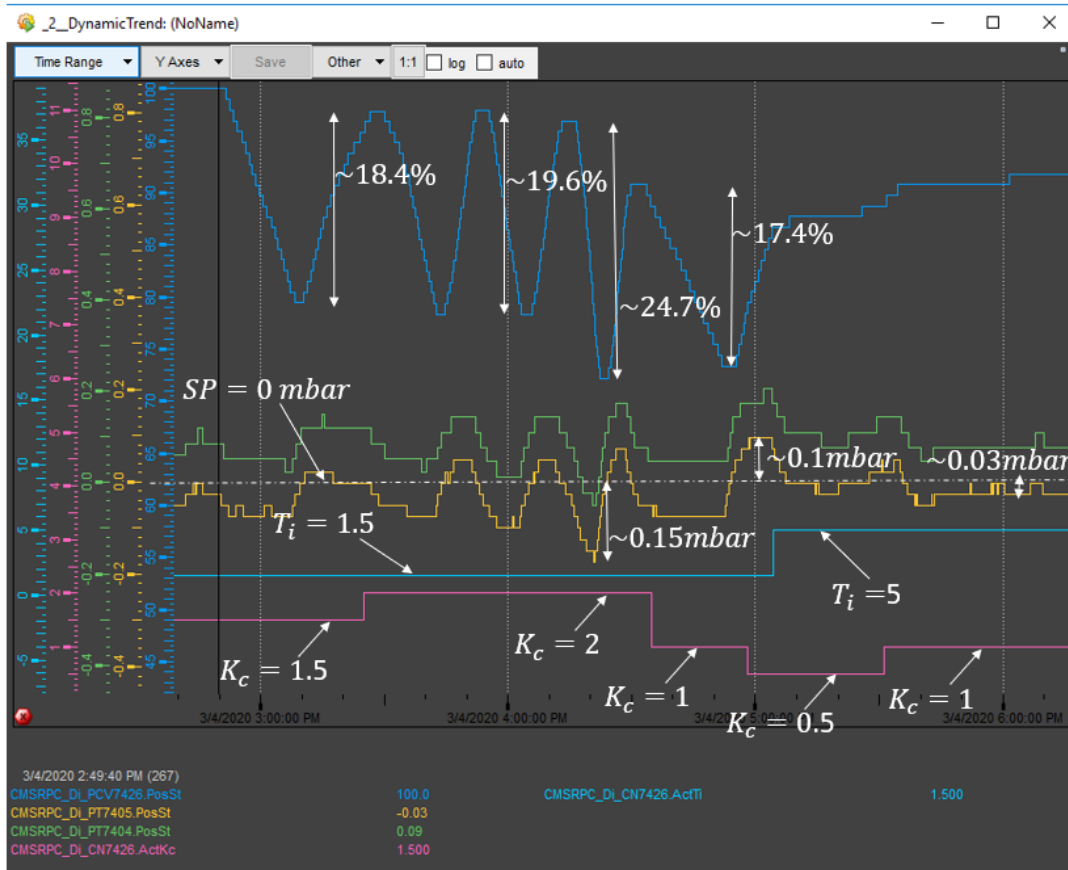


FIGURE 4.60: BURKERT PID tuning

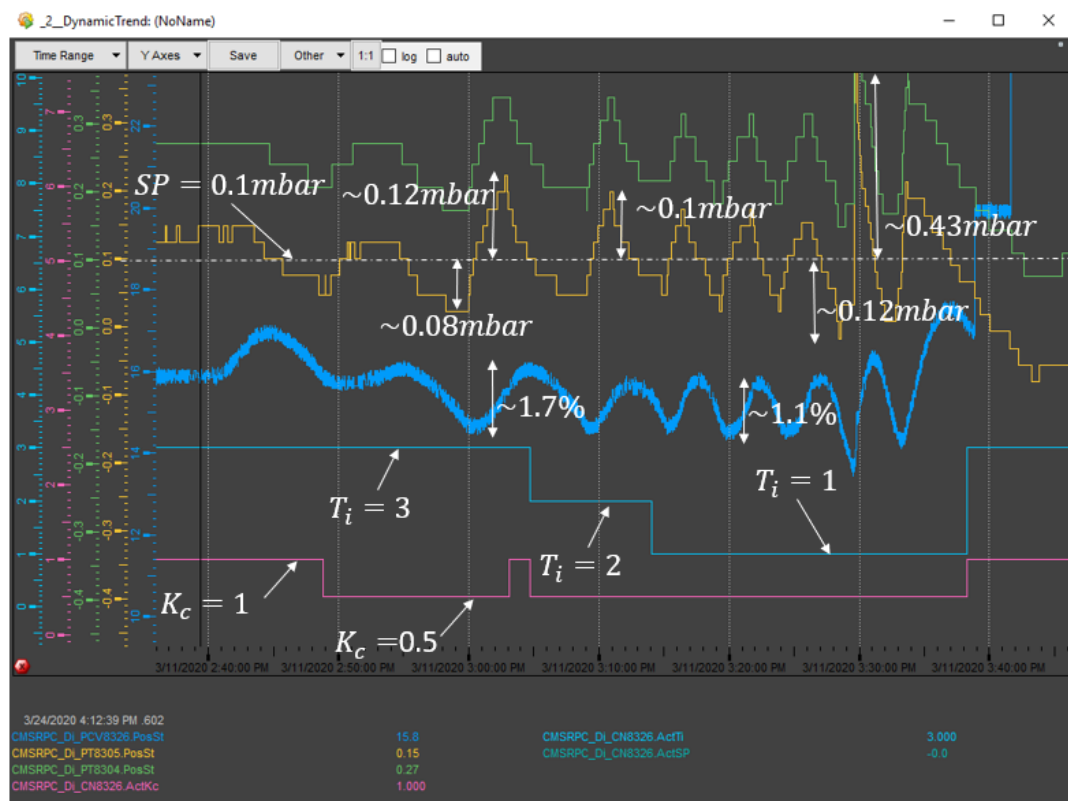


FIGURE 4.61: ASCO PID tuning

Flow change test

For the ECONEX valve a different disturb has also been tested: some step changes in the flow were made and the valve response was monitored. Both positive and negative changes were tested, with different step size and different set of PID. Some tests results are reported in figg. 4.62 and 4.63.

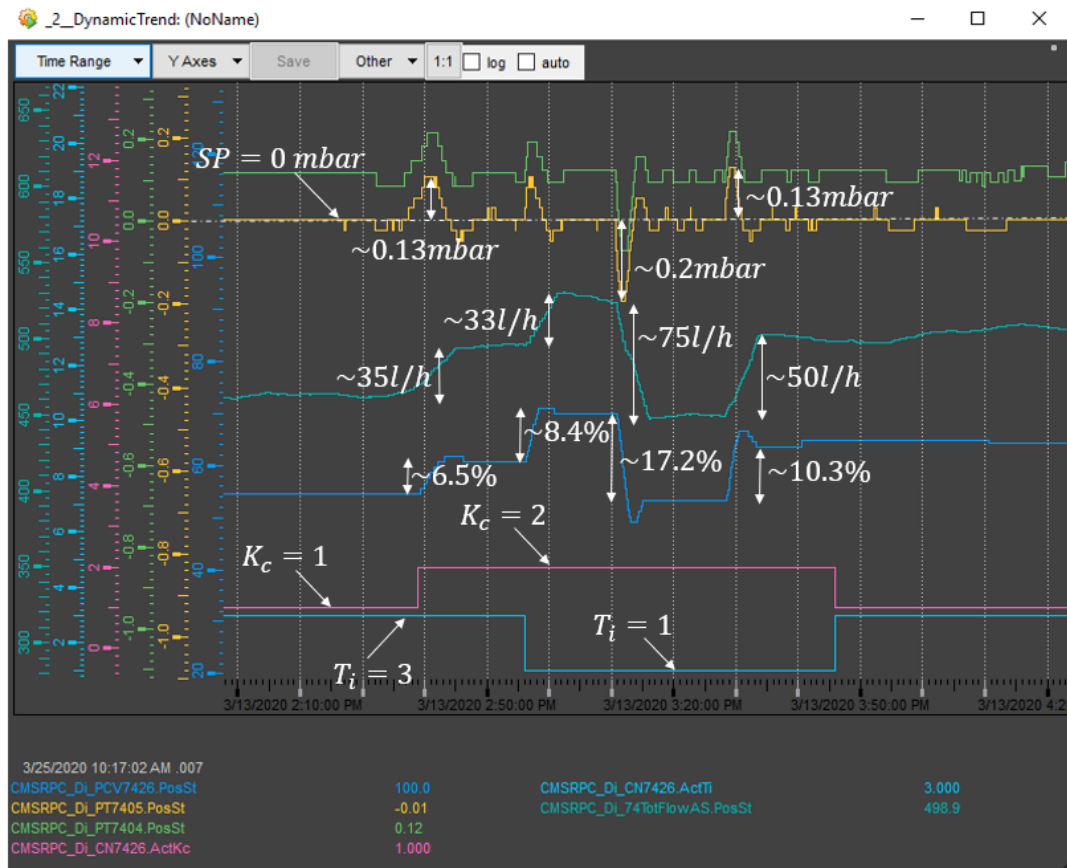


FIGURE 4.62: Flow change test - ECONEX MPV

Flow change test ECONEX rack 74													
time	$\Delta flow$	max Δp camera	max Δp dummy	%before	%after	$\Delta\%$ valve	Valve peak	K_c	T_i	Δp group	$\Delta\%$ group valve	Response time [min]	
10:10	+ 50	0.1	0.12	62.5	71.3	8.8	73.9	2	1	- 0.02	+ 0.4	10	
10:35	+ 25	0.06	0.07	71.3	78	6.7	80	2	1	- 0.02	+ 0.5	12	
10:55	- 55	0.42	0.42	78	66.1	-11.9	61.4	1	3	+ 0.23	- 1	20	
11:20	- 34	0.22	0.22	66.3	57.6	-8.7	56.6	1	3	+ 0.2	- -0.8	20	
11:40	- 25	0.06	0.1	57.5	53.5	-4	53.2	1	3	+ 0.02	- 0.9	15	
12:00	- 16	0.06	0.07	53.6	49.5	-4.1	49.5	1	3	- 0.21	- 0.6	25	
12:30	+ 30	0.1	0.1	49.5	54.6	5.1	55.3	1	3	+ 0.04	+ 1	15	
14:38	+ 35	0.1	0.13	54.7	61.2	6.5	61.9	2	3	0	+ 1	15	
14:55	+ 33	0.1	0.08	61.1	69.5	8.4	72.1	2	1	0	+ 0.4	10	
15:10	- 75	0.2	0.2	70.2	53	-17.2	48.5	2	1	- 0.2	- 1	15	
15:30	+ 50	0.1	0.13	53.7	64	10.3	67.1	2	1	- 0.2	+ 1	10	

FIGURE 4.63: Flow change test table

Some considerations can be done having a look at the numbers, especially flow changes $\Delta flow$, chamber Δp , response time and PID values. Valve $\Delta\%$ can also be taken into account, but it's less significant because highly dependent on valve

position (i.e. with same $\Delta flow$, Δp and other parameters, valve $\Delta\%$ can be different if the change takes place starting from different valve position). We also have to keep in mind that flow changes were done manually with a rotameter on the Pre-Distribution Input racks, meaning with always different speed and intensity: some peaks might be due to too high velocity in the manual rotation of rotameter flow controller. PID parameters seem to strongly affect the behavior of the valve. Here some cases example are reported:

- Regarding the response velocity, generally speaking, faster responses are obtained with $K_c = 2$ ($\sim 10min$) than with $K_c = 1$ ($\sim 20min$). See for example fig. 4.64: given a flow change around 50 L/h in both cases, in the second case the valve is definitely too slow in the response, thus producing a higher pressure change.

$\Delta flow$	max Δp camera	max Δp dummy	%before	%after	$\Delta\%$ valve	Valve peak	K_c	T_i	Response time [min]
+ 50	0.1	0.12	62.5	71.3	8.8	73.9	2	1	10
- 55	0.42	0.42	78	66.1	-11.9	61.4	1	3	20

FIGURE 4.64: PID tuning example 1

- We also notice that for smaller steps the response to same flow change is more similar in terms of pressure. Difference due to different PID parameters is spot only with higher intensity of disturb in the flow. See for example fig. 4.65.

$\Delta flow$	max Δp camera	max Δp dummy	%before	%after	$\Delta\%$ valve	Valve peak	K_c	T_i	Response time [min]
+ 25	0.06	0.07	71.3	78	6.7	80	2	1	12
- 25	0.06	0.1	57.5	53.5	-4	53.2	1	3	15
- 16	0.06	0.07	53.6	49.5	-4.1	49.5	1	3	25

FIGURE 4.65: PID tuning example 2

- By changing the PID parameters, it is possible to see how the valve reacts at same flow change, see for example fig. 4.66. Δp is similar, slightly better in the third case (also response time is lower). So far the best set seem to be $K_c = 2$ and $T_i = 1$.

$\Delta flow$	max Δp camera	max Δp dummy	%before	%after	$\Delta\%$ valve	Valve peak	K_c	T_i	Response time [min]
+ 30	0.1	0.1	49.5	54.6	5.1	55.3	1	3	15
+ 35	0.1	0.13	54.7	61.2	6.5	61.9	2	3	15
+ 33	0.1	0.08	61.1	69.5	8.4	72.1	2	1	10

FIGURE 4.66: PID tuning example 3

- This set makes the difference in bigger steps, as we can see from the example in fig. 4.67: a higher flow change causes a smaller Δp and lower response time. The response might be optimized in this direction: high K_c , small T_i .

Δ flow	max Δp camera	max Δp dummy	%before	%after	$\Delta\%$ valve	Valve peak	K_c	T_i	Response time [min]
- 55	0.42	0.42	78	66.1	-11.9	61.4	1	3	20
- 75	0.2	0.2	70.2	53	-17.2	48.5	2	1	15

FIGURE 4.67: PID tuning example 4

4.3.4 Magnetic field test

Unfortunately, this test could not be performed due to the outbreak of Covid-19; here only a short description of the test and the machine are given. The test will be performed by gas team once back at CERN.

A magnetic field test with the tested valve operating with external magnetic field is necessary, since during LHC RUN a magnetic field of few mT is present in USC, where the valves will be installed. The ferromagnetic components of normal valves may not work due to electromagnetic interference. For this reason, pneumatically operated solutions are often preferred but, in this case, since the pressures involved are very low, the pneumatic valves would have been very bulky and therefore difficult to install in existing systems. Since the residual magnetic field present in the USC is not as high as that in the UXC, it was considered worthy to study the behaviour of the valves in presence of this disturbing magnetic field.



FIGURE 4.68: The MNP17 magnet test machine.

The machine available for the test is the magnet MNP17, shown in fig. 4.79 which can produce a uniform magnetic field in the range 0 to 500 mT. The available space for the test is a cubic volume with a height gap of 30cm, where the valve should be fit. The test will be performed with a magnetic field intensity of 100mT. To produce this field 70A DC is needed. At zero current a residual magnetic field is present: this represents a zero offset to be taken into account in the measurements.

The setup will be similar to the one used in laboratory: it will consist of a gas supply bottle (most likely simple N_2) with pressure regulator, pressure sensor and flow meter. The gas will be then exhausted in the room. For the data acquisition and storage a data logger will be used. The valves will be tested in the same conditions they were tested in the Lab for the characterisation and same curves should be obtained if not affected by the external magnetic field. If some change is noticed, then it would be necessary to evaluate and analyse the entity of this change and understand if acceptable or not.

The test will be particularly interesting for the ECONEX valve, which was showing the most satisfying behaviour so far. If the test will be not as satisfactory as the others, a pneumatic actuated MPV could be taken into consideration, even if more expensive and even bigger.

4.4 Final Choice and Integration in the System

As already discussed, after all the tests and considering all the other factors, the best solution seems to be the ECONEX valve.

The only issue with this valve is its dimensions: given its size, it would not be easy to fit it in the already crowded available space on top of the CMS RPC gas racks. Hence, a study on the integration in the system is necessary to find the best valves layout and provide the technicians with some schematic drawings so they know where to install the valves.

A 3D drawing has been modelled simulating the integration layout of the valves in the respecting pre-distribution racks of the different parts of the RPC system: barrel, endcap positive and endcap negative.

Fortunately these valves can be mounted in whatever position (i.e. vertically or horizontally). The best and neatest possible configuration has been investigated, resulting in the solutions showed as example below in fig. 4.69 and 4.70 and for the barrel and positive endcap respectively.

Considering the space constraints, in order to install the valves as shown, some modifications are required:

- a water cooling pipe must be moved a bit further towards the back of the rack
- 7 (5 for barrel, one each for endcaps) pipes must be modified and redone

Considered the new shape of the barrel modified pipes, a pressure drop calculation on the new singularities (two 90° curves and a straight pipe) has been performed: here below is reported a simple example [11] [13].

Given:

- d_i : hydraulic diameter of the pipe,
- Q : volumetric flow rate,
- ρ : fluid density,
- ν : kinematic viscosity,
- ℓ, α : pipes lengths and geometry

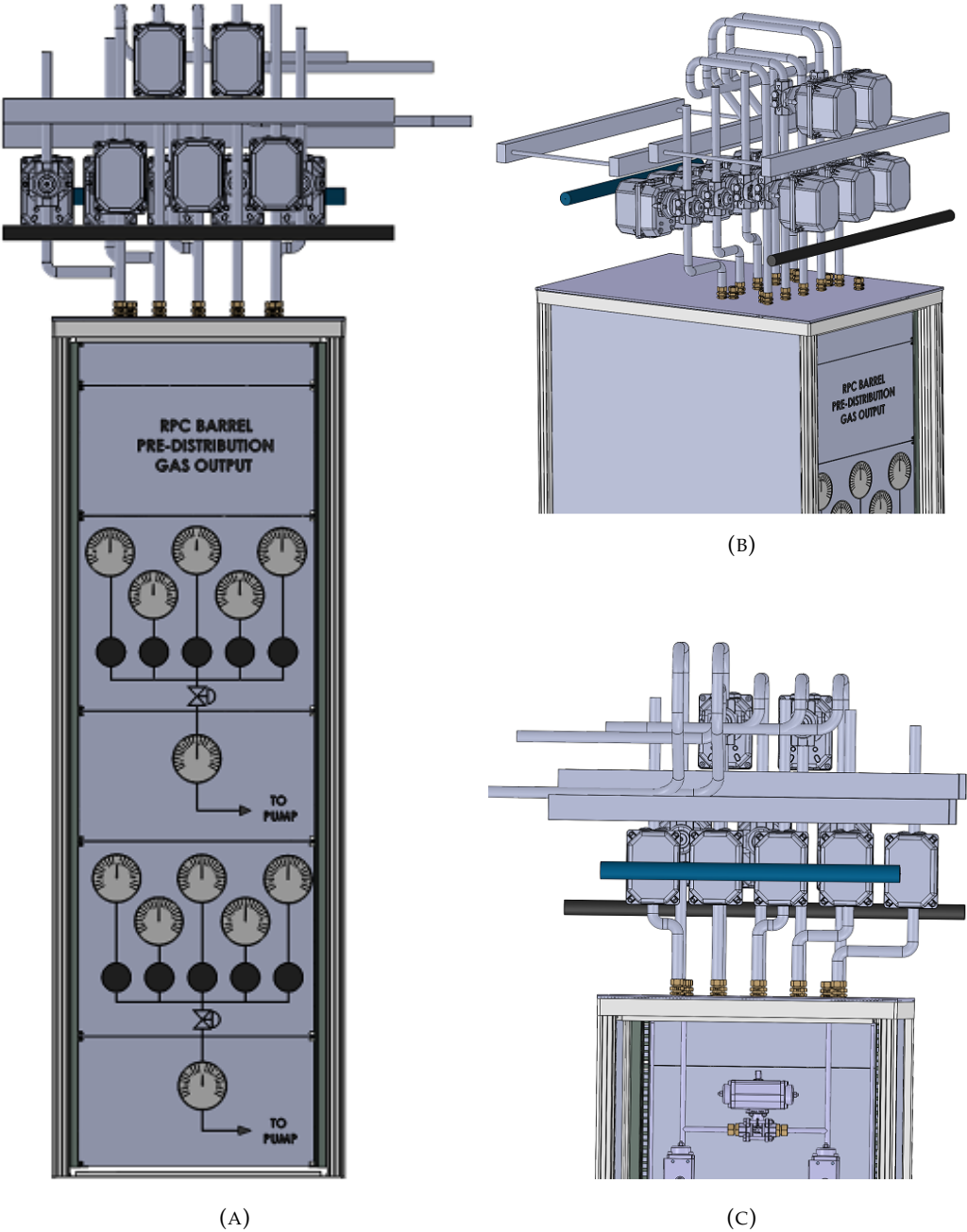


FIGURE 4.69: Barrel Integration

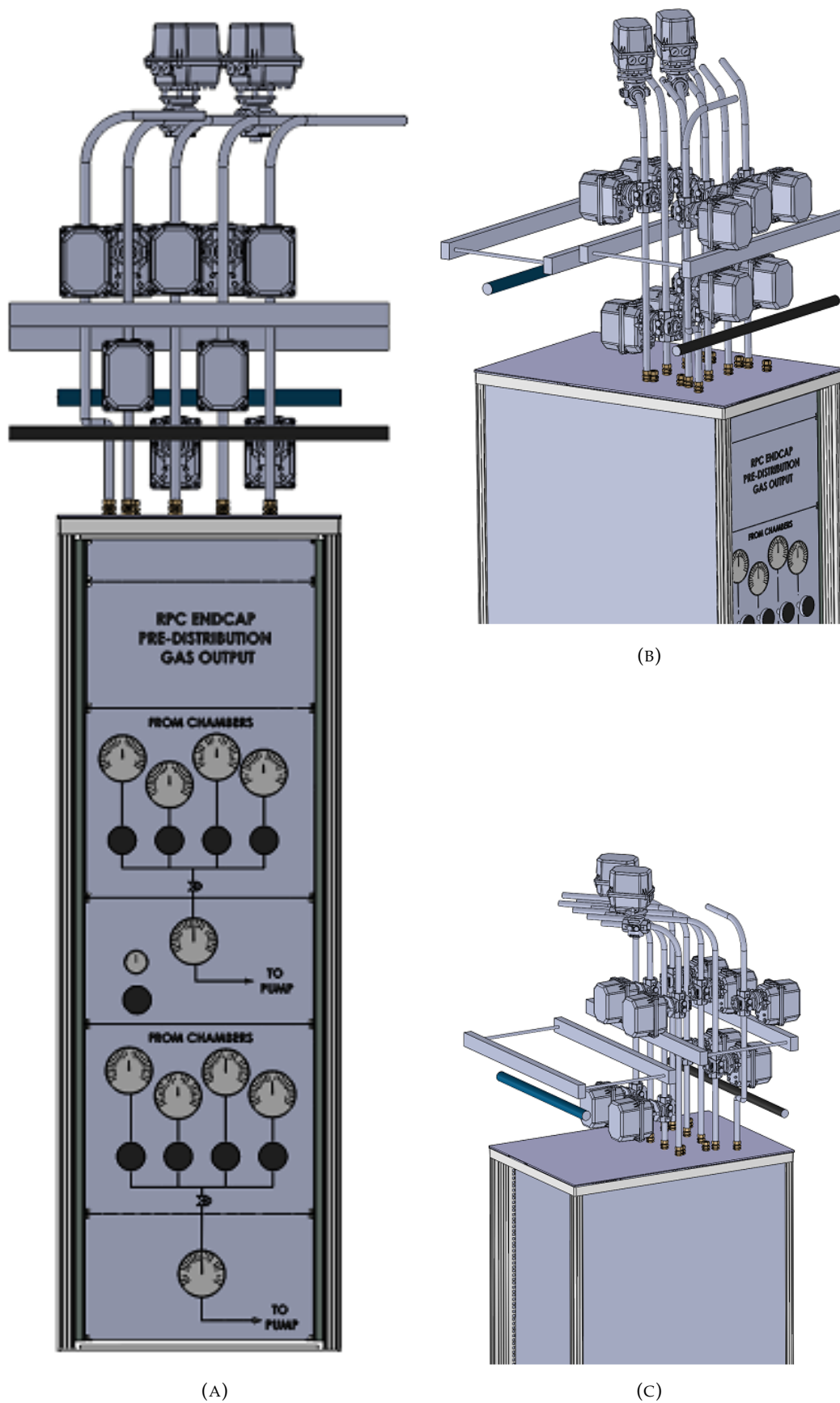


FIGURE 4.70: Positive Endcap Integration

The Reynolds number can be calculated as $Re = \frac{4 \cdot Q}{\pi \cdot v \cdot d_i}$. Then, assuming a design value for absolute surface roughness for a steel pipe of $\epsilon = 0.006 \text{ cm}$, the friction coefficient f can be numerically calculated solving the Colebrook equation:

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{\epsilon}{d_i} + \frac{2.51}{Re \cdot \sqrt{f}} \right) \quad (4.4)$$

which gives a result of $f = 0.046$.

For the distributed pressure losses:

$$R_d = f \cdot \frac{\ell}{d_i}$$

$$\Delta p_d = \rho \cdot R_d \frac{w^2}{2}$$

For the singularities, which are the pressure losses in the curves, considering curves at 90deg:

$$R_c = 0.95 \cdot \sin^3 \left(\frac{\alpha}{2} \right) + 2.05 \cdot \sin^4 \left(\frac{\alpha}{2} \right)$$

$$\Delta p_c = \rho \cdot R_c \frac{w^2}{2}$$

The total pressure drop introduced by the modified pipe is then:

$$\Delta p_{tot} = \Delta p_d + 2 \cdot \Delta p_c = 8.5 \times 10^{-6} \text{ bar}$$

The pressure drop is of the order of thousandths of mbar and can therefore be considered negligible.

As soon as other the other tests are finished, if the result is positive, the valves will be ordered and installation will be done as described.

Chapter 5

Conclusions

In this master thesis work the operation of the gas systems delivering the required gas mixture to the particles detectors at the CERN LHC experiments has been described.

These gas systems, divided into functional modules, are composed of hundreds of components which operate together in different working conditions. They are locally controlled by an industrial PLC and remotely accessible with a Gas Control System (GCS) interface. A possible failure of a gas system can lead to the stop of the gas system causing a loss of data during an LHC Run. Furthermore, a wrong manipulation of the gas system could bring to damages of the detector chambers, which often are difficult or impossible to replace or repair.

All the main functional modules have been described in this work (Chapter 2), also describing the main blocks for installing an LHC-like gas system test bench in a laboratory. After a design-phase of the layout distribution of the different modules, the system was installed in the laboratory and it is now fully operational and remotely controllable via GCS (Chapter 3). This test-bench gas system aims to faithfully reproduce the operation of a real LHC gas system: it can be used for training and will allow to test new components, new way of working and software updates. Thanks to this, it is possible to perform characterization and optimisation of the gas systems. Furthermore, the validation in a laboratory allows reducing time, costs and risks related to the operation of the real system.

In the past years during LHC RUN Phases, the gas systems show a remarkable reliability (always greater than 99%). Considering that gas systems construction was carried out in the years 2003-2007 and that they started being operated in 2007, it is clear that a proper intensive maintenance and consolidation program is necessary in order to maintain and possibly improve this exceptional reliability in the years to come.

As well known, good maintenance can lead to a longer life-time of systems components, reduce downtime and cost of operations both in terms of materials and manpower. Experience-based or sporadic maintenance can often be unreliable and difficult to manage, control and evaluate. Maintenance procedures are then needed to help the operations and make the system reliable. New maintenance procedures for each functional module have been developed in this thesis work (Chapter 3).

The maintenance procedures have been developed for each module taking into account: the analysis of historical data, the technicians' experience-based feedbacks and the in-depth study of the *modus operandi* of each module. Nonetheless, the gas system test bench has been really useful in the development of the maintenance procedures: it helped to identify the critical parts and possible failures (a sort of Failure Mode and Effect Analysis) as well as the evident problems. It was also useful to test and validate the procedure itself and, eventually, to improve it.

The procedures are "standard", meaning that, given a certain module, they are meant to work for all the same kind of modules for the different systems, if not for some special exceptions. The procedures have been written in a way that any operator, even if not familiar with the gas system, can perform the maintenance following each step. An effort has been made in trying to optimize and minimize the execution times of the procedures, so as not to be heavy and perceived as pedantic waste of time by operators, and, also, to limit their cost. An important requirement for maintenance procedure is to be user-friendly and simple to read and understand. Furthermore, it has to be well organised and traceable, therefore an interactive excel spreadsheet was chosen as solution. The sheet has been designed also keeping in mind some visual management tools. The generic procedure has been divided into three parts, corresponding to the different phases and working conditions in which a generic system can be operating. For each phase, an analysis of the required or feasible actions has been performed and for each component the possible failure modes and the corresponding best maintenance technique have been identified. For each module, a list of checks/actions is the result of all these steps, thus generating the procedure. For each step (i.e. test or check to perform on some component) there is a description, check-boxes displaying the status and the outcome of the check and, accordingly to the result, the form suggests a corrective action to take. Also, solved problems are recorded. Different colours have been used so that at first look one can get a hint about the status of the module. Moreover, specific attention has been paid to leak tests, being gas leaks one of the main and most insidious reasons of efficiency losses of the systems as well as a cost and, often, a source of emission of harmful, polluting or toxic gases. Two different leak test methods are used in the procedures aiming to quantify the leaks and localise the leaking spots. For each module a detailed description of the actions to take is provided and acceptance thresholds (leak rejection limits) are set.

Several upgrades of the LHC gas systems are on-going for the LHC Run 3 among which the search for new regulation valves for the CMS RPC distribution system. Dedicated studies have been performed on the search and testing of several regulation valves, here presented in Chapter 4.

Nowadays manual regulation valves are installed in Pre-Distribution racks to regulate chamber pressures for each distribution rack and equalize the pressure between different detector zones. A regulation through automatic regulation valves is done only for group of 5-6 distribution racks.

The regulation is particularly critical during the gas filling and emptying phase, or when the gas mixture changes. During these phases, which can last several days, the operation with the manual valve is very critical, time consuming and unstable. Moreover, manual regulation might be not effective enough to avoid pressure fluctuations or peaks and therefore keeping the chamber pressure constant. Pressure fluctuations might lead to the breaking of the fragile detector connectors, which are often not accessible, so not fixable nor replaceable, leading to chambers leakage.

The search for an automatic valve was challenging because of the application and its requirements: very low pressure (few mbars), high precision, space constraints, presence of a magnetic field, the particularity of the gas media and budget constraints (about 30 valves are needed).

Given these technical specifications, several valves (e.g. solenoid valves, pneumatic and electrical actuated, pinch valves, etc.) were selected to find the best suitable product.

A series of tests were performed to characterise the different valves and see their behaviour. First, a test in laboratory in which all the valves were tested at the design

flow-rates to see in which pressure range they could regulate. Most of the valves struggled to work in the same pressure regulation range as the manual one, used as reference. On the basis of these tests results and after having passed an ageing test, five regulation valves (i.e. the ones showing a behaviour closer the manual target one) were installed in the experiment for a test in real conditions and for a first PID parameters tuning. In this test, the automatic regulation was tested and valves' dynamical response was monitored. Only two of the installed valves showed an ideal behaviour, while the others were unacceptable due to oscillations or peaks in pressure. Then, since during LHC RUN a magnetic field of few mT is present in USC, where the valves have to be installed, an external magnetic field test was also considered necessary (but impossible to be performed in this thesis work, due to the outbreak of COVID-19). After all the tests and considering all the other involved factors, the (so far) best solution was identified and proposed as potential final solution.

Given the proposed solution valve size, it would not be easy to fit it in the already crowded available space on top of the CMS RPC gas racks. Hence, the best and neatest possible configuration has been investigated with the modelling of 3D drawings, simulating the integration layout of the valves and identifying the necessary modifications for the eventual installation.

Final tests will be performed by the Gas Team and, according to the results, the proposal final solution will be rejected or confirmed. In the latter case, the installation and integration of 28 regulation valves in the CMS RPC gas system will be done before the end of LS2 period to be ready for LHC Run 3.

Appendix A

Mixer Module Maintenance Procedure

In the following procedure, the result *Problem* is selected and the correspondent Action List is shown.

MIXER MAINTENANCE PROCEDURE						
Complete the form and print it at the end						
SYSTEM:		START DATE:		END DATE:		OPERATOR:
Mixer in RUN system ON						
WHAT	DESCRIPTION	STATUS		RESULT	ACTION LIST	Notes
LEDs check	Press the button in the mixer chassis and check if the leds are ok	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe and record the problem. Contact electrical technician	
Check Pressure Reducers	Check PI-1X03 reading and compare their value with the corresponding PT-1X03 reading on WinCCOA. Is error less than 20%?	☒	Done	☐ Ok ☒ Problem ☐ Solved	Take note of the two readings. If possible, set the corresponding PCV to zero and see which one doesn't read zero	
Lines pressure	Check if the pressure of each line is <i>equal</i> to the DMFC calibration pressure (indicated on the device).	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust the pressure reducer or try to fix the problem. If it doesn't reach the desired value, check the supply pressure on the panel.	
	Compare PCV Tescom gauge pressure with supply pressure on the wall panel for each line: regulator pressure should be 0.3-0.5 bar lower than network pressure	☒	Done	☐ Ok ☒ Problem ☐ Solved	Take note of the two values. Supply pressure has to be increased. Contact David Jaillet.	
	Check that pressure master MFC PI-1103 is lower than pressure slaves MFCs	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to adjust and set it 0.3-0.5 bar below master pressure	
	Make sure that the smallest concentration line has the highest pressure	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust the pressure reducer and try to fix the problem. Describe and record the issue	
Read PI-1009 pressure and compare its value with the PT-1009 reading on WinCCOA	2-3 gauge divisions difference acceptable	☒	Done	☐ Ok ☒ Problem ☐ Solved	If possible, set the 3-way-valve HV-1011 to exhaust and check the error on the zero. Eventually, replace the device not reading zero	
If present, check PICV-1502 setting (which is pressurizing the Zimmerli PCV-1007). If not, if the system is in real Run (not to exh), check spring setting	If the system is in: - recirculating mode: ~ 200mbar below PT1009 reading pressure - open mode: ~ 600 mbar For the spring: p ~ 300 mbar	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust the PICV setting. Describe and record the problem	
Check YV-1008 bypass is closed		☒	Done	☐ Ok ☒ Problem ☐ Solved	Close it	

Mixer in STOP system ON or OFF							
Documentation check	P&ID (and electrical) drawings are present in the rack	☒	Done	☐ Ok ☒ Problem ☐ Solved		Print it from EDMS, after having done next step	
	Documentation is present in EDMS and up to date.	☒	Done	☐ Ok ☒ Problem ☐ Solved		Ask the responsible of the system to update it	
Drawing VS Reality	Check every component has a label in accordance to the name on the P&ID	☒	Done	☐ Ok ☒ Problem ☐ Solved		Correct wrong/add missing labels	
Safety valves check	Check on the labels if they are up-to-date (at least 1 year within expiry date)	☒	Done	☐ Ok ☒ Problem ☐ Solved		Contact the person in charge of Safety Valves calibration	
PI-1009 Zero Check	Turn the 3-way-valve HV-1011 to exhaust and make sure that PI-1009 reads 0 mbar	☒	Done	☐ Ok ☒ Problem ☐ Solved		Take note of the value read. If this is more than 50 mbar or less than 0 mbar PI must be replaced	
MFC	Check that all DMFCs read 0 l/h	☒	Done	☐ Ok ☒ Problem ☐ Solved		Check Deadbeand has a reasonable value (not too high)	
	Put MFCs in manual mode (regulated) and check they reads zero flow	☒	Done	☐ Ok ☒ Problem ☐ Solved		Dismount the MFC and give it to the responsible for check	
	If the system uses a flammable gas (or R134a) first perform a N2 purge of the mixer. Close HV gas supply inside the rack, Yvs 1X05 and 1X08, manual valves after the DMFCs. Remove flammable gas detection head and put it outside the rack. Switch off Mixer power supply. Double check the label on the MFC corresponds to the correct gas and properties. Dismount the DMFCs for the check of calibration and internal PID settings. They will show Profibus communication error: put Mixer module in Force Mode	☒	Done	☐ Ok ☒ Problem ☐ Solved		Describe the problem	
Leak tests							
Leak test	Follow the procedure for: Detectable Gas Leak Test	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the issue	

Mixer to RESTART system ON or OFF							
Check all Hand Valves position	HV-1X15 closed HV-1X07 and HV-1X1X10 open FIV-1005 open	☒	Done	☐ Ok ☒ Problem ☐ Solved		Adjust all the valves for the RUN	
Make sure the 3-way-valve HV-1011 is to exhaust and try to restart the mixer in RUN mode	Check errors. Wait until Mixer is in RUN and doesn't stop.	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem and/or contact Patrick/Michal	
Leak test	Only if something has been touched after the Leak test in STOP	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem	
MFC flow stability check	Make sure the 3 DMFCs' flows and concentrations are stable (fluctuation has to be less than 0.5% of flow reading)	☒	Done	☐ Ok ☒ Problem ☐ Solved		Check PID parameters and/or contact Michal	
Deadband/archiving monitoring	Procedure for Michal/technicians	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem	
Regulation of FIV-1005 and PCV-1007	to be defined	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem	

LEAK TEST PROCEDURE - MIXER

For open mode systems HV-5014 is replaced by HV-6131 or HV6123
In case dedicated Analysis Modules are present for the mixer check if other valves have to be closed (e.g. IR).

Leak test inside the rack: Put **Mixer Module in Forced Mode**.

- **Detectable Gas Leak test** (after having re-mounted the DMFCs): use the most convenient gas among the available ones in the mixer lines. If present, CO₂ is preferable
 - a) Close supply valves inside the rack (HV-1X01)
 - b) Turn HV -1011 to System and close HV-5014
 - c) Open the valves:
 - HV-1X15
 - YV-1X05, YV-1X08
 - HV-1X07 and HV-1X10
 - YV-1004, YV-1006, YV-1008
 - (FIV-1005 and PCV-1007)
 - d) Send selected detectable gas to each line from the correspondent supply valve inside the rack (e.g. if only CO₂: open the CO₂ valve)
 - e) Set PCV-1X02 to ~0.5bar less than relief pressure of PSV-1010
 - f) Open the DMFCs (manual mode → regulated, set a set point flow)
 - g) When the system reaches everywhere the set pressure, close the supply valve and close again the valves HV-1X15 to isolate each line
 - h) Take note of PT-1X03 and PT-1009 reading (Check dead-band is less or equal to 0.1 bar)
 - i) Perform a first **Leak identification** using a sniffer in every line. If any leak is spotted, try to fix it.
 - j) Wait at least 6h.
 - k) Then compare the PI readings to the previous ones:
 - If the values did NOT change → No leak, turn the HV-1101 to Vent and go ahead with the procedure
 - If they did change → Fill the [excel table](#) for leak test:
 - If the result is ok, go ahead with the procedure
 - If not acceptable perform again **Leak Identification** using a Sniffer and fix the leaks. Then perform again the leak test and check if there are no more leaks

[Check drawing for final configuration](#)

Once all the leaks are fixed, empty the system from the detectable gas turning the HV-1101 to Vent.

Appendix B

Exhaust Module Maintenance Procedure

In the following procedure, the result *Problem* is selected and the correspondent Action List is shown.

EXHAUST MAINTENANCE PROCEDURE Complete the form and print it at the end						
SYSTEM:		START DATE:		END DATE:		OPERATOR:
Exhaust in RUN system ON						
WHAT	DESCRIPTION	STATUS		RESULT	ACTION LIST	Notes
LEDs check	Press the button in the exhaust chassis and check if the leds are ok	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe and record the problem. Contact electrical technician	
Check Pressure Indicators	Check PI-5005 and PI-5011 reading and compare their values with the corresponding PTs reading on WinCCOA. Is error less than 20%?	☒	Done	☐ Ok ☒ Problem ☐ Solved	Take note of the two readings. If possible, check the zero reading of the two devices	
Buffer pressure check	Check it is reaching the pressure setpoint. Is Buffer deviation less than 10%? Are there oscillations?	☒	Done	☐ Ok ☒ Problem ☐ Solved	Contact the main responsible and try to adjust PID settings.	
Check YV-5003	If running in open mode, it should be closed. If in closed mode, open.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to fix the problem	
If present, check DPT-5030 reading on filter 5030	If higher than H threshold (7mbarg) foresee filter replacement at first technical stop	☒	Done	☐ Ok ☒ Problem ☐ Solved	GF-5030 must be inspected or DPT doesn't work properly?	
FIT-5010	Check total flow cells flow reading corresponds to the FIT-5010 reading. Check the FIT-5010 reading is stable.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Make sure the FIT is working within its design nominal conditions. If not contact the main responsible	
Pneumatic lines check	check pneumatic lines pressure to be ~4bar	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust pressure with the reducer	
	Leak test with Milles Bulles on the pneumatic tubes and connectors	☒	Done	☐ Ok ☒ Problem ☐ Solved	Fix the leaks as soon as possible	
PCV-5001	Set pressure to 1bar on WinCCOA (Recipe: "Pressure Regulation Level: MPosR") and set zero the mechanical spring pressure	☒	Done	☐ Ok ☒ Problem ☐ Solved		

Exhaust in STOP system ON or OFF						
Documentation check	P&ID (and electrical) drawings are present in the rack	☒	Done	☐ Ok ☒ Problem ☐ Solved	Print it from EDMS, after having done next step	
	Documentation is present in EDMS and up to date.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Ask the responsible of the system to update it	
Drawing VS Reality	Check every component has a label in accordance to the name on the P&ID	☒	Done	☐ Ok ☒ Problem ☐ Solved	Correct wrong/add missing labels	
PIs zero reading check	Take note of the value read by PI-5005 and PI-5011: is it less than 50 mbar and more than 0 mbar?	☒	Done	☐ Ok ☒ Problem ☐ Solved	PI must be replaced	
Safety valves check	Check the labels of SV-5019 and SV-5029/X if they are up-to-date (at least 1 year within expiry date)	☒	Done	☐ Ok ☒ Problem ☐ Solved	Contact the person in charge of Safety Valves calibration	
Pneumatic lines	Check if all the pneumatic lines connectors are well connected and the conditions of the plastic hoses. Fix eventual leaks spotted.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Change connectors/hoses	
Filter 5030 replacement	Check if filter mesh is 1um. Clean/replace filter if dirty or DPT-5030 reading is not zero.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Take note here of the current filter mesh and order a new 1um mesh filter to install as soon as possible	
XMFC-5002	Check that the XMFCread 0 l/h	☒	Done	☐ Ok ☒ Problem ☐ Solved	Check Deadbeand has a reasonable value (not too high)	
	Put XMFC in manual mode and check it reads zero flow	☒	Done	☐ Ok ☒ Problem ☐ Solved	Dismount the MFC and give it to the responsible for check	
	Dismount the XMFC for the check of calibration and internal PID settings. Remount it in its position afterwards.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe the problem	
Leak tests						
Leak test	Follow the procedure for: Detectable Gas Leak Test	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to fix the problem. Describe and record the issue	

Exhaust to RESTART system ON or OFF						
Check all Hand Valves position	Open HV-5014 HV-5024, HV-5025 HV-5026, HV-5028 HV-5021 HV-5031 HV-5032,HV-5033 RP valves, Humidifier valves Close HV-5027	☒	Done	☐ Ok ☒ Problem ☐ Solved		Adjust all the valves for the RUN
Leak test	Only if something has been touched after the Leak test in STOP	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem
System in RUN	Check errors. Wait until Exh is in RUN and doesn't stop.	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem and/or contact Michal
PID check	General check of main PID parameters	☒	Done	☐ Ok ☒ Problem ☐ Solved		Contact Michal or main responsible
Deadband/archiving monitoring	Procedure for Michal/technicians	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem

LEAK TEST PROCEDURE - EXHAUST

Gas will be supplied from Mixer module

Use CO2 if present or any other detectable gas if not

Leak test inside the rack: Put **Exhaust Module in Forced Mode**.

○ Detectable gas Leak test :

1. Isolate the Exhaust Module from the whole System:
 - a) Close HV-5021 and HV-5031
 - b) Close HV-5017 and HV-5018 (or HV-5032 if you don't want to test the RP-1919 also)
2. Leak test
 - a) Close
 - PV-5001
 - HV-5033 (or XMFC-5002)
 - Sampling valves
 - HV-5102, HV-5103, YV-5104/X (if Humidifier present)
 - b) Open
 - HV-5014
 - Filter related valves: HV-5026, HV-5027, HV-5028
 - HV-5024, HV-5025, YV-5101 (if Humidifier present)
 - c) Make sure HV-1011 (in Mixer Module) is turned to SYS and send supply gas until the PTs read X bar (check SV release pressure), then close gas supply and HV-5014
 - d) To isolate the different parts of the system, close YV-5003
 - e) Take note of the PT-5005 and PT-5011 readings and perform a first check with a sniffer. Fix the eventual leaks found
 - f) Wait for ?hr (**volume needed**)
 - g) Fill the excel leak test if you notice a pressure decay
 - h) If the leak test is not passed try to spot and fix the remaining leaks

✓ Leak Identification

1. Sniffer carefully every single spot of the system. Mark the leak detected with a marker and take note of the points for future reference (dangerous leak spots "black list")
2. According to the type of leaking spot (connection, pipe, valve, reducer...) perform the best appropriate reasonable action in order to try to eliminate the leak (e.g. for a connection at first attempt, if possible, tighten the threads). Once done perform again the test.
3. If no more leak detected, great! Otherwise a deeper investigation is needed (e.g. maybe the connections or the seals must be replaced because damaged. A list of possible causes can be done based on technicians experience)

Appendix C

Pump Module Maintenance Procedure

In the following procedure, the result *Problem* is selected and the correspondent Action List is shown.

PUMP MAINTENANCE PROCEDURE Complete the form and print it at the end						
SYSTEM:		START DATE:		END DATE:		OPERATOR:
Pump in RUN system ON						
WHAT	DESCRIPTION	STATUS		RESULT	ACTION LIST	Notes
LEDs check	Press the button in the pump chassis and check if the leds are ok	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe and record the problem. Contact electrical technician	
Inlet Pressure Control	Check PI-4004 reading and compare its value with the corresponding PT-4004 reading on WinCCOA. Is error less than 20%?	☒	Done	☐ Ok ☒ Problem ☐ Solved	Take note of the two readings. If possible, check the zero reading of the two devices	
	Check that setpoint is equal to PT-4004 reading on WinccoA. Setpoint Value should be as listed in this <i>Inlet Pressure Table</i>	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to adjust parameters	
loop regulation check	Valve PV-4003 setting around 50-80%	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust HV-4030	
Check YV-4002 bypass is closed		☒	Done	☐ Ok ☒ Problem ☐ Solved	Close it	
Outlet pressure control	Read PI-4006 pressure and compare its value with the PT-4006 reading on WinCCOA. 2-3 gauge divisions difference acceptable	☒	Done	☐ Ok ☒ Problem ☐ Solved	check zero reading	
	pressure value must be in the range 0.5-1 bar	☒	Done	☐ Ok ☒ Problem ☐ Solved	Check loop regulation	
check DPT reading	If higher than H threshold (50mbarg) foresee filter replacement at first technical stop	☒	Done	☐ Ok ☒ Problem ☐ Solved	GF-4020 must be inspected or DPT doesn't work properly?	
check membrane pressure	it should be zero or few mbar	☒	Done	☐ Ok ☒ Problem ☐ Solved	Switch to another pump and replace the membrane	
N2 supply	check N2 supply pressure and PICV-4021 setting (~4bar)	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust supply pressure/ contact David Jaillet	
	Leak test with Milles Bulles on the pneumatic tubes and connectors	☒	Done	☐ Ok ☒ Problem ☐ Solved	Fix the leak as soon as possible	

Pump in STOP system ON or OFF						
Documentation check	P&ID (and electrical) drawings are present in the rack	☒	Done	☐ Ok ☒ Problem ☐ Solved	Print it from EDMS, after having done next step	
	Documentation is present in EDMS and up to date.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Ask the responsible of the system to update it	
Drawing VS Reality	Check every component has a label in accordance to the name on the P&ID	☒	Done	☐ Ok ☒ Problem ☐ Solved	Correct wrong/add missing labels	
PI zero reading check	Take note of the value read: is it less than 50 mbar and more than 0 mbar?	☒	Done	☐ Ok ☒ Problem ☐ Solved	PI must be replaced	
rubber dampers supporting the pump	Are they in good conditions?	☒	Done	☐ Ok ☒ Problem ☐ Solved	Replace them if cracked	
N2 supply	Check if all the pneumatic lines connectors are well connected and the conditions of the plastic hoses	☒	Done	☐ Ok ☒ Problem ☐ Solved	Change connectors/hoses	
Von Rohr check?	ask to Patrick	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe the problem	
NV valves	During a LS, consider to change NV valves	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe the problem	
Leak tests						
Leak test	Follow the procedure for: Detectable Gas Leak Test	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to fix the problem. Describe and record the issue	

Pump to RESTART system ON or OFF						
Running hrs pumps check	check if the pumps are about to reach the maximum running time	☒	Done	☐ Ok ☒ Problem ☐ Solved		Consider to replace the pump mebranes before restarting
Check all Hand Valves position	HV-4005 and HV-4041 HV-4007 open HV-4X10 and HV-4X13 open HV-4008 and HV-4009 (buffer) open HV points de pickage closed	☒	Done	☐ Ok ☒ Problem ☐ Solved		Adjust all the valves for the RUN
Leak test	Only if something has been touched after the Leak test in STOP	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem
System in RUN	Check errors. Wait until Pump is in RUN and doesn't stop.	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem and/or contact Michal
PID check		☒	Done	☐ Ok ☒ Problem ☐ Solved		Contact Michal
Deadband/archiving monitoring	Procedure for Michal/technicians	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem
Regulation of PV-4003 and HV-4030	to be defined	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem

LEAK TEST PROCEDURE - PUMP

Leak test inside the rack: Put **Pump Module in Forced Mode**.

- **Detectable gas Leak test :**

1. Isolate the Pump Module from the whole System:
 - a) Close HV-4005 and HV-4041
 - b) Open YV-4001 and YV-4040
2. Buffer leak test
 - a) Close
 - HV-4007
 - PCV-4018, YV-4002
 - HV-4009
 - b) Connect supply gas to HV-4010
 - c) Make sure HV-4008 is open and send gas opening HV-4010
 - d) Fill the vessel until **pressure reaches 0.8 p_max**, then close again supply valve
 - e) Take note of the PT-4004 reading and perform a first check with a sniffer. Fix the eventual leaks found
 - f) Wait for ?hr (**ask for buffer volume**)
 - g) Fill the excel leak test if you notice a pressure decay
 - h) If the leak test is not passed, try to spot and fix the remaining leaks
3. Pressurize the whole system
 - a) Keep HV-4008 and HV-4009 closed, then
 - Close HV-4X10
 - Open HV-4007
 - Close HV-4X11
 - Open HV-4X13
 - Open HV-4X14
 - Make sure, if existing, HV-4014 and HV-4016 are closed
 - Make sure HV-4020/X are in position to send gas to the filter GF-4020
 - Open HV-4021/X
 - Open YV-4002
 - Open if possible PV-4003
 - b) Send gas from HV-4010 **at 2 bar** (to check which is the most critical component max-pressure-wise: pressure sensor, NV?) .

Gas will be supplied from Points de
Pickage: add manual valve+bouchon if
not present

**Which gas is available from wall panel
in USC?**

**Bring gas bottle? pressure reducers
needed**

- c) If present, open the PCV-4018 at supply pressure
- d) Once every PT reads supply pressure, turn th HV-4020/X to fill the bypass line too
- e) Close supply valve when every PT reads supply pressure again
- f) Fully close PCV-4018 and YV-4002 to separate two parts
- g) Take note of the PT-4004 and PT-4006 readings and perform a first check with a sniffer. Fix the eventual leaks found
- h) wait for ? hrs. **(pump module volume)**
- i) Fill the excel leak test if you notice a pressure decay
- j) If the leak test is not passed try to spot and fix the remaining leaks
- k) Empty the system opening HV-4016

✓ **Leak Identification**

1. Sniffer carefully every single spot of the system. Mark the leak detected with a marker and take note of the points for future reference (dangerous leak spots “black list”)
2. According to the type of leaking spot (connection, pipe, valve, reducer...) perform the best appropriate reasonable action in order to try to eliminate the leak (e.g. for a connection at first attempt, if possible, tighten the threads). Once done perform again the test.
3. If no more leak detected, great! Otherwise a deeper investigation is needed (e.g. maybe the connections or the seals must be replaced because damaged. A list of possible causes can be done based on technicians experience)

Appendix D

Purifier Module Maintenance Procedure

In the following procedure, the result *Problem* is selected and the correspondent Action List is shown.

PURIFIER MAINTENANCE PROCEDURE Complete the form and print it at the end						
SYSTEM:		START DATE:		END DATE:		OPERATOR:
Purifier in RUN system ON						
WHAT	DESCRIPTION	STATUS		RESULT	ACTION LIST	Notes
LEDs check	Press the button in the Purif chassis and check if the leds are ok	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe and record the problem. Contact electrical technician	
PI and PT readings comparison	Check PI-2X08 reading and compare their values with the corresponding PTs reading on WinCCOA. Is error less than 20%?	☒	Done	☐ Ok ☒ Problem ☐ Solved	Check zero reading	
check FIV setting	Verify FIV 2004 flow is about 40% of total flow	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust the flow accordingly	
	If in Purge, check FIV-2X12 flow is set around 400l/h	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust the flow accordingly	
Check pneumatic valves compressed air pressure	Check pneumatic lines pressure to be ~4bar. Check pilot valves YY-2001/X, YY-2X03, YY-2X07 with the corresponding YVs.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Adjust pressure with the reducer	
	Leak test with Milles Bulles on the pneumatic tubes and connectors	☒	Done	☐ Ok ☒ Problem ☐ Solved	Fix the leaks as soon as possible	
Vacuum pump check	Does it reach -600/-700mbar?	☒	Done	☐ Ok ☒ Problem ☐ Solved	Verify if there are air intakes, otherwise change the pump	

Purif in STOP system ON or OFF						
Documentation check	P&ID and electrical drawings are present in the rack	☒	Done	☐ Ok ☒ Problem ☐ Solved	Print it from EDMS, after having done next step	
	Documentation is present in EDMS and up to date.	☒	Done	☐ Ok ☒ Problem ☐ Solved	Ask the responsible of the system to update it	
Drawing VS Reality	Check every component has a label in accordance to the name on the P&ID	☒	Done	☐ Ok ☒ Problem ☐ Solved	Correct wrong/add missing labels	
Safety valves check	Check SV- 2X-13 labels if they are up-to-date (at least 1 year within expiry date)	☒	Done	☐ Ok ☒ Problem ☐ Solved	Take them out and bring them for recalibration. Then put them back	
Heater check	Open Purge, set Regeneration T with heater TuZ2X01 and check the temperature is increasing and reaching the setpoint (to be done before replacing material: if there is a problem you may need to remove the material again!)	☒	Done	☐ Ok ☒ Problem ☐ Solved	Contact the electrical technician	
Material Refill (when needed)	Follow Material Replacement procedure	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to fix the problem	
Regeneration test	Put in Regeneration mode and follow the different regeneration phases	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe the problem	
Filter at the output	Inspect and clean/replace filter 2009	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to fix the problem	
	Verify that filter 2009 has bypass line, otherwise add	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to fix the problem	
PI zero reading check	Take note of the value read by PI-2X08 and PI-2005: is it in the range 0-50 mbar?	☒	Done	☐ Ok ☒ Problem ☐ Solved	PI must be replaced	
Input and output column valves inspection	Open valves YV-2X07 and YV-2X03 for inspection and eventually cleaning	☒	Done	☐ Ok ☒ Problem ☐ Solved	Describe the problem and try to fix it. If needed, change the valve body	
Vacuum pump check	Check presence of water in vacuum pump exhaust line	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to remove water and to fix the problem	
Leak tests						
Leak test	Follow the procedure for: Detectable Gas Leak Test	☒	Done	☐ Ok ☒ Problem ☐ Solved	Try to fix the problem. Describe and record the issue	

Purif to RESTART system ON or OFF						
Check all Hand Valves position	All hand valves must be ready for run (check output filter bypass valves, sampling valves AV-2006/X)	☒	Done	☐ Ok ☒ Problem ☐ Solved		Adjust all the valves for the RUN
System in RUN	Check errors. Wait until Purif is in RUN and doesn't stop.	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem and/or contact Patrick/Michal
Leak test	Only if something has been touched after the Leak test in STOP	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem
PID check		☒	Done	☐ Ok ☒ Problem ☐ Solved		Contact Michal
Deadband/archiving monitoring	Procedure for Michal/technicians	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem
	to be defined	☒	Done	☐ Ok ☒ Problem ☐ Solved		Try to fix the problem. Describe and record the problem

LEAK TEST PROCEDURE - PURIFIER

Leak test inside the rack: Put Purifier Module in Forced Mode

○ **Detectable Gas Leak test :**

1. Valves configuration

a) Close

- YV-2007/X and YV-2008
- AV-2006/X
- FIV-2112
- YV-5003 (in exhaust module)
- YV-4005 (in pump module)

b) Open

- YV-2X10 and YV-2X11
- YV-2X05, YV-2X06, YV-2X07
- YV-2X03
- YV-2X04
- FIV-2004
- YV-2001/X

c) In Vacuum Pump line

- Put a stopper (bouchon or closed hand valve) in the exhaust line
- Close Purge and N2 valves

2. Pressurize the whole system

- Open CO2 supply purge valve YV-2007/1
- Regulate PICV-2007 pressure to 1.5 bar (check maximum allowed pressure on SV 2005) and adjust FIV-2X12 flow (around 400l/h is ok)
- Once every PT has reached supply pressure close supply valve

3. Separate different parts of the system

- Close YV-2X10 and YV-2X11
- Close YV-2X04
- Close YV-2007, YV-2105, YV-2203

4. Leak test

- Take note of the PT-2X08 and PI-2005 readings and perform a first check with a sniffer. Fix the eventual leaks found
- Wait for ? hrs. **(parts purif module volume)**
- Fill the excel leak test if you notice a pressure decay
- If the leak test is not passed try to spot and fix the remaining leaks
- Empty the system opening to exhaust (e.g. FIV-2112) or think if you can use and test the vacuum pump

Regenerant material replacement

Before starting, keep in mind that putting the Purif in STOP, you bypass it -> some maintenance can be done even when the system is ON

Material needed for the operation: gloves, mask, aspirator, vacuum cleaner and funnel.

Same procedure to be done for the two columns

1. Empty the module from gas in the gas room (Surface/Underground)
 - a. Depressurize the columns opening YV-2X04
 - b. Take out the SV 2X13 (only if you need to re-validate them. Once validated, put them back)
2. Remove old material: **DANGER**: the regenerant material can be toxic and heats up with air, take proper safety protections, e.g. gloves, mask.
 - a. Open metal flanges underneath the column
 - b. Recuperate the material with the metal basket (shake if necessary: material may be stuck). Verify material removed corresponds to the one listed in the ppt file*
 - c. Change the flange joints (mesh on the top/bottom of the purifier column)
 - d. Put back the flange
3. Leak test
 - a. Open YV-2X10 and YV-2X06
 - b. Flush columns for about 10 volumes
 - c. Pressurize with CO₂ (or Ar) up to 1-1.5 bar (PT-2X08)
 - d. Close YV-2X10 again
 - e. Wait to see if pressure decreases, find and fix the leaks (critical spots: SV, flange, valves). Fill excel leak test
Tip: valve YV- 2X07 is often cause of the leak: replace the body in case.
4. Material refill: **DANGER**: the regenerant material can be toxic and heats up with air, take proper safety protections, e.g. gloves, mask.
 - a. Open the top flange
 - b. Refill with new regenerant material (see required quantities in ppt file*)
 - c. Put back the flange with new joints
 - d. Put a label on the column with refill date and refill material. Give notice to Andrea about the quantity used (for stock management)
 - e. Perform again Leak test. Reminder: pressure can decrease or increase because of the reaction of the new material with fresh gas; if the case do another purge.
 - f. Fix the eventual leaks

Ppt file : G:\Departments\PH\Groups\TA1\Gas_group\Purificateurs\2014 Produit regeneration\Purrier regenerant-14032017.ppt

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