Primary refrigeration system commissioning based on a transcritical 2-stage R744 cycle

A review of control system implementation and simulated controller design

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Declaration

This thesis/dissertation has been submitted to the Turnitin module (or equivalent similarity and originality checking software) and I confirm that my supervisor has seen my report and any concerns revealed by such have been resolved with my supervisor.

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Abstract

This report gives a brief background into the use of carbon dioxide as a refrigerant (R744) and describes the development of a two-stage trans-critical cooling system that is intended to be used as a chiller for the detectors at CERN's Large Hadron Collider (LHC). It then goes on to describe the steps taken to prepare the system for start-up. These steps include the process of defining how the system should operate and translating this into actuator and PLC logic; identifying the safety limits and implementing alarms to prevent accidents; testing the PLC redundancy to understand its failure modes; testing the programmed logic and wiring; and testing the alarms before clearing the system for start-up.

Once the system is started, the controllers are manually tuned by an operator to achieve stable and reliable performance. However, this project aims to determine whether a better performance can be achieved by first modelling the system, determining the transfer function of each control loop and designing the controllers mathematically. To do this, the system is modelled in Simulink, and the performance of the model is verified by comparing the outputs of the model to that of the physical system while running with the same operating conditions.

With the verified model, the transfer function of each control loop can be determined, and various control methods can be used to design the PI controllers. Due to the complexity of the control problem, and the interaction between the multiple control loops, care is taken when defining the desired performance of the controllers to maximise disturbance rejection and ensure that the controllers can operate independently without causing instability in other control loops.

The designed controllers are implemented in the simulated model of the plant to verify the performance of the control loops under different operating conditions and with realistic disturbances. This is compared to the performance of the physical system with its manually tuned controllers. The comparison finds that the designed controllers perform better, with less oscillation and better disturbance rejection than the manually tuned controllers. From this it can be concluded that the process of simulating the system and designing the controllers mathematically provides more stable performance than the manual operator tuning. However, this process is much more time-consuming and requires a deep understanding of the instabilities, disturbances, and possible failures of the system. This may not be practical for the commissioning of multiple, large, complex systems with restrictive deadlines but may be worthwhile for systems that will be multiplied several times as the Primary R744 chiller at CERN will be.

Table of Contents

List of Figures

List of Tables

Table of Acronyms

CERN	European Organisation for Nuclear Research
LHC	Large Hadron Collider
ATLAS	A Toroidal LHC ApparatuS
CMS	Compact Muon Solenoid
LHCb	Large Hadron Collider beauty
ALICE	A Large Ion Collider Experiment
2PACL	2 Phase Accumulator Controlled Loop
p-p	Proton-Proton
A-A	Nucleus-Nucleus
HL-LHC	High Luminosity Large Hadron Collider
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
FC	Fluorocarbon
CFC	Chlorofluorocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
P&ID	Piping and Instrumentation Diagram
PH	Pressure-enthalpy
IO	Input/Output
RIO	Remote Input/Output
PCO	Process Control Object
SP	Set Point
LP	Low Pressure
MP	Medium Pressure

UAB	UNICOS Application Builder
GPN	General Public Network
TN	Technical Network

1. Introduction

1.1 Background to the study

The European Organization for Nuclear Research, CERN, is one of the world's foremost laboratories for particle physics research. Their Large Hadron Collider (LHC) is currently the largest particle accelerator in the world and was instrumental in the discovery of the Higgs Boson particle. The accelerator is 26.7 kilometres long and located between 45 m and 170 m underground, with four particle detectors located at different points along the accelerator. These detectors are ALICE, CMS, LHCb and ATLAS. The detectors are placed at points where groups of particles collide with each other, and the radiation emitted by these collisions is measured [1].

Each detector has very high cooling requirements and a lot of work goes into making sure these machines do not overheat. The large scale and extreme temperature requirements mean that CERN is constantly developing new cooling methods to keep up with the ever-increasing demand of the upgraded equipment. Along with the need to increase cooling capacity and reach even lower temperatures, CERN is also under pressure to seek out more environmentally friendly refrigerants that are also radiation hard. This is what led to the introduction of carbon dioxide (R744) as a refrigerant. R744 has a global warming potential (GWP) of 1 compared to 9300 for C_6F_{14} and 8830 for C_3F_8 [2], which are the refrigerants used in the current primary cooling systems at CERN. R744 also has the possibility of cooling to temperatures as low as -53°C.

Since it is not possible to introduce new technology or perform large system changes when the detector is running, it is important to build a test system first to confirm the predicted behaviour and work out any potential problems before the final system is installed underground during the long shutdown of the beam. For this purpose, the Primary R744 System A was built on the surface and tested with a dummy load. This report covers the testing and commissioning of System A and includes a breakdown of the problems that were encountered in the process.

1.2 Objectives of this study

The purpose of this study is to prepare the R744 Primary System A for start-up and perform some initial testing and controller tuning. This system is being used as a prototype for several new chillers which will be installed in ATLAS and CMS, so the objective of the system is validate the chiller performance and determine its suitability for detector cooling at CERN. Additionally, this study aims to develop a reasonable dynamical model of the system and evaluate the usefulness of such a model as a tool for system testing and controller tuning.

1.3 Scope and Limitations

The scope of this study does not include the design of the mechanical or electrical system which was completed before the start of this study. The scope, however, does include system modelling and simulation as well as the preparation, commissioning, and testing of the system before starting up. This is followed by PID tuning and performance testing.

While the future design of the system is intended to make use of multiple, modular compressor slices, this study is limited to 2 such slices. This is done to minimise the cost and space requirement as the proof of concept can be verified with 2 compressor slices.

This report focuses on my own contributions to the project, however, the entire project was completed by a large team made up of technicians, students, and several mechanical, process, control and electrical experts. My contribution was focused on the electrical and programming work as I assisted with updating documentation, commissioning the system signals and logic, making electrical changes in the cabinets, preparing logic templates for program generation, preparing SCADA panels for the system, testing the PLC redundancy, and tuning controllers after the system started up. All of these activities were done alongside other members of the control team or under their supervision and guidance. The work that was done entirely on my own was the development of the system's Simulink model and all testing, tuning and programming and controller design related to this.

1.4 Plan of development

The report starts with a review of the literature relating to CERN and to the use of carbon dioxide as a refrigerant. This gives context to the project by discussing the history of carbon dioxide refrigeration and giving insight into the detector cooling needs at CERN. The review of literature is followed by a description of the mechanical and process design of the primary chiller. With this background and context to the project, the report moves into the functional analysis of the system. This breaks down how the system will operate from a control and program point of view by dividing the system into control objects, actuators and sensors. It also describes the PLC architecture and communication infrastructure. The next chapter describes the steps taken to prepare the system for start-up. This includes the creation of the specification file and UNICOS templates, generating the PLC program, preparing WinCC OA and SCADA, and testing the system logic, inputs, outputs, alarms, and PLC redundancy. After discussing the steps taken to prepare the physical system, the report moves on to describe the creation of a Simulink model of the system. The model is verified by comparing the performance to the real system and then transfer functions for each control loop are obtained from simulated step responses. With these step responses and the controller performance requirements, a PI controller is designed for each control loop. These controllers are then implemented in the simulation and their response to sudden load changes and system disturbances are compared to the responses of the corresponding controllers in the physical system. The comparison between these controllers is discussed in detail and the usefulness of the simulation as a commissioning tool is examined. Finally, conclusions are drawn, and recommendations are made for future research.

2. Literature Review

2.1 CERN, the Large Hadron Collider, and the ATLAS Project

"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 [1]." The experimental data from the LHC is recorded by the four detectors that are located in parts of the LHC where particle collisions occur. These are ATLAS, CMS, LHCb and ALICE. The ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) detectors were both built for the detection of p-p (proton-proton) and A-A (nucleus-nucleus) collisions [3] [4].

The detector caverns are separated into the experimental and service caverns. The experimental cavern houses the detector and cooling apparatus. These detectors are in close proximity to the accelerator beam and the radiation this produces. Such high levels of radiation can be harmful to the silicon inside the sensors and instrumentation, so it is important that the detectors be kept at very low temperatures to minimise the damage caused. The high levels of radiation present when the beam is running also means that it is not possible to enter the experimental cavern during beam operation. The service cavern, which is isolated from the radiation of the experimental cavern, houses all additional services that do not need to be in the experimental cavern. This allows for system maintenance and services to continue even when the beam is on.

These factors drive the specific requirements for detector cooling. The limited space in and around the detector means that the volume of cooling pipes must be as small as possible. The different operational periods of the detectors call for a cooling system which has high temperature stability and can cope with large variations in load and operational temperature. In addition to this, it is crucial that the system is as reliable as possible since there is no access to parts of the system during operation. The currently adopted model for cooling these detectors makes use of two separated cooling loops. First, there is the primary cooling, which exchanges heat with the 2-Phase Accumulator Controlled Loop (2PACL). The 2PACL system is then used to cool the detectors.

Historically, both stages of these systems have made use of fluorocarbon (FC) refrigerants, namely C_6F_{14} single phase in CMS and C_3F_8 two-phase in ATLAS [5]. During the last detector upgrades between 2013 and 2016 both ATLAS and CMS detectors required more cooling power. This opportunity was used to apply the 2PACL cooling concept as well as to change the refrigerant to CO_2. The evaporative CO_2 systems are able to use smaller cooling tubes in the detector and are therefore better for the detector applications. CO_2 is also more environmentally friendly than FCs, is radiation hard, and can provide cooling at very low temperatures. In ATLAS, the 2PACL system was designed with a cooling capacity of 3 kW and makes use of a two stage Bitzer compressor as the primary cooling. This primary chiller uses the refrigerant R404a [6]. In CMS, the primary chiller uses R507a and the 2PACL system has a cooling capacity of 15 kW [5].

Now CERN is preparing for another upgrade of the LHC which is expected to start in 2026. This upgrade is the High Luminosity programme (HL-LHC) and will increase the luminosity of the LHC by a factor of 10. This will subsequently increase the radiation in the detectors. These detectors are also undergoing upgrades to cope with the high luminosity accelerator. With these detector upgrades, the cooling requirements for both ATLAS and CMS detectors will increase to 300 kW and 500 kW respectively. The higher radiation levels also mean that the required cooling temperature will decrease to -43 °C. The 2PACL systems are being upgraded to increase the cooling capacity, but the general concept will remain the same. However, the primary systems will undergo much larger changes as the FC-based chillers are replaced with a two stage trans-critical CO_2 chiller. The move to CO_2 comes with CERN's goal of decreasing their negative environmental impact, as well as the benefit of using smaller pipes which is an advantage of evaporative CO_2 cooling [7].

The requirements of the new CO_2 chiller are very stable cooling at temperatures below -50 °C capable of handling large load variations [7]. Additionally, due to limited space, large amounts of heat produced, and the risk of asphyxiation in the event of a leak, the system needs to be installed on the surface [8]. Due to the 80m height difference between the chiller on the surface and the evaporator underground, low-pressure refrigerants would introduce too many losses, making the high-pressure CO_2 system ideal for this application [7].

2.2 Use of Carbon Dioxide as a Refrigerant (R744)

R744 has been used as a refrigerant since as early as the mid-1800s. It was initially used in refrigerators for ice production but was eventually expanded into air conditioning applications. It was particularly favoured for its non-toxicity and non-flammability, which made it ideal for human and food-related industries. However, these systems were inefficient as they made use of a conventional subcritical refrigeration cycle. There were also issues with sealing and capacity loss related to the high pressures of R744. All of these factors lead to a search for more efficient refrigerants and resulted in the discovery of chlorofluorocarbons (CFCs). These refrigerants could operate more efficiently without the safety and cost issues associated with the high pressure of R744 [9].

CFC refrigerants dominated the industry until the move to more environmentally friendly refrigerants came in the late 1980s. As the effects of CFCs and hydrochlorofluorocarbons (HCFCs) on the ozone in the atmosphere became clearer, the Montreal Protocol called for the elimination of these substances to reduce the negative impact on the environment. The environmental impact was measured based on ozone depletion potential (ODP), which is the "relative measure of a kind of gas's ozone depletion effect in comparison to an equal mass of R11" [9]. Moving away from CFCs and HCFCs, industries turned to FCs and hydrofluorocarbons (HFCs). These substances have no ODP and were considered to be the environmentally friendly alternative.

As our understanding of climate change has evolved, there has been a move to also reduce the global warming potential (GWP) of refrigerants. This is the "relative measure of the heat trapping effect of a gas in comparison to an equal mass of carbon dioxide over a given period in the atmosphere" [9]. While the shift from CFCs and HCFCs to FCs and HFCs removed the issue of ozone depletion, there was no improvement in the GWP of these refrigerants. Additionally, the production of these refrigerants produces toxic and harmful waste products which are released into the environment. This led to the need for naturally occurring refrigerants such as hydrocarbons, ammonia, and carbon dioxide. Of these, carbon dioxide (R744) is a highly suitable refrigerant as it is non-toxic, non-flammable, and is widely available both in the atmosphere and as a by-product of industrial processes. Additionally, it is relatively inert and compatible with most lubricants and equipment materials.

There are some safety concerns to consider with the use of R744. Although it is non-toxic, it does pose a risk of suffocation in high concentrations. This can be managed by ensuring the area is well ventilated and equipped with R744 detectors to trigger an alarm in case of a leak. Another safety concern is the high operational pressure of R744 systems. The risk of explosion can be reduced by installing over-pressure release valves on all pressurised equipment, and pressure testing equipment with sufficient safety margins [10].

R744 has a very low critical temperature of 31.1 °C. This means that it cannot be effectively used in a conventional subcritical refrigeration cycle because the condenser is unable to transfer heat above the critical temperature. However, using a transcritical cycle, i.e., bringing the CO_2 above the critical pressure in the heat-rejection stage, solves this issue and increases the operational temperature range to span from -50 °C to 120 °C [10]. This solution was previously impractical due to the high critical pressure of R744 (73.7 bar), but technological advances have made this much more feasible. Additionally, the vaporizing latent heat and high volumetric refrigeration capacity mean that the size of compressors and other components can be smaller than those for other refrigerants. There is also very good heat transfer thanks to the low operation viscosity of R744, which produces turbulent flow even at low flow rates [9].

A two-stage transcritical cycle provides several benefits compared to a single-stage cycle. The first is the ability to apply intermediate cooling between the compressors to reduce the outlet temperature of the final compressor stage. The second is the reduced work input of the compressors and improved volumetric efficiency caused by a lower pressure differential across each compressor. The interstage cooling can be achieved with an external cooling source such as air or water coolers. Alternatively, this can be achieved with flash intercooling, which uses flash gas from the storage vessel of the system and mixes it with the warm refrigerant at the outlet of the first compressor [9].

The current state of the art in transcritical R744 refrigeration for supermarket cooling is discussed in detail by Gullo, Hafner and Banasiak where they summarise the many different system configurations being used across the world. Their analysis points to the fact that there is not one generally accepted approach, rather, there are many available configurations that are used. These configurations can include either one or two compressor stages, parallel compressors, flash gas removal, and compressor bypass valves. The regulation of the systems therefore depends on the system configuration and can either be reliant on the compressor output, the compressor bypass valve opening, or both [11].

3. Description of the Mechanical Design of the R744 System

The R744 System A is made up of one common unit and two modular chiller units referred to as slices. The common unit contains a liquid accumulator and an external water-cooling system. Each chiller slice has a cooling capacity of approximately 50 kW and is made up of two compressors, each followed by a cooling unit. There is a hot-gas bypass on each compressor which is used to control the cooling capacity of the slice. Figures 1-3 below show the piping and instrumentation diagrams (P&IDs) of these units and will be used to provide a more detailed description of the operation. The numbered points on the P&IDs correspond to the colours and numbers indicated on the pressure-enthalpy (PH) diagram in Figure 4.

The system is designed as a trans-critical cycle with the specific requirements of detector cooling in mind. The detector cooling systems at CERN require very stable temperatures at a wide range of loads. Since the temperature needs to be maintained both when the detector is running and when it is turned off, it is important to be able to adjust the cooling capacity of the system to match the load. The concept of smaller, modular 50 kW slices helps with this as slices can be turned on or off as the load changes. To provide finer control, each slice has a hot-gas bypass to adjust the capacity of the individual slice between 0 and 100%. This should allow a 2-slice cooling system to provide a constant cooling temperature of -53 °C (saturation temperature at the compressor inlet) for a load which ranges from 0 to 100 kW.

To simplify documentation, each mechanical component has been given a tag which is shown in Table 1. This table is useful to connect verbal descriptions of the system's components to the alpha-numeric names that can be found in both the piping and instrumentation diagrams (P&IDs), and the controller designs.

Table 1: Actuator descriptions

Actuator	Description	Actuator	Description
CV5002	Common circuit high-pressure line valve	**CV5114**	Liquid injection valve
CV2004	Common circuit heat exchanger water valve	**CV5186**	High pressure hot gas bypass
EV5166	Suction gas shut-off valve	**CV5192**	Gas cooler three-way valve
GP5171	Low pressure compressor	**HX5194**	Air cooled gas cooler
EH1171	LP compressor integrated oil heater	**EV5196**	Suction gas shut-off valve
CV5176	Low pressure hot gas bypass	**EV5178**	Drain line valve
GP5181	High pressure compressor	**EV1189**	Coarse oil separator drainage valve
EH1181	MP compressor integrated oil heater	**EV1191**	Fine oil separator drainage valve
EV5106	Suction gas shut-off valve	**EV1181**	MP compressor oil supply valve
CV5110	Flash gas regulation	**EV1171**	LP compressor oil supply valve
EV5112	Liquid injection shut-off valve	**CV2176**	Water cooler valve

The actuator descriptions above also make it easier to identify and understand how the actuators are used to control and operate the system. All valves with the prefix “CV” are control valves which are adjustable at 0-100% opening. This is used to regulate the pressure, temperature, or saturation temperature at different points in the cycle. Valves with the prefix “EV” are electrically operated shutoff valves that are used to open or close different sections of the system. A more detailed breakdown of these acronyms is included in Table 3.

In addition to the actuated components, there are non-piloted mechanical components such as manual valves, which are usually used for maintenance purposes. A full summary of these non-piloted equipment units is shown in Table 2 below.

Table 2: Non-piloted Equipment Units

Equipment Tag	Description	Equipment Tag	Description
AC5004	Common unit accumulator	**MV5172**	LP compressor outlet manual shutoff valve
MV5020	Accumulator output manual shutoff valve	**S5178**	Phase separator before the MP compressor
MV5026	Load manual shutoff valve	**S5188**	Coarse oil separator
MV5170	LP compressor inlet manual shutoff valve	**S5190**	Fine oil separator

The equipment tags follow a specific naming convention which provides context of the device type, fluid circuit, subsystem and location. This convention is explained in Table 3.

Table 3: Equipment Tag Naming Convention

Digit	Value	Description
1st and 2nd digits	CV	Control Valve
	EV	Electrically operated shutoff valve
	MV	Manual Valve
	GP	Gas Pump (Compressor)
	EH	Electrical Heater
	HX	Heat Exchanger
	AC	Accumulator
	S	Separator
3rd digit	1	Oil system
	2	Water/air cooling
	5	Chiller circuit
4th digit	0	Common Unit
	1	SLICE 1
	2	SLICE 2
5th and 6th digits	00-99	State point

Not included in the above table is the equipment prefix. This prefix describes the system to which the equipment belongs as well as the physical location within CERN. For example, it is useful to know at which experiment the installation can be found, whether it is on the surface or underground, and what type of installation it is. Since all the equipment discussed in this report is part of the same installation, it is not necessary to include this prefix when discussing these components. However, a description of the prefix naming convention is included in Appendix A – CERN naming conventions.

With these device tags in mind, the P&IDs can be better understood. The P&IDs are separated into 3 categories of the system: the common unit, the modular slices, and the interface with the 2PACL system. The simplified P&ID of the common unit can be seen in Figure 1 below.

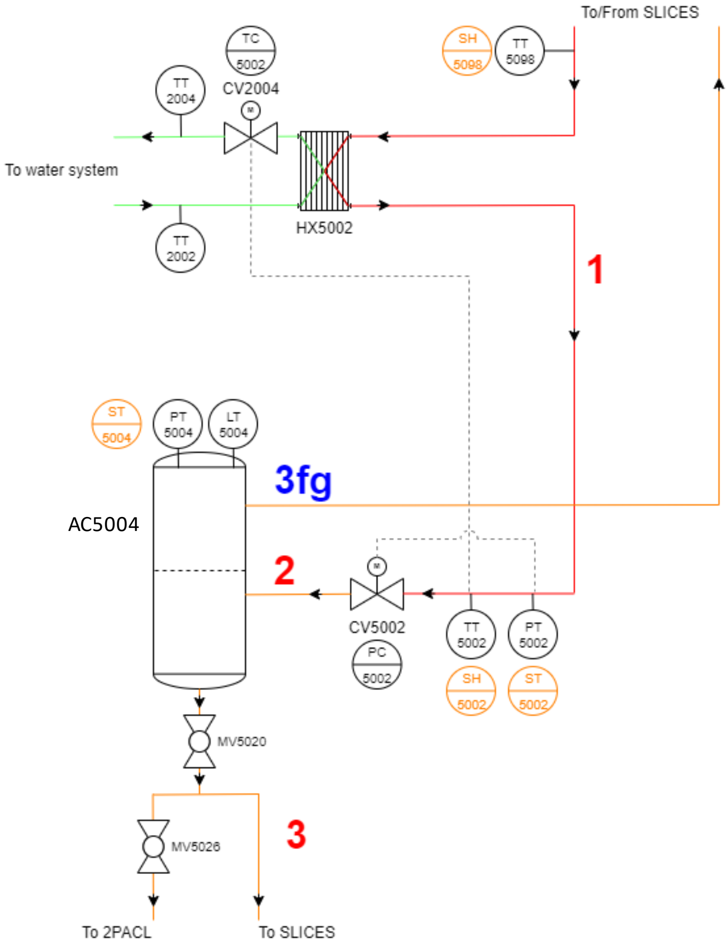


Figure 1: R744 system A - common unit simplified P&ID [12]

The line colours represent different parts of the system. Light blue represents the slice suction piping. Green shows intermediate gas piping or water cooling, and orange represents intermediate liquid piping. Red lines represent the slice discharge piping and pink lines show the oil system pipes. The bold numbers correspond to points on the pressure-enthalpy (PH) diagram shown in Figure 4 and the colour of the number corresponds to the flow-loop in the diagram of the same colour.

The liquid from the accumulator is used to absorb heat from the load through a series of heat exchangers. These heat exchangers are shown in the P&ID in Figure 2.

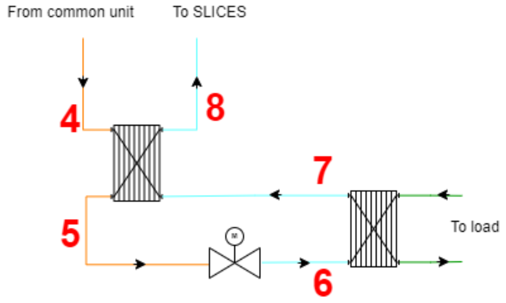


Figure 2: R744 system A – P&ID of the load heat exchangers [12]

In the final system, this load should include a heat exchanger which interfaces with a 2PACL system. However, this 2PACL system will not be ready in time to use in the R744 System A initial testing and commissioning. Instead, a small dummy load will be connected to generate heat and simulate the load that needs to be cooled.

The chiller slices are identical and can therefore be represented by a single P&ID which can be found in Figure 3.

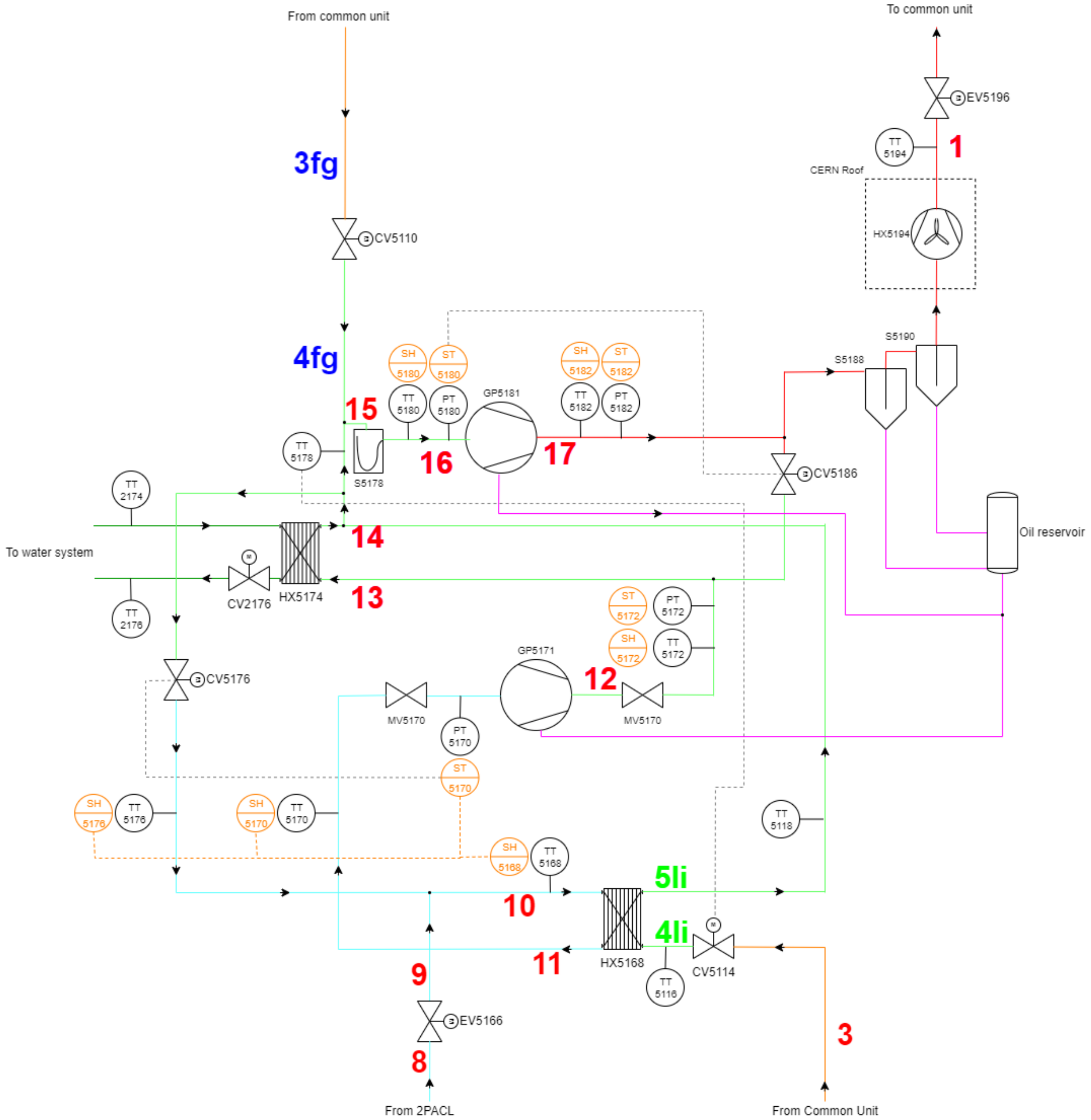


Figure 3: R744 system A – Slice 1&2 simplified P&ID [12]

The main CO_2 loop goes from the liquid outlet of the common unit accumulator (point 3), through the external heat exchangers (points 4-8) to the slices (points 8-17) and then back to the common unit (points 1-2).

The high-pressure liquid from the common accumulator (3) is cooled by the gas returning from the evaporator (4-5) before being expanded by means of a control valve (5-6) which is regulated by the interfacing system (2PACL or dummy load). The low-pressure fluid is then evaporated by the load (6-7) and superheated by the incoming high-pressure liquid (7-8). This low-pressure superheated gas is then sent to the compressor slices (8-9) and pre-cooled by interfacing with the liquid injection loop (10-11). The gas is then sent to the low pressure (LP) compressor (11-12) and the output of the compressor undergoes interstage cooling by means of an external water-cooling system (13-14). If the cooling load is too low, the saturation temperature at the inlet of the LP compressor will also be low. In this case, some of the gas from the LP compressor outlet will be recirculated back to the inlet of the LP compressor by means of the LP compressor bypass valve, CV5176 (14-10). Otherwise, the gas undergoes a second stage of compression through the medium pressure (MP) compressor (16-17). This is also recirculated to the inlet of the MP compressor by means of a bypass valve, CV5186 (17-13), in the case that cooling load is too low. If not, the outlet of the MP compressor is cooled by an air-cooled gas cooler (17-1) and circulated back to the common unit. Once in the common unit, the hot fluid is further cooled by a water cooler (1) and fed into the accumulator. The pressure at the outlet of the slices is controlled by CV5002 (1-2).

In addition to this main loop, there are 2 other loops of CO_2 in the system. The first is the flash-gas loop. This is used to regulate the pressure in the accumulator by removing flash gas from the tank if the pressure gets too high. If gas is indeed removed, it is injected at the inlet of the MP compressor (15) to provide additional interstage cooling. The second loop is the liquid injection. In the case that the outlet of the LP compressor is too hot for the water-cooler to handle, additional cooling is provided by injecting liquid directly from the accumulator at the outlet of water-cooling heat exchanger (14). This loop also pre-cools the gas coming from the cold box to the compressor slices (4li-5li). The low-pressure of the gas in the main CO_2 loop ensures that there is no risk of creating liquid at the inlet of the LP compressor. However, there is also a phase separator just after the liquid and flash gas insertion points to remove any liquid if it is present.

The expected behaviour of the system when connected to load is shown in the pressure-enthalpy diagram in Figure 4. The main flow-loop is shown in red, while the liquid injection and flash-gas bypass are shown in green and blue respectively. The numbered points in the PH-diagram correspond with the points in the P&IDs of Figures 1-3.

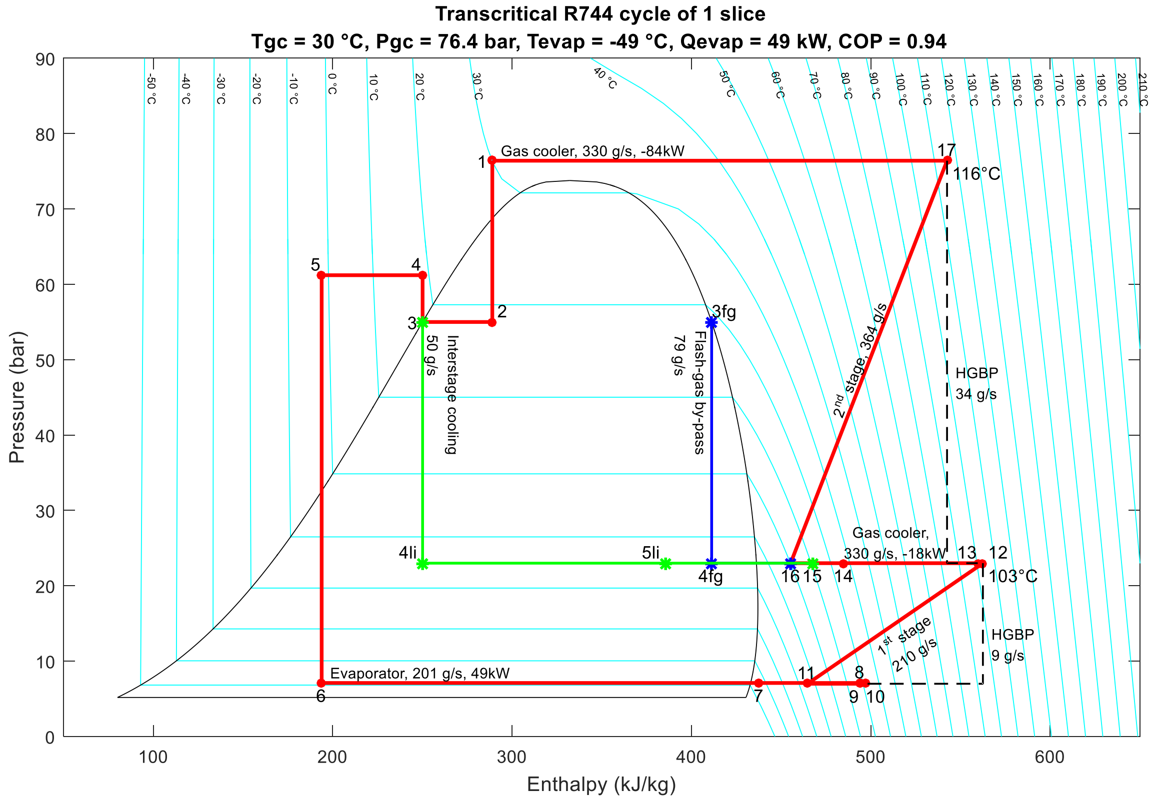


Figure 4: The transcritical cycle with flash gas and hot gas control in the PH-diagram [13]

Starting at point 1 on the diagram, just after the water-cooled gas cooler HX5002 in the common unit, there is a pressure drop as the CO_2 moves through a control valve CV5002 into the accumulator at point 2. At point 3, purely liquid CO_2 leaves the accumulator and undergoes a pressure increase as it is transported to the heat exchangers at point 4 which, in the final system, are approximately 100m below the surface. From here, the liquid is precooled and undergoes expansion before reaching the evaporator. After evaporation, the gas is super-heated by the same heat exchanger which pre-cools the liquid from point 4 to 5. This warm gas returns to the surface and is then sent to the compressor slices where it is mixed with the CO_2 from the hot gas bypass CV5176 of the low-pressure compressor, GP5171. This is pre-cooled by a heat exchanger HX5168 at point 10-11 which is cooled by the liquid injection for the interstage cooling. This gas is then compressed by the low-pressure compressor (11-12) and mixed with the hot-gas bypass, CV5186, of the medium pressure compressor. The CO_2 is then cooled by HX5174 and mixed with the interstage cooling from the liquid injection and the flash gas from the accumulator. This is compressed by the medium-pressure compressor GP5181 (16-17) before being cooled by an air-cooled gas cooler HX5194 within the slice as well as a water-cooled gas cooler HX5002 in the common unit.

The second flow loop is the interstage cooling in green. This is also referred to as liquid injection and is used to further reduce the temperature between the compressors by adding cold liquid directly from the common storage vessel.

The third flow loop is the flash gas bypass shown in blue on Figure 4. This is used to regulate the pressure inside the common storage vessel. If the pressure in the vessel is too high, some of the gas is injected into the SLICEs between the compressors by opening control valve CV5110.

The regulation of cooling capacity is carried out by one slice at a time. If a slice is regulating its cooling capacity, it is considered the active slice. This slice will close the compressor bypass valves to increase the capacity of the individual slice. All other slices will be either off or operating at full load. For example, if the cooling requirement is 75 kW, there will be one slice fully on, cooling at a maximum capacity of 50 kW with the bypass valves fully closed. The second slice will be on and reducing its cooling capacity to 25 kW by opening the compressor bypass valves and regulating the saturation temperature at the inlet of each compressor.

4. Functional Analysis of R744 System A

The functional analysis is a document created during the system design process which gives a detailed description of how the system should function from a control perspective. This includes an overview of the control hardware, system hierarchy, control systems and alarm actions.

4.1 Control system architecture

The electrical design of the system makes use of separate control cabinets for different parts of the system. The main control cabinet contains the system PLC and IO (Input/Output) cards for the common unit. Each compressor slice has its own control cabinet and IO cards which are connected to the PLC in the master cabinet through the remote IO (RIO) loop. This is a closed network connection with industrial ethernet. There are also separate power cabinets for the high-power components of each SLICE. This separation eliminates the issue of high-power components causing noise on the IO signals. The structure of the electrical cabinets and communication network is shown in Figure 5.

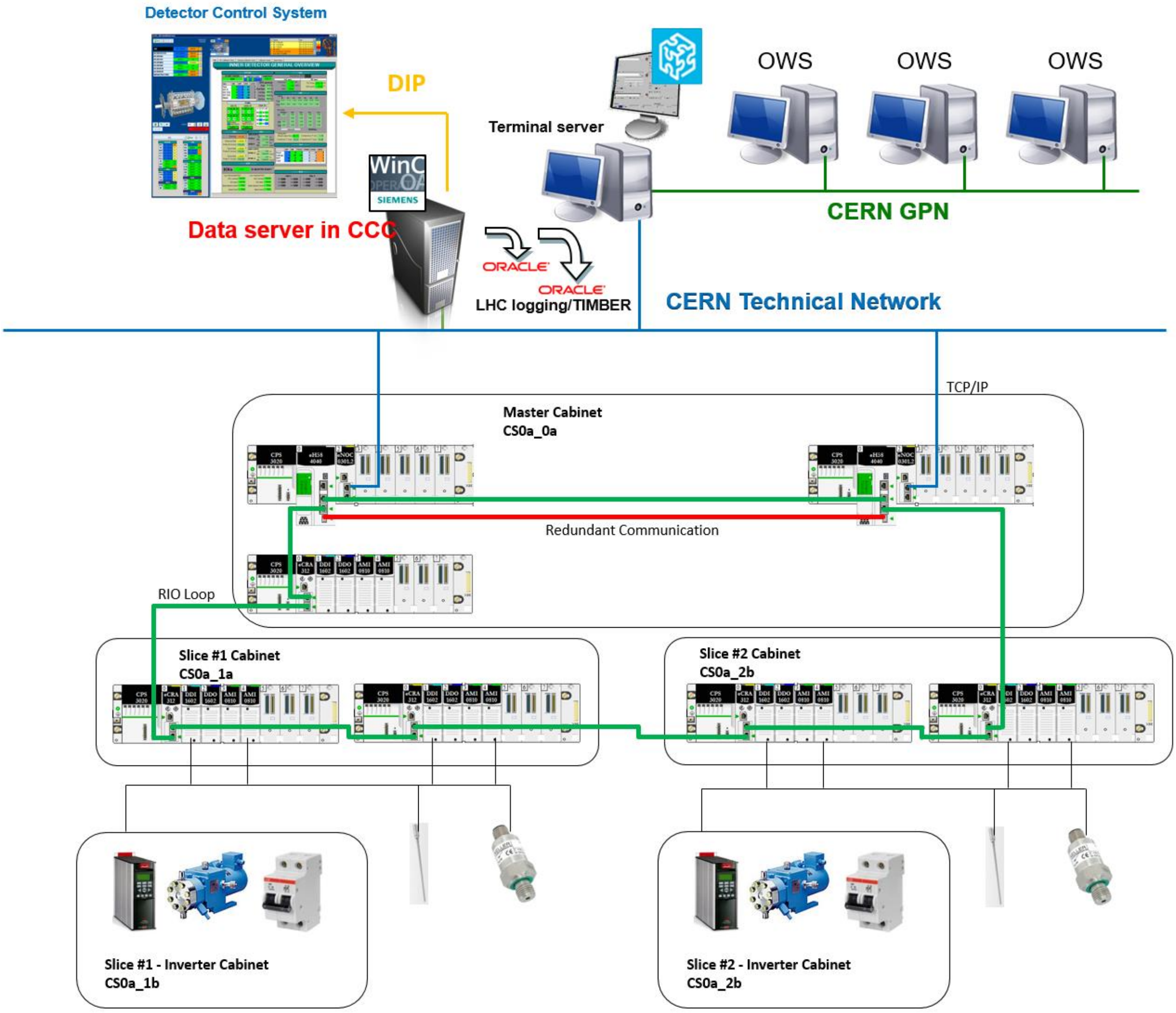


Figure 5: System A control hardware breakdown [14]

The information from the PLC is communicated to the Siemens WinCC OA SCADA server via the CERN technical network. This can be used to both monitor and operate the system without the need for a direct hardware connection from the operator's PC to the PLC.

This system makes use of Schneider M580 redundant PLCs. This means that there are two separate PLCs connected to the control loop with identical logic. While one PLC is running the system (the primary PLC), the other PLC is in standby mode. The standby PLC is ready to take over control should anything happen to the primary PLC. This transition should be seamless and keep the system running without any interruption. Failure on the primary PLC is detected by a hot standby ethernet communication link between the two PLCs and the standby PLC will take over automatically once it detects a loss of communication from the primary PLC. Because of this automatic switchover, it is recommended to run the same program on both PLCs. This ensures that operation on either PLC is exactly the same and there is no difference between running on PLC A or PLC B. This does not protect the system in case of a fault caused by software or by a loss of system hardware (for example, sensor or valve failure). There are systems at CERN that make use of redundant sensors and hardware to protect in case of such failures, but space restrictions and budget concerns led to the decision not to include such redundancy in this system.

4.2 Process Control Object Breakdown

The PLC code structure comprises a hierarchy of process control objects (PCOs) which contain other PCOs and system actuators. This cooling system is composed of three PCOs which are described in Figure 6 below.

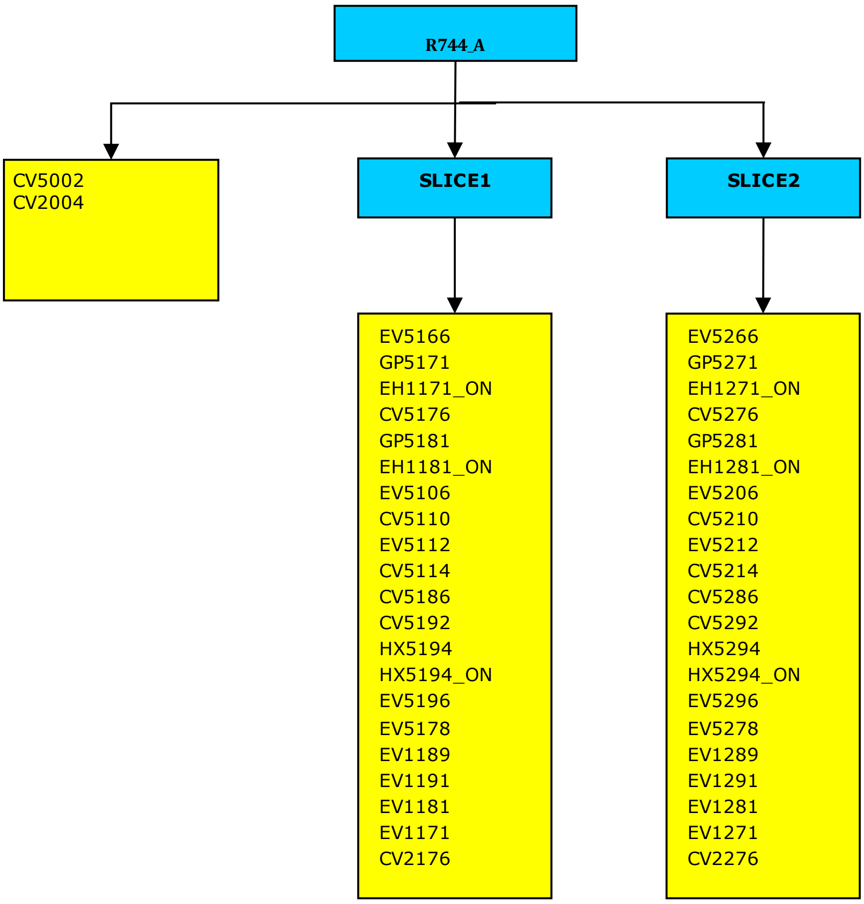


Figure 6: R744 System A PCO structure

This process breakdown shows the hierarchy of the three PCOs (in blue) and the actuators (in yellow) which are controlled by each PCO. The R744_A PCO controls all system slices as well as all the common unit actuators, namely the control valves that regulate the accumulator temperature and pressure. The SLICE PCOs are identical and can be replicated many times in future systems based on the overall cooling capacity needed.

Each actuator and PCO has a specified safety position which is maintained while its parent PCO is off. These safety positions can be found in Appendix B – Actuator Safety Positions.

4.3 Common unit description

The function of the main R744_A PCO is to control the common unit equipment and manage the starting or stopping of the SLICE PCOs. This starts by turning on one of the SLICE PCOs and once the active slice nears its maximum cooling capacity, the R744_A PCO will start up an additional SLICE PCO to increase the overall cooling capacity. Similarly, this main PCO can turn off the SLICE PCOs if the cooling requirement decreases.

The R744_A PCO is manually turned on or off by the operator and once running, it regulates the temperature at the inlet of the accumulator by using CV2004 to control the water flow in the heat exchanger. The slices are turned on or off based on the cooling requirements and the order of slices turning on is determined by a calculated slice priority based on compressor working time and slice availability. Once one or more slices are running, the pressure in the accumulator is regulated by supplying flash-gas to the running slices. At this point, the trans-critical pressure will also be regulated with a control valve (CV5002) at the inlet of the accumulator (AC5004).

4.3.1 Common unit controllers

In the common unit, there are 3 measurements that need to be regulated. These are the transcritical cycle pressure (PT5002), the transcritical cycle temperature (TT5002) and the pressure in the storage vessel (PT5004). There are three separate PID controllers which are used to regulate these values.

PC5002
Transcritical cycle pressure controller

The transcritical cycle pressure (PT5002) is regulated by the common circuit high-pressure valve CV5002, which controls the flow of CO_2 into the accumulator. This valve is regulated when either SLICE1 or SLICE2 are in the compressors start up step (step 2) or higher. The slice stepper is described in further detail in section 4.4.2 and can be seen in Figure 7. If the slices are off or in step 1 (pressurisation), the valve is in the safety position (open) to allow the slices to empty into the accumulator. The set point of this controller is slightly more complex than that of the other controllers in this system. Instead of having a fixed value, it is calculated depending on the transcritical temperature. The logic used to calculate this setpoint is as follows:

```
If TT5002 < 19°C
        PC5002_SP = 60 bar
Else if TT5002 < 38°C
        PC5002_SP = $(0.05546 \times (TT5002)^2 - 1.046 \times TT5002 + 60.227)$ bar
Else
        PC5002_SP = 100 bar
```

TC5002
Transcritical cycle temperature controller

The transcritical cycle temperature (TT5002) is regulated by the water circuit valve CV2004 which controls the flow of water through the heat exchanger HX5002. This valve is regulated when SLICE1 or SLICE2 are in the compressors start up step (step 2) or higher. Otherwise, it is closed.

PC5004
Storage vessel pressure controller (Flash gas)

The pressure in the storage vessel (PT5004) is regulated by the flash gas injection valves CV5110 and CV5210 which send flash gas to their respective compressor slices. These valves are regulated when their respective slices are in the pressurization step (step 1) or higher. Otherwise, they are 10% open.

4.3.2 Common unit alarms

There are several types of alarms that will either send a warning to the operator or stop an actuator, set of actuators or PCO depending on the severity of the conditions. These alarms are separated into groups to simplify troubleshooting and these groups as well as the type of alarms they contain are described below.

Pressure alarm group

There are two types of pressure alarms in this group.

1. Pressure reading is too high or low.
2. Differential pressure calculation is too high or low.
3. There is an IO error or possible wire break on one of the sensors related to pressure or differential pressure.

Valve alarm group

There are two types of alarms in this group.

1. There is an IO error or possible wire break on one of the pressure or temperature sensors related to the inlet, outlet, or control conditions of a valve.
2. There is a warning signal from the valve actuator.

Temperature alarm group

There are two types of alarm conditions in this group.

1. The value received from a temperature sensor is too high or low.
2. There is an IO error or possible wire break on one of the temperature sensors.

Level alarm group

There are 3 types of alarms in this group.

1. The liquid level in the accumulator is too high or low.
2. There is an IO error or possible wire break on the level sensor.
3. Accumulator pressure control is not possible because the inlet temperature is too low, therefore flash-gas cannot be injected into the compressor slices.

Water alarm group

There is only one alarm in the water alarm group.

1. The water temperature at the inlet of the heat exchanger is too high to cool the incoming CO_2.

Cabinet alarm group

The cabinet alarm group contains 10 different alarm types.

1. One of the emergency stop buttons has been activated.
2. A circuit breaker for the PLCs or internal cabinet fan and light has tripped.
3. One of the PLCs is in stop or wait mode.
4. PLC redundancy is not available.
5. The hot standby or supplementary link between PLCs is not OK.

6. There is a firmware mismatch between the PLCs.
7. There is a logic mismatch between the PLCs.
8. The PLC RIO loop is broken.
9. One or more IO cards are unavailable.
10. The three-phase power supply to the cabinet is not OK (phase imbalance or voltage level is not OK).

24V alarm group

There are 7 alarm types for the 24V alarm group.

1. The circuit breaker for the 24V circuit tripped.
2. A circuit breaker for one of the 24VDC power supplies tripped.
3. One of the 24VDC power supplies is not OK.
4. A circuit breaker for the redundancy module tripped.
5. The redundancy module is not OK.
6. The circuit breaker for the current transducer tripped.
7. The cabinet's current consumption is too high.

4.4 Slice description

Each slice consists of two compressor-cooler pairs. Each compressor has a hot-gas bypass valve (CV5176 bypassing the LP compressor and CV5186 bypassing the MP compressor) which can be used to alter the cooling capacity of the slice. Since each slice is identical except for the brand of compressors used, the description of the slice control will focus on that of slice 1. However, any differences between the slices will be highlighted.

The cooling capacity of the slice is controlled by both the hot-gas bypass valve on the low-pressure compressor and that of the medium-pressure compressor. When these valves are both fully closed, the slice is cooling at its maximum capacity. As the valves open, the cooling power of the slice is reduced.

4.4.1 SLICE PCO start up conditions

Once the main R744_A PCO is running, the system will automatically start up the SLICE PCOs based on the following conditions:

SLICE 1 starts as the first slice:

If R744_A is on and SLICE 1 has a higher priority than SLICE 2, SLICE 1 will start. The priority is a calculation based on user request, compressor run time and compressor off time. This is to balance the running time of each slice, as well as prevent the compressors from starting up too soon after turning off.

SLICE 1 starts as second slice and moves to standby step:

Since the cooling capacity of the slice is dependent on the position of the compressor hot-gas bypass valves, this can be used to determine whether another compressor slice needs to start up or switch off. If the bypass valves are fully open, then the cooling of the slice is higher than the load demands. If the bypass valve is fully closed, then the slice is cooling at maximum capacity and may not be able to meet the demands of the load.

If R744_A is on, SLICE 2 is in the active step or higher (see section 4.4.2) and SLICE 1 is available but has the lower priority, SLICE 1 will start up only if the cooling requirements are higher than SLICE 2 can accommodate. If the opening of the SLICE 2 low pressure bypass valve is less than 30% for more than

20 minutes, this indicates that SLICE 2 is nearing the limit of its cooling capacity and SLICE 1 will start and move into the standby step.

SLICE 1 running as the secondary slice stops when cooling requirements decrease:

If R744_A is on, SLICE 2 is in the active step and SLICE 1 is in the standby step, this means the cooling capacity is being regulated by SLICE 2 and SLICE 1 is on standby ready to start cooling. If the SLICE 2 low pressure bypass valve is more than 30% open for more than 20 minutes, this indicates that the cooling capacity of one slice is enough for the load and SLICE 1 will stop.

4.4.2 Slice stepper description

The SLICE PCOs are more complex than the main R744_A PCO and make use of a stepper to change their behaviour during different stages of operation. A stepper is a set of operating states with state-transition conditions which define the system operation. The SLICE stepper has six steps which are shown in Figure 7 below.

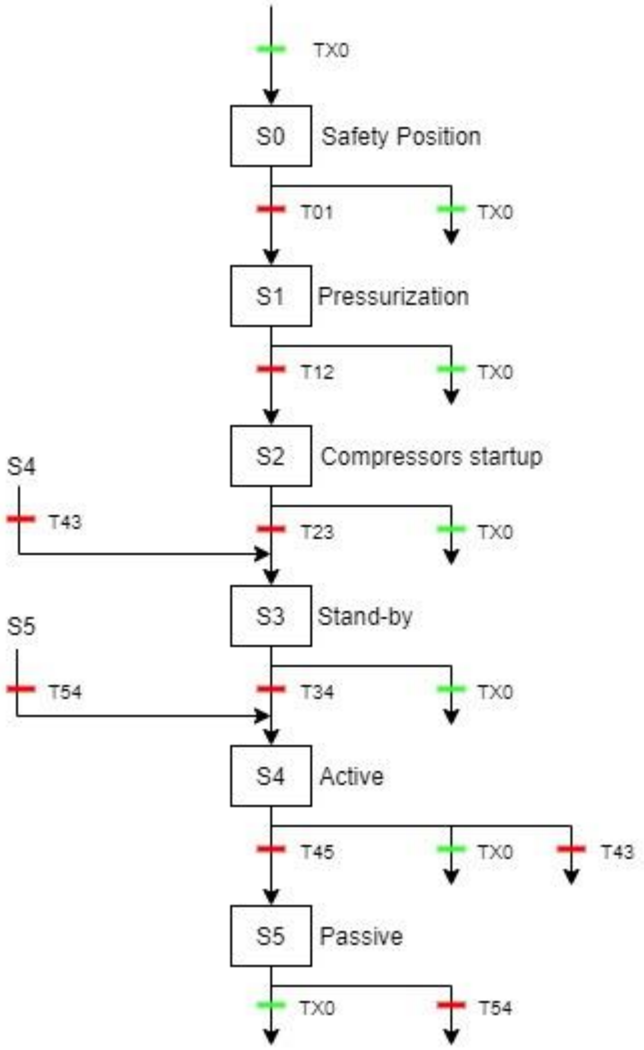


Figure 7: SLICE stepper sequence. See Table 4 below for transition conditions.

The logic for the actuators and controllers can be customised to behave differently in each step depending on how the system needs to operate. A brief description of each step and its function is shown below.

0: **Safety Position** – All actuators are in their safety state. These safety states are shown in Appendix B – Actuator Safety Positions.

1: **Pressurization** – The flash gas valve, CV5110, is open in order to ensure the required pressure of CO_2 for the start-up procedure.

2: **Compressors start up** – Compressors GP5171 and GP5181 are activated, and their inlet saturation temperatures are controlled by bypass valves CV5176 and CV5186. The liquid injection valve CV5114 starts regulating.

3: **Standby** – The slice operates with supply gas valve EV5166 closed in order to be ready for start operation in *Active* step as quickly as possible.

4: **Active** – The supply gas valve EV5166 opens, and the slice operates with active capacity control using the hot gas bypasses, CV5176 and CV5186. The slice operating in this step controls the capacity of the whole system.

5: **Passive** – The slice operates with the hot gas bypass valves, CV5176 and CV5186, fully closed, delivering maximum cooling power. This slice operates in parallel with another slice in the *Active* step.

The transition conditions between these steps for SLICE 1 are described in Table 4 below. The same logic is used for SLICE 2 (with SLICE 1 and SLICE 2 being swapped).

Table 4: Stepper transition logic for SLICE 1

Transition	**Conditions**
TX0 (Transition from any step to *Safety position*)	NOT (SLICE 1 run order) AND NOT (R744_A run order)
T01 (Transition from *Safety position* to *Pressurization)*	(SLICE 1 run order)
T12 (Transition from *Pressurization* to *Compressors start-up*)	(SLICE 1 run order) AND (flash gas supply valve open) AND (suction gas valve open) AND (discharge gas valve open) AND (drain valve closed)
T23 (Transition from *Compressors start-up* to *Standby*)	(SLICE 1 run order) AND (LP compressor running) AND (MP compressor running) AND (liquid supply valve open) AND ((SLICE 2 run order) XOR (suction gas valve open)) For t = 5 seconds

T34 (Transition from *Standby* to *Active*)	(SLICE 1 run order) AND (LP compressor bypass valve of active slice closed) AND (2PACL return pressure greater than threshold and greater than suction pressure) AND (SLICE 1 in step 3) For t = 5 seconds
T45 (Transition from *Active* to *Passive*)	(SLICE 1 run order) AND (SLICE 2 in step 4) AND (SLICE 1 priority > SLICE 2 priority) *
T43 (Transition from *Active* to *Standby*)	(SLICE 1 run order) AND (LP compressor bypass valve of active slice open) AND (suction pressure lower than threshold) AND (SLICE 2 in step 5) For t = 10 seconds
T54 (Transition from *Passive* to *Active*)	(SLICE 1 run order) AND (SLICE 2 in stand-by step or lower step)

* This logic is only valid for a 2-slice system. This needs to be developed to an n-slice system to compare the priorities of multiple slices at once.

4.4.3 Slice controllers

In each slice, there are 6 parameters that need to be controlled. These are the saturation temperature at the inlet of the low-pressure compressor (ST5170), the saturation temperature at the inlet of the medium-pressure compressor (ST5180), the slice discharge outlet temperature (TT5196), the gas cooler outlet temperature (TT5194), the interstage temperature (TT5178) and the water-cooler outlet temperature (TT5174). The sensors and actuators related to the slice 1 controllers are shown in the simplified system P&ID in the figure below.

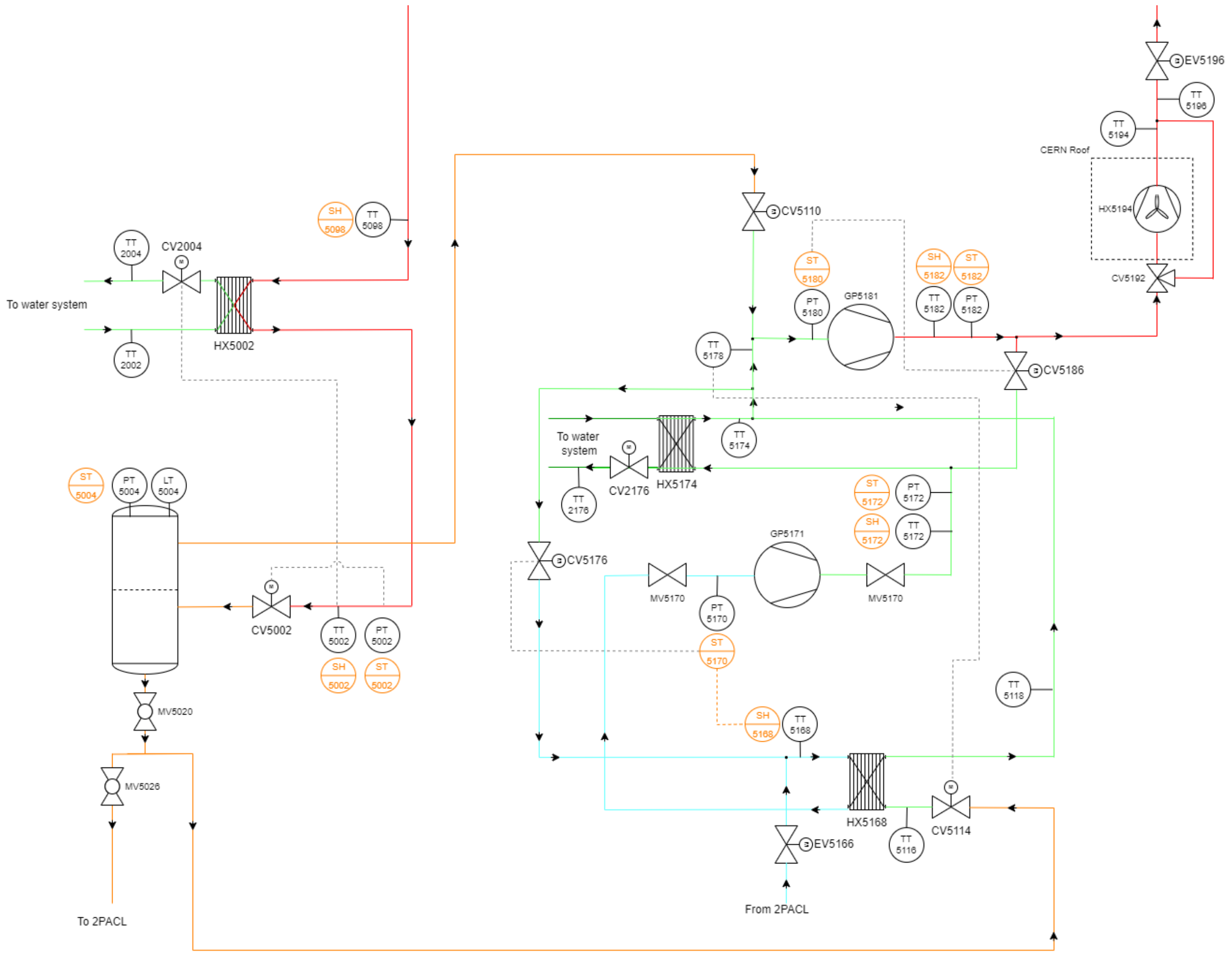


Figure 8: Simplified P&ID of common unit and slice 1 [12]

Regulating ST5170

Saturation temperature at the inlet of the low-pressure compressor

The saturation temperature at the inlet of the low-pressure compressor depends on two actuators: the hot-gas bypass valve opening (CV5176) and the compressor speed (GP5171). The inlet saturation temperature decreases with decreasing pressure. The pressure can be decreased by either closing the bypass valve or increasing the speed of the compressor. There are two controllers used to regulate the two actuators, STC5170a and STC5170b. This approach relies predominantly on the hot-gas bypass valve (CV5176) to regulate the saturation temperature (STC5170a). However, if this controller is unable to keep the measured value within a specified range of the setpoint, the second controller will kick in and use the compressor speed (GP5171) to return the saturation temperature back to the accepted margin (STC5170b).

Regulating ST5180

Saturation temperature at the inlet of the medium-pressure compressor

Regulation of the saturation temperature at the inlet of the medium pressure compressor is much the same as that of the low-pressure compressor. The saturation temperature depends on two actuators: the hot-gas bypass valve opening (CV5186) and the compressor speed (GP5181). The two actuators are controlled by STC5180a and STC5180b respectively. These two controllers operate in the same way as those for the low-pressure compressor (STC5170a and STC5170b).

TC5196

Slice discharge outlet temperature controller

The temperature of the slice discharge outlet (TT5196) is regulated by the three-way valve CV5192, which controls how much of the CO_2 flow goes through the gas-cooler and how much goes directly to the discharge outlet.

TC5194

Gas-cooler outlet temperature controller

The temperature at the outlet of the gas-cooler (TT5194) is regulated by the fan speed of the gas cooler. The higher the fan speed, the lower the outlet temperature will be.

TC5178

Interstage temperature controller

The interstage temperature at the inlet of the medium-pressure compressor (TT5178) is controlled by the liquid injection valve (CV5114). This valve controls the flow of liquid CO_2 from the accumulator into the interstage region to further reduce the temperature after the water-cooling.

TC5174

Water-cooler outlet temperature controller

The temperature at the outlet of the water cooler (TT5174) is regulated by the water-cooled heat exchanger circuit valve (CV2176). This valve controls the flow of water through the heat exchanger and the larger the valve opening, the greater the cooling will be.

4.4.4 Slice alarms

There are several types of alarms that will either send a warning to the operator or stop an actuator, set of actuators or PCO depending on the severity of the conditions. These alarms are separated into groups to simplify troubleshooting and these groups as well as the type of alarms they contain are described below.

Safety chain alarm group

The safety chain is set a set of hardwired signals which will cut power to certain actuators which are particularly dangerous, such as heaters and compressors. This is an additional layer of safety which means that dangerous equipment can still be stopped even if there is an issue with the PLC communication. There are 2 types of alarms in this group.

1. A pressure switch tripped.
2. A thermal switch tripped.

LP compressor alarm group

It is imperative to the operation of the compressors that there is sufficient oil in the compressor and that there is no liquid CO_2 at the suction. There are 10 types of alarm in this group.

1. Oil pressure is too low.
2. Discharge pressure is too high.
3. Discharge temperature is too high.
4. Suction pressure is too low.
5. Suction superheating is too low.
6. The compressor has started and stopped too many times in a short time span.
7. The compressor circuit breaker tripped.
8. The frequency inverter is not OK.
9. There is a temperature or pressure sensor wire break.
10. The suction temperature is too low.

MP compressor alarm group

Similar to the LP compressor, the MP compressor group has 10 types of alarms.

1. Oil pressure is too low.
2. Discharge pressure is too high.
3. Discharge temperature is too high.
4. Suction pressure is too low.
5. Suction superheating is too low.
6. The compressor has started and stopped too many times in a short time span.
7. The compressor circuit breaker tripped.
8. The frequency inverter is not OK.
9. There is a temperature or pressure sensor wire break.
10. The suction temperature is too low.

Coolers alarm group

There are 3 types of alarms related to the air- and water-cooled gas coolers.

1. The outlet temperature is too high.
2. The air-cooled gas cooler circuit breaker tripped.
3. There is a temperature sensor wire break.

Pressure alarm group

There are 3 types of pressure alarms.

1. The pressure reading is too high or low.
2. The differential pressure is too high or low.
3. There is a pressure sensor wire break.

Temperature alarm group

There are 2 types of temperature alarms.

1. The temperature reading is too high or low.
2. There is a temperature sensor wire break.

Valve alarm group

There are 3 types of valve alarms in this group.

1. There is an error signal received from the valve actuators.
2. There is a temperature sensor wire break.
3. There is an error detected on the valve end-switches.

Heaters alarm group

There is only one alarm type in the heaters alarm group.

1. The heater circuit breaker tripped.

Oil filters alarm group

There are 7 types of alarms related to the oil filters.

1. There is a wire break on the oil reservoir pressure sensor.
2. The oil reservoir pressure is too high or low.
3. The oil reservoir's oil level is too low.
4. The compressor oil level is too low.

5. The oil filter's oil level is too high.
6. The compressor oil filling limit has been exceeded.
7. There is too high pressure difference over the oil filter.

Cabinet alarm group

There are 9 alarms for the control and power cabinets.

1. One of the emergency stop relays are activated.
2. The three-phase power supply to the cabinet is not OK (phase imbalance or voltage level is not OK).
3. The circuit breaker for the cabinet light and fan tripped.
4. The circuit breaker for the 24VAC transformer tripped.
5. PLC backplane ethernet communication is lost.
6. Power cabinet cooling unit fault or circuit breaker tripped.
7. Circuit breaker for digital output (DO) cards tripped.
8. PLC backplane circuit breaker tripped.
9. PLC RIO loop is broken.

24V alarm group

There are 6 types of alarms in the 24V group.

1. One of the circuit breakers for the 24VDC control loop tripped.
2. One of the 24VDC power supplies is not OK.
3. One of the 24VDC power supplies circuit breaker tripped.
4. The redundancy module is not OK.
5. Cabinet current consumption is too high.
6. Current transducer circuit breaker tripped.

5. Preparing System A for Start-up

Several months were spent on site at CERN preparing the cooling system for start-up and testing. This process started with the preparation of documentation and the process description. Once the system's operation is fully designed, a specification file of all the PLC inputs, outputs and objects is created and used to automatically generate the PLC code. Before starting the system, it is important to test each aspect from the PLC logic to the wiring and actuator response. Once all of these steps have been completed, the system can start, and the controllers can be tuned both with and without load. After finding a stable system response, the performance and operation of the system is tested.

5.1 Preparation of PLC and Logic

CERN makes use of an application called UNICOS Application Builder (UAB) to automatically build UNICOS applications and generate the PLC code. This application makes it much easier to create and update UNICOS projects without having to manually write the PLC logic.

5.1.1 Specification file creation

Once the functional analysis document has been created, it is used to populate an Excel template known as the system specification file. This file contains the details of all inputs, outputs, parameters, calculated variables, controllers, and any other information that needs to be included in the PLC code.

5.1.2 UNICOS template creation

UNICOS templates are used to autogenerate PLC code from the specification file. There are many default templates for standard operations such as the creation of analog and digital input and output objects. There are also templates with common calculations such as addition, subtraction, multiplication and more. However, there are some functions which are specific to each project. In this case, a specific template must be created for this logic so that the UAB application can generate the correct PLC code for these functions. For example, each project will have a different PCO structure and therefore different steppers and transition logic. A new template was created for the SLICE PCOs according to the logic seen in Figure 7 and Table 4.

Another template that needed to be created for this project was a specific general logic template that detailed the calculation of slice priority as well as the calculation for oil heating time. The logic for oil heating is specific for this system as it takes into account heating from either an electric heater or from the operation of the compressors.

5.1.3 UAB Automatic Code Generation

Once the specification file is complete and all the necessary templates have been created, the UAB tool can be used to generate the PLC code. Once this code has been generated, it needs to be opened in Control Expert and built. Then, either from a PC connected to CERN's technical network or by connecting the PC to the PLC via USB, the code can be uploaded to the PLC.

5.1.4 WinCC OA and SCADA

The UAB tool can also be used to generate widgets in WinCC OA. Once this information has been loaded into the database, it can be displayed in a user interface known as SCADA. SCADA panels can be created to display a wide array of information about the system and can also be used for operation. An example of one of the SCADA panels created for this system is shown in Figure 9 below.

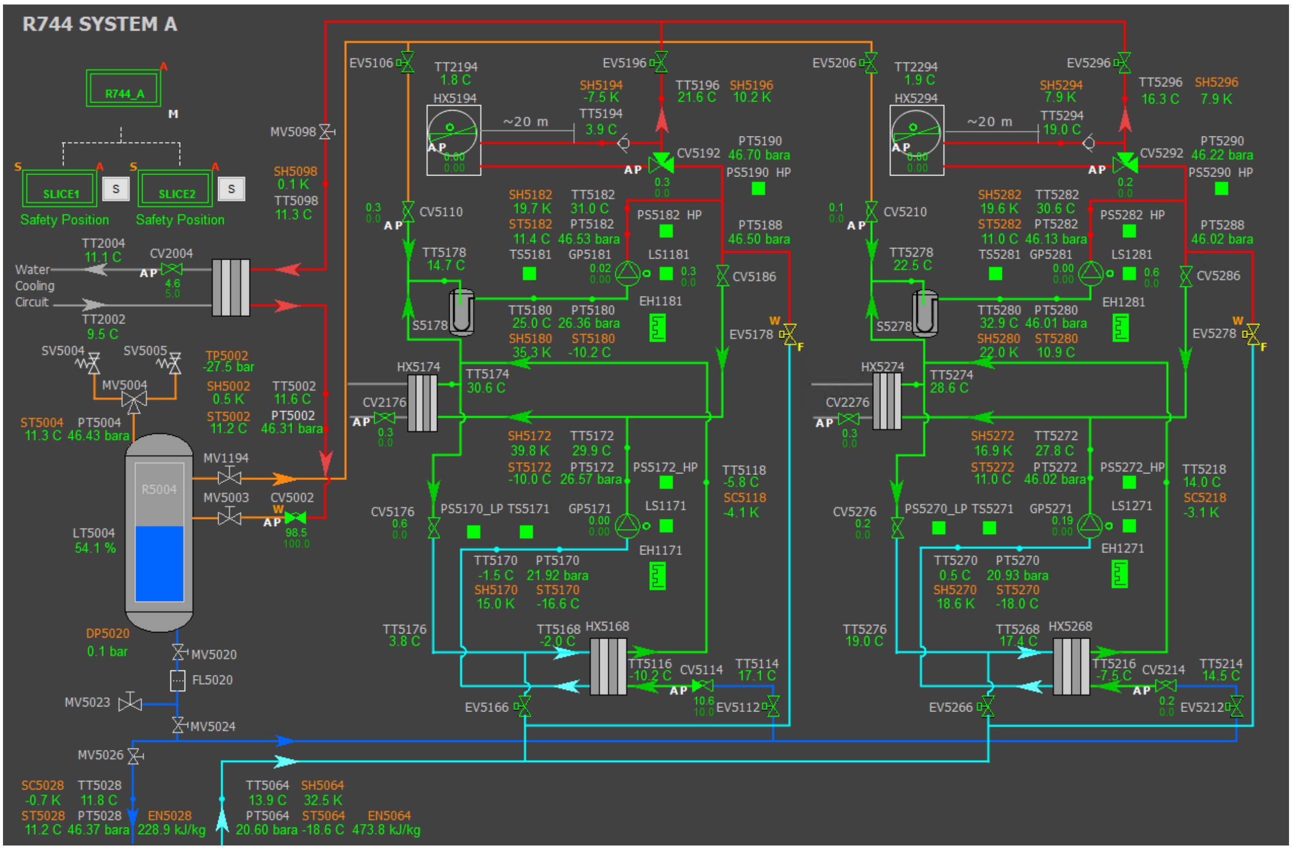


Figure 9: System A Overview SCADA Panel

5.2 IO Commissioning and Logic Testing

Before starting the system, it is important to first test that each aspect is working as expected. This includes both hardware and software. A commissioning file is generated from the specifications document with a list of all PLC inputs, outputs, controllers, alarms, and calculations. For each item, there is space to note whether the PLC connection is OK, the correct information is displayed, and the behaviour is as expected. If there are any issues, there is a space to write a detailed description of how the object is behaving so that it can be rectified in the specifications document.

This process involves testing both the physical connection of each signal as well as checking that the signal makes sense. This is a useful diagnostic tool and requires a deep understanding of how the system should work. The procedures to test each type of signal are included in Appendix C – I/O Testing Procedures and Acceptance Test Protocols.

5.3 PLC redundancy tests

The reliability of the PLC is paramount to the operation of the system. In the application of detector cooling, there are disastrous consequences to a system failure. Therefore, the decision was made to use redundant PLCs with RIO loop and hot-standby connection. A breakdown of the PLC configuration is included in in section 4.1 above (Figure 5 in the description of the control structure).

To understand the limitations of the redundant PLC system, several tests were carried out to check in each case whether there was redundancy.

Table 5: Test cases of redundant PLC operation

Case	System reaction	Alarms
PLC B in stop/wait	PLC A – primary Communication with SCADA – OK	• PLC redundancy not available Possibly: • PLC B switched off • PLC B CB tripped
PLC A in stop/wait	PLC B – primary Communication with SCADA – OK	• PLC redundancy not available Possibly: • PLC A switched off • PLC A CB tripped
Primary PLC loses connection to SCADA	Other PLC becomes primary, and the PLC with no SCADA connection moves to standby	No alarms
One PLC stopped, the other has no connection to SCADA	There will be no communication between SCADA and the system, but the running PLC will continue to run the system as the primary	• PLC redundancy not available Possibly: • PLC B CB tripped • PLC B switched off • PLC A CB tripped • PLC A switched off
Lose hot standby connection link between PLCs	System runs as normal	• Hot standby connection link between PLC not OK
Lose both hot standby connection link and hot standby supplementary link between PLCs	System runs as normal	• Hot standby connection link between PLC not OK • Hot standby supplementary link between PLC not OK
Lose hot standby connection link between PLCs AND Lose hot standby supplementary link between PLCs AND One PLC loses communication with SCADA	Rapid switching between primary and standby	• Hot standby connection link between PLC not OK • Hot standby supplementary link between PLC not OK
PLC A logic different from PLC B	Primary PLC continues to run the system. Other PLC is in wait	• Primary PLC logic different than standby PLC • PLC redundancy not available

Connection between main PLC and backplane is lost	System runs as normal	• PLC RIO loop broken
Connection between two or more backplanes are lost	Communication with the backplanes between the wire breaks is lost	• PLC backplane ethernet communication lost • PLC RIO loop broken
One backplane is completely disconnected from the RIO loop AND A temporary connection is made across the missing backplane to close the RIO loop (in case of maintenance or testing)	The rest of the system will continue to operate as normal	• PLC backplane ethernet communication lost

From the tests described in the above table, it is clear that the PLC with SCADA connection will always become the primary PLC where possible. However, system operation is prioritised over SCADA communication. In most cases, the system is able to run smoothly without any interruption. The only unexpected result is in the case of SCADA communication loss with no hot standby or supplementary link between the PLCs. The reason for the rapid switching of primary PLC is unknown, however, this use case is highly unlikely and not of great concern. The results of these tests are discussed in further detail in a conference paper prepared for the 2020 ICALEPCS conference is Shanghai [15].

6. Simulation of R744 System A in Simulink

To understand how the system will work and predict the system behaviour, a simplified model of the system is created in Simulink. This model makes use of the Simscape and two-phase fluids packages in Simulink and has an accompanying MATLAB script to generate the pressure enthalpy diagram for the system.

6.1 Scope and Limitations of the Model

There are several aspects of the system which are necessary in reality but which are not needed in simulation. These include safety features such as alarms, interlocks, and safety valves. It is also not necessary to simulate the compressors' oil system since the simulated compressors can run without this. For these reasons, the scope of the model is limited to just the CO_2 lines without any alarms or safety systems.

All control valves are ball valves and the opening area of the valve relative to the opening percentage is calculated accordingly. All simulated valves have a delay corresponding to the opening speed of each valve actuator. Similarly, all sensors have a delay corresponding to the response time of each sensor type (PT100, thermocouple, pressure transmitter, etc.).

Each slice has a different brand of compressor used, Dorin and Bok. The compressor curves used are those of the Dorin compressors.

Additionally, the system usually starts up by proceeding through a number of steps based on certain conditions in the system. This stepper is useful to apply different control conditions in different stages of the transient from standstill to active operation. It is also useful to start up an additional cooling slice and keep it in passive mode so that it is not yet cooling but it is ready for when the load increases above the capacity of the active slices. However, the simulation is limited to one slice in active step as this is where the system is expected to operate for the largest proportion of its lifecycle.

Several of the control loops in the system are dependent on outside resources or processes which cannot be predicted. For example, the air-cooled gas coolers are dependent on the outside air temperature which fluctuates depending on the weather. There are also the water-cooled gas coolers which receive a supply of cooled water from an external CERN system. This external system has its own temperature regulation which can change with no warning or indication. Because of the complexity this introduces, the regulation of these systems will not be included in the model. Instead, these will be modelled as disturbances with rapid and unexpected temperature changes.

6.2 Model design

The model is designed as a simplified version of the P&ID, including only the regulated actuators and CO_2 lines. This model makes use of pre-existing two-phase components which are included in Simulink's example program of a basic transcritical CO_2 system [16]. The final model of the CERN system with a single slice can be seen in Figure 10, Figure 11, and Figure 12 below.

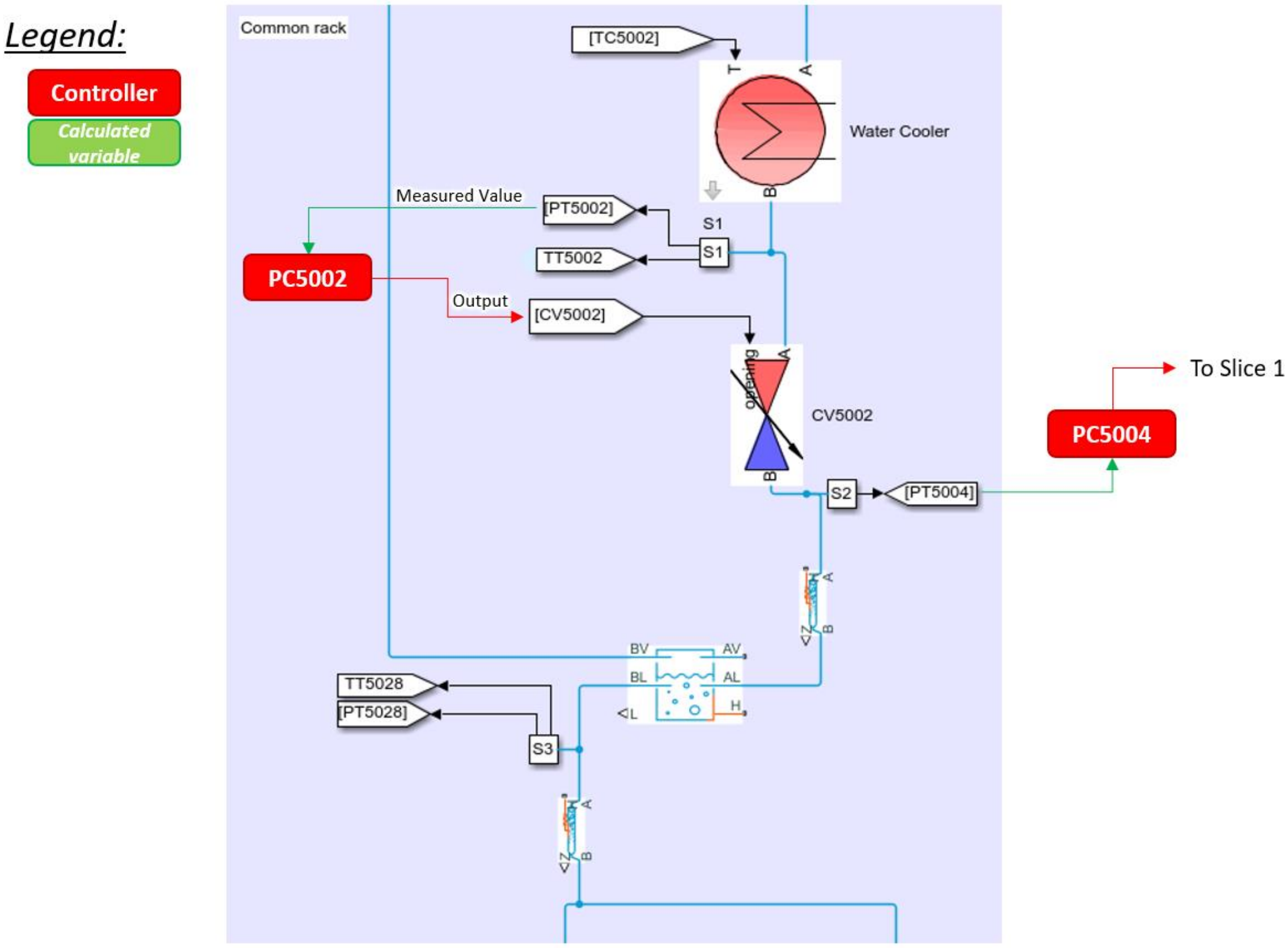


Figure 10: Simulink model of the R744 System A common unit

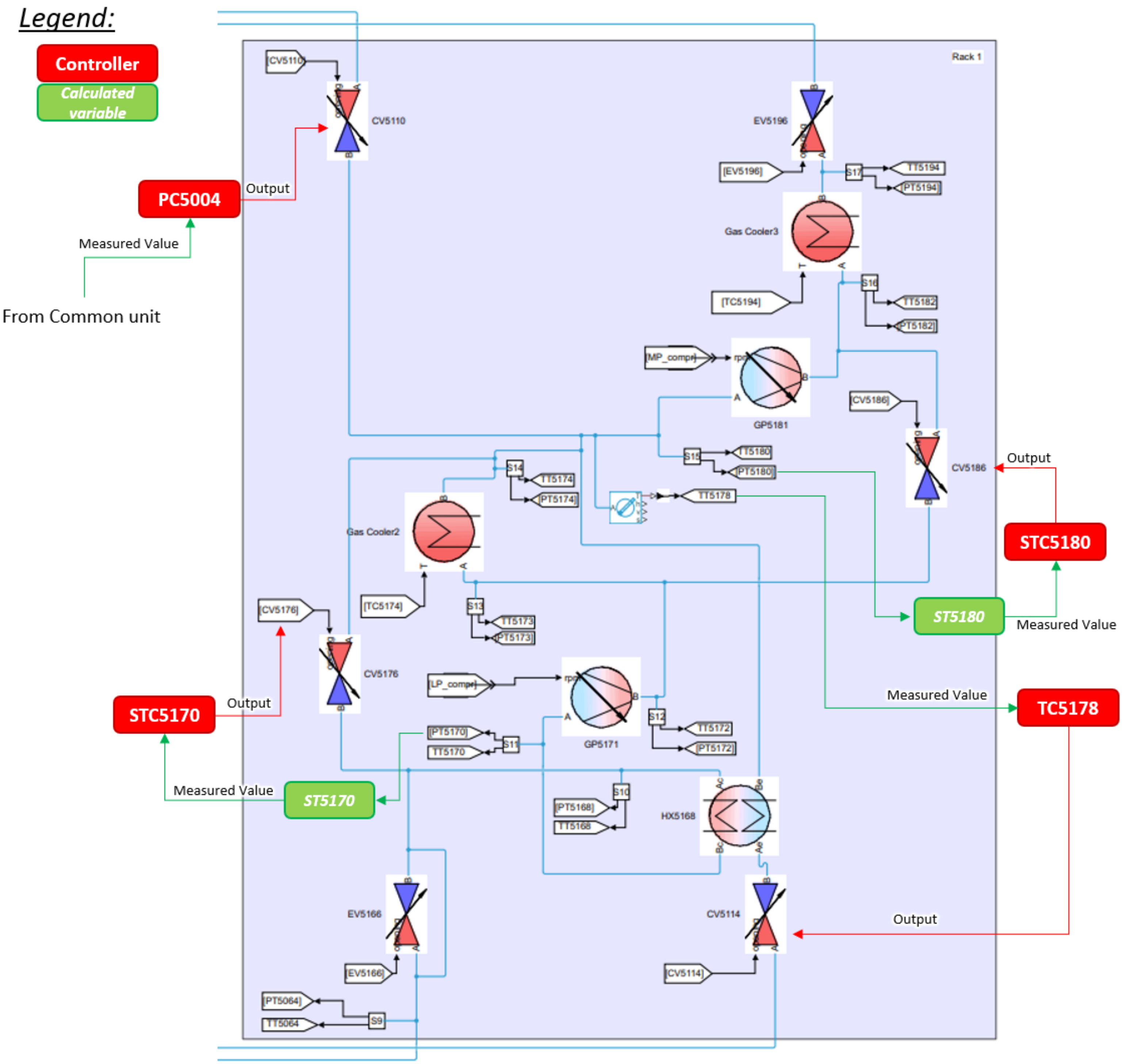


Figure 11: Simulink model of the R744 System A compressor slice

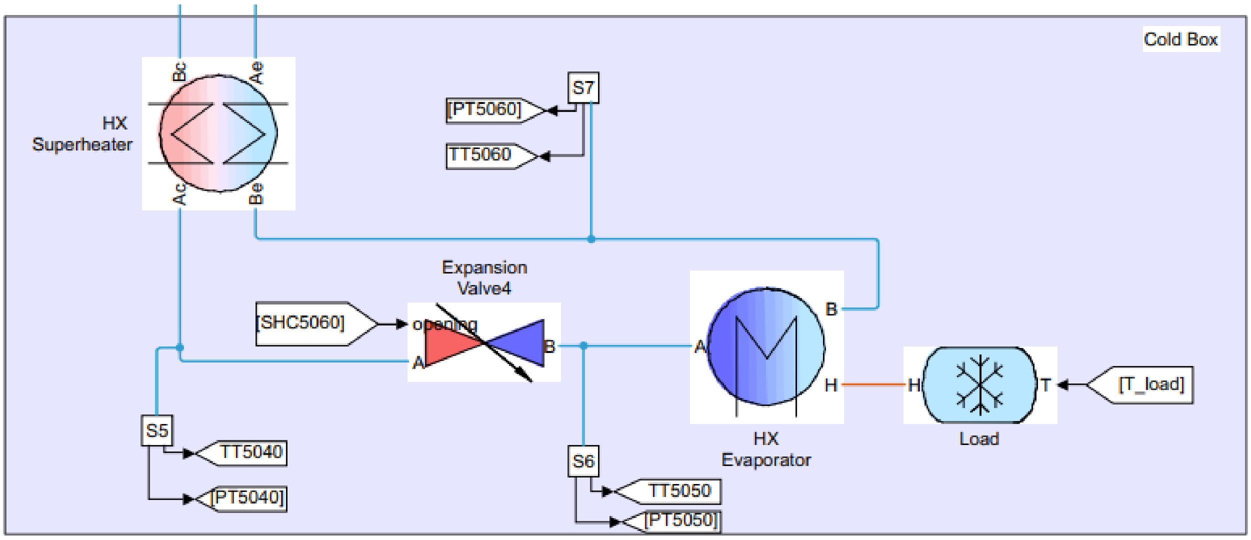


Figure 12: Simulink model of the cold box and system load

Function blocks have been created for the controllers of each actuator based on the control descriptions mentioned in the functional analysis. The controllers implemented are TC5176, TC5186, PC5002, PC5004, and TC5178. The dynamics of each actuator have been modelled in individual function blocks which are detailed in Appendix D – Actuator and component model details.

The same example program includes a Matlab script which has been adapted to show the pressure-enthalpy diagram of the simulated CO_2 loop as well as that of the physical system [16]. This can be used to compare the simulation as a whole to the physical system.

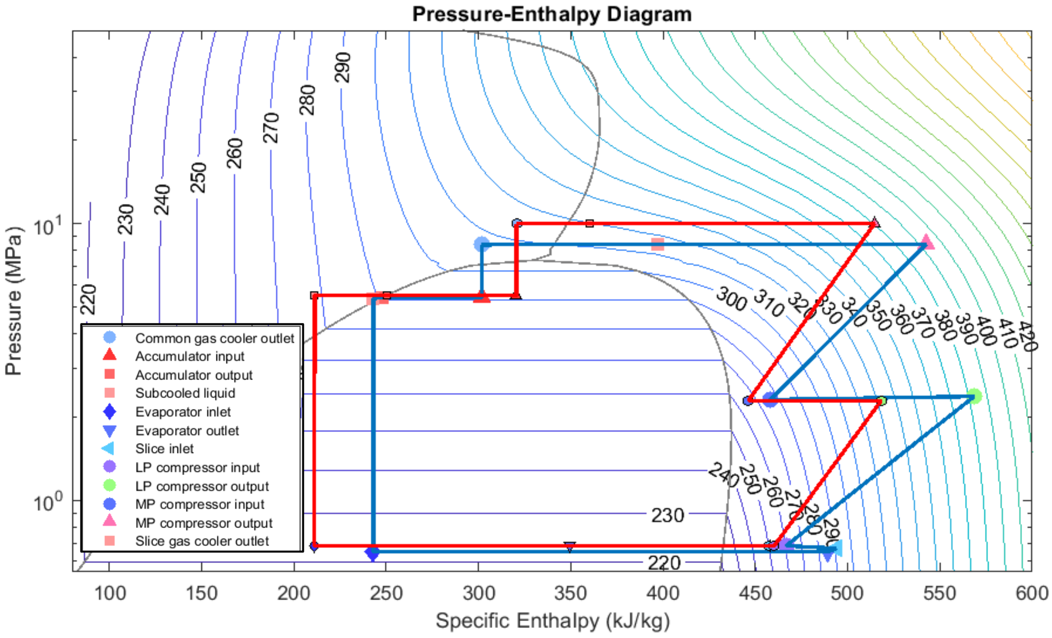


Figure 13: Pressure-enthalpy diagram of the physical system (blue) and the simulated system (red)

From the pressure-enthalpy diagrams shown in Figure 13, the simulation can be compared to the physical system to judge its accuracy. The general shapes of the diagrams are similar, with the simulation having slightly less enthalpy throughout. This higher enthalpy in the real system could be caused by higher temperatures in the air- and water-cooling circuits due to environmental heat changes (these tests were performed during the summer). However, the basic functionality of the simulation is very similar to that of the real system and can therefore be used to predict the system behaviour.

6.3 Simulink Controller Step Response

In order to design controllers for the system, it is important to first obtain the step response of each control loop. To achieve this, the simulation is run until all controllers are in steady state. At this point, all actuators are frozen. For one control loop, the corresponding actuator is given a step change in its output position and the response of the measured value is recorded. The results of these tests are shown for each controller below.

An important point to note is that the system is carefully designed for one specific set point per controller which will not be changed throughout the foreseen operation of the system. Therefore, it makes sense to evaluate the response of the control loop at only the one desired set point. This simplifies the control problem by not designing for unnecessary use cases. However, if the operating point does change, this simplification may affect the robustness of the controller. If the robustness is later found to be an issue, then it may become necessary to examine multiple step sizes and directions at different operating points.

6.3.1 Transcritical pressure controller PC5002

The purpose of this controller is to regulate the transcritical pressure at the inlet to the common unit. A summary of the controller is contained in below.

Table 6: Transcritical pressure controller PC5004 operation summary

	Name	**Description**
Measured value	PT5002	Transcritical pressure
Controlled actuator	CV5002	Transcritical cycle control valve
Expected set point	7.6 MPa	

Once the simulation stabilises, the control valve CV5002 is 1.9 % open. The step response is obtained by changing this opening to 21.9 % and observing the effect on the valve's inlet pressure, PT5002.

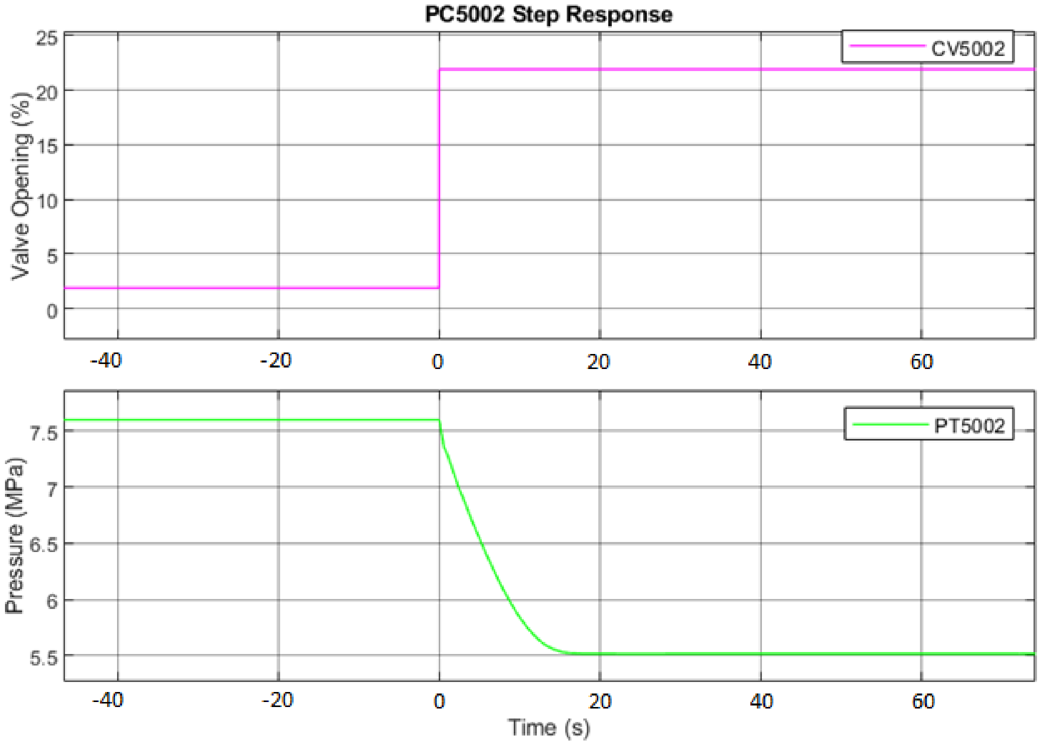


Figure 14: Step response of transcritical pressure controller PC5002

With a change of valve opening from 1.9 % to 21.9 %, the inlet pressure decreases from 7.6 MPa to 5.52 MPa. The process gain is therefore as follows:

$$K = \frac{5.52 - 7.6}{21.9 - 1.9}$$

$$K = -0.104\ MPa/\%$$

After decreasing by 63% of the total gain, the pressure is 6.19 MPa. This pressure is reached approximately 7.3 seconds after the step. Therefore T=7.3 s. There is no discernible response delay so τ=0.

Since this is a first-order response, the transfer function of the control loop is as follows:

$$G\_PC5002(s) = \frac{-0.104}{7.3s + 1}\ MPa/\%$$

6.3.2 *Low-pressure compressor bypass valve saturation temperature controller STC5170*

This controller is used to regulate the saturation temperature at the inlet of the low-pressure compressor. The important parameters of this controller are shown below.

Table 7: Low-pressure compressor bypass valve saturation temperature controller STC5170 operation summary

	Name	**Description**
Measured value	ST5170	Saturation temperature at low-pressure compressor inlet
Controlled actuator	CV5176	Low-pressure compressor bypass valve
Expected set point	-46 °C	

Once the system stabilises, the control valve CV5176 is 3.2 % open. The step response is obtained by opening the valve to 13.2 % and observing the effect on the saturation temperature at the inlet of the low-pressure compressor, ST5170.

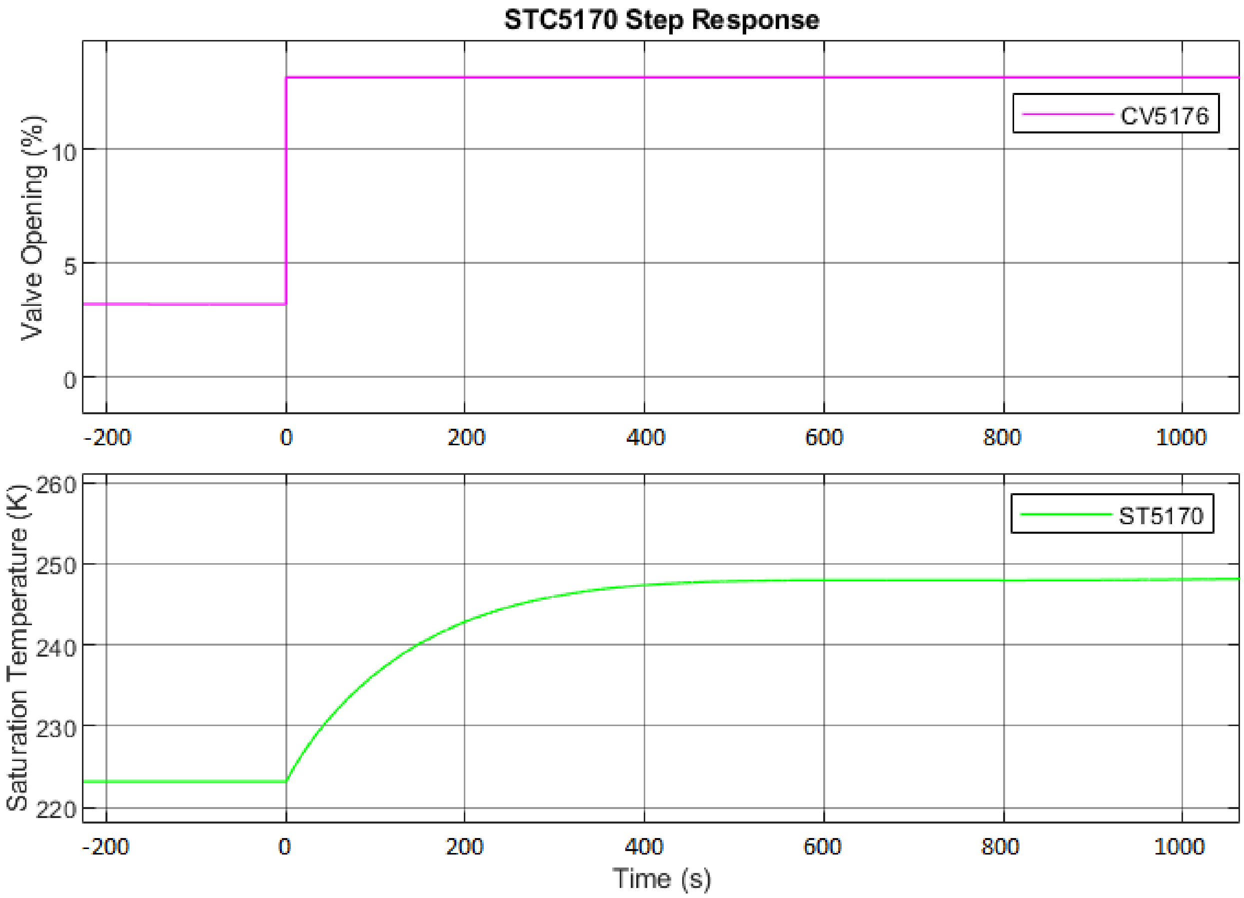


Figure 15: Step response of low-pressure compressor bypass valve saturation temperature controller ST5170

When opening the valve by 10%, the saturation temperature increases from -50 °C (223.15 K) to -25.2 °C (247.95 K). The process gain is therefore as follows:

$$K = \frac{-25.2 - (-50)}{10}$$

$$K = 2.48\ °\mathrm{C}/\%$$

After rising by 63 % of the total gain, the saturation temperature is -33.384 °C (239.766 K). This saturation temperature is reached approximately 141.7 seconds after the step. Therefore T=141.7 s.

This is a first-order response so the transfer function of the control loop is:

$$G\_STC5170(s) = \frac{2.48}{141.7s + 1}\ °C/\%$$

6.3.3 Medium-pressure compressor bypass valve saturation temperature controller STC5180

The controller is used to regulate the saturation temperature at the inlet of the medium-pressure compressor. The important parameters of this controller are shown below.

Table 8: Medium-pressure compressor bypass valve saturation temperature controller STC5180 operation summary

	Name	**Description**
Measured value	ST5180	Saturation temperature at medium-pressure compressor inlet

Controlled actuator	CV5186	Medium-pressure compressor bypass valve
Expected set point	-14.8 °C	

Once the system stabilises, the control valve CV5186 is 2.6 % open. The step response is obtained by increasing the opening to 22.6 % and observing the effect on the saturation temperature at the inlet of the medium-pressure compressor, ST5180. There is no discernible response delay so τ=0.

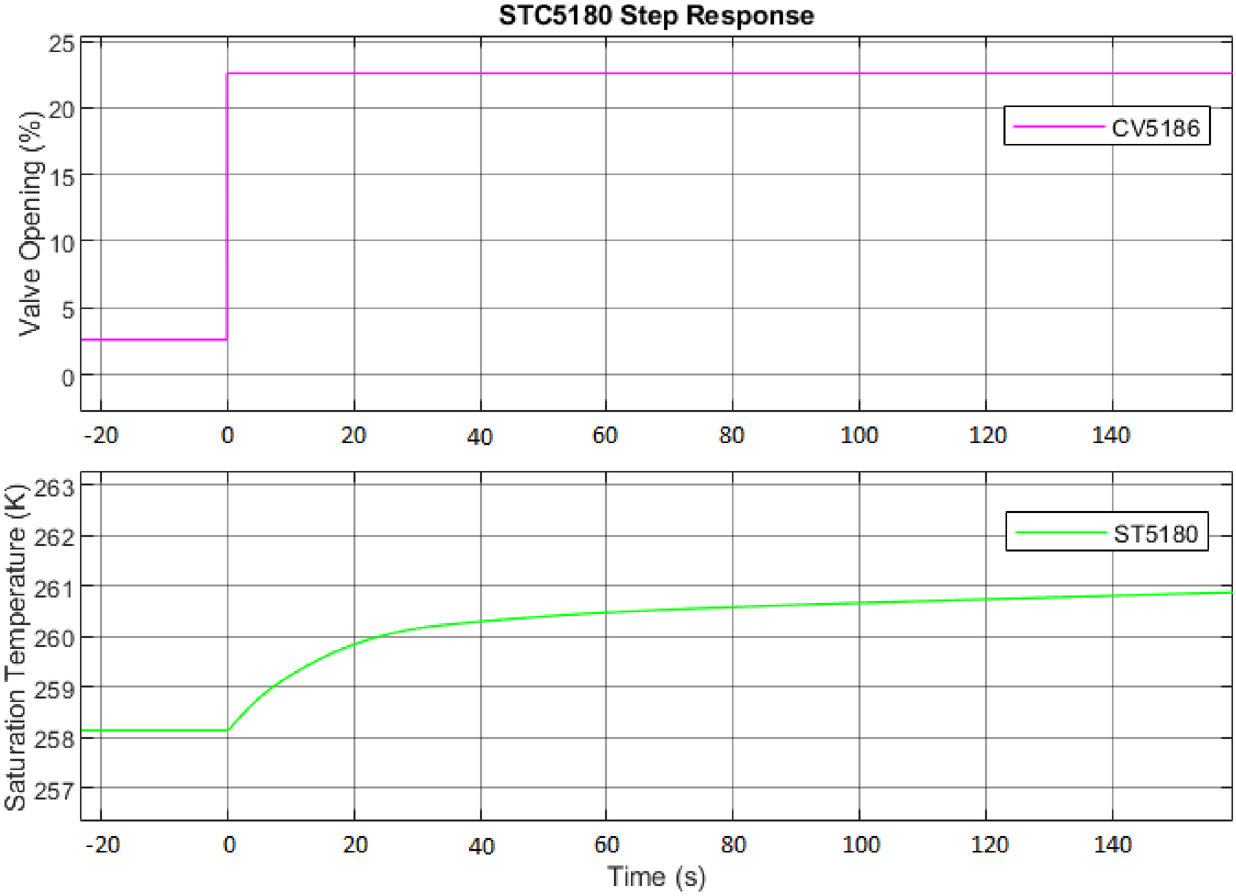


Figure 16: Step response of medium-pressure compressor bypass valve saturation temperature controller ST5180

After opening the valve from 2.6 % to 22.6 %, the saturation temperature increases from -15.01 °C (258.14 K) to -12.15 °C (261 K). The process gain is therefore as follows:

$$K = \frac{-12.15 - (-15.01)}{22.6 - 2.6}$$

$$K = 0.143\ \text{°C}/\%$$

After rising by 63 % of the total gain, the saturation temperature is -13.15 °C (260 K). This saturation temperature is reached approximately 25.85 seconds after the step. Therefore T=25.85 s.

For this first-order control loop, the transfer function is given by:

$$G\_STC5180(s) = \frac{0.143}{25.85s + 1}\ °C/\%$$

6.3.4 Storage vessel pressure controller PC5004

The controller is used to regulate the pressure at the inlet of the storage vessel by injecting hot gas from the vessel into the compressor slices at the inlet of the medium-pressure compressor. The important parameters of this controller are shown below.

Table 9: Storage vessel pressure controller PC5004 operation summary

	Name	**Description**
Measured value	PT5004	Storage vessel pressure
Controlled actuator	CV5110	Flash gas injection valve
Expected set point	5.5 MPa	

Once the system stabilises, the control valve CV5110 is 1.225 % open. The step response is obtained by changing this opening to 31.225 % and observing the effect on the storage vessel inlet pressure, PT5004.

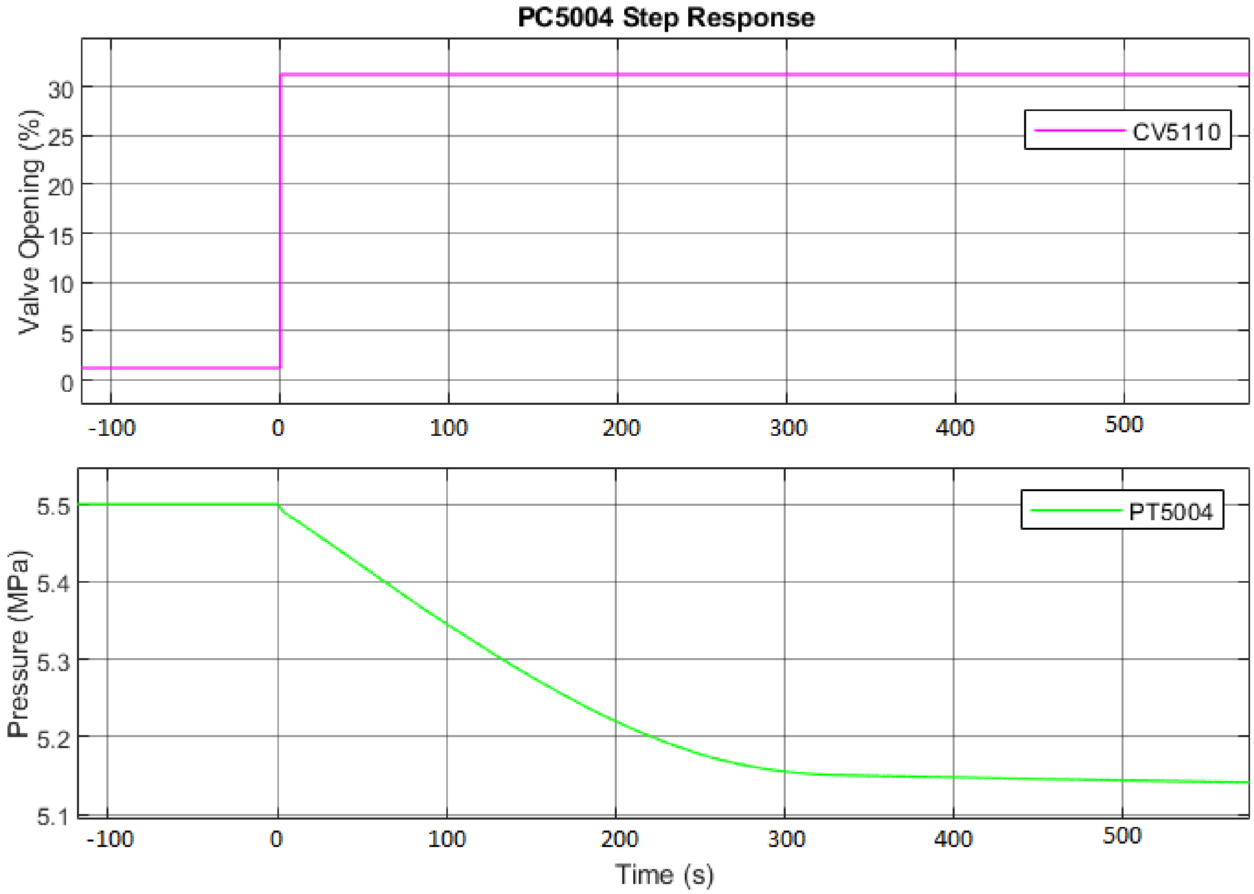


Figure 17: Step response of storage vessel pressure controller PC5004

With a change of valve opening from 1.225 % to 31.225 %, the accumulator pressure decreases from 5.5 MPa to 5.145 MPa. The process gain is therefore as follows:

$$K = \frac{5.145 - 5.5}{31.225 - 1.225}$$

$$K = -0.0118\ MPa/\%$$

After decreasing by 63 % of the total gain, the pressure is 5.26 MPa. This pressure is reached approximately 162 seconds after the step. Therefore T=162 s.

For this first-order control loop, the transfer function is given by:

$$G\_PC5004(s) = \frac{-0.0118}{162s + 1}\ MPa/\%$$

6.3.5 Interstage cooling liquid injection controller TC5178

The controller is used to regulate the temperature at the inlet of the medium-pressure compressor. The important parameters of this controller are shown below.

Table 10: Interstage cooing temperature controller TC5178 operation summary

	Name	**Description**
Measured value	TT5178	Interstage temperature
Controlled actuator	CV5114	Liquid injection valve
Expected set point	0 °C	

Once the system stabilises, the control valve CV5114 is 1.7 % open. The step response is obtained by changing this opening to 21.7 % and observing the effect on the medium-pressure compressor inlet temperature, TT5178.

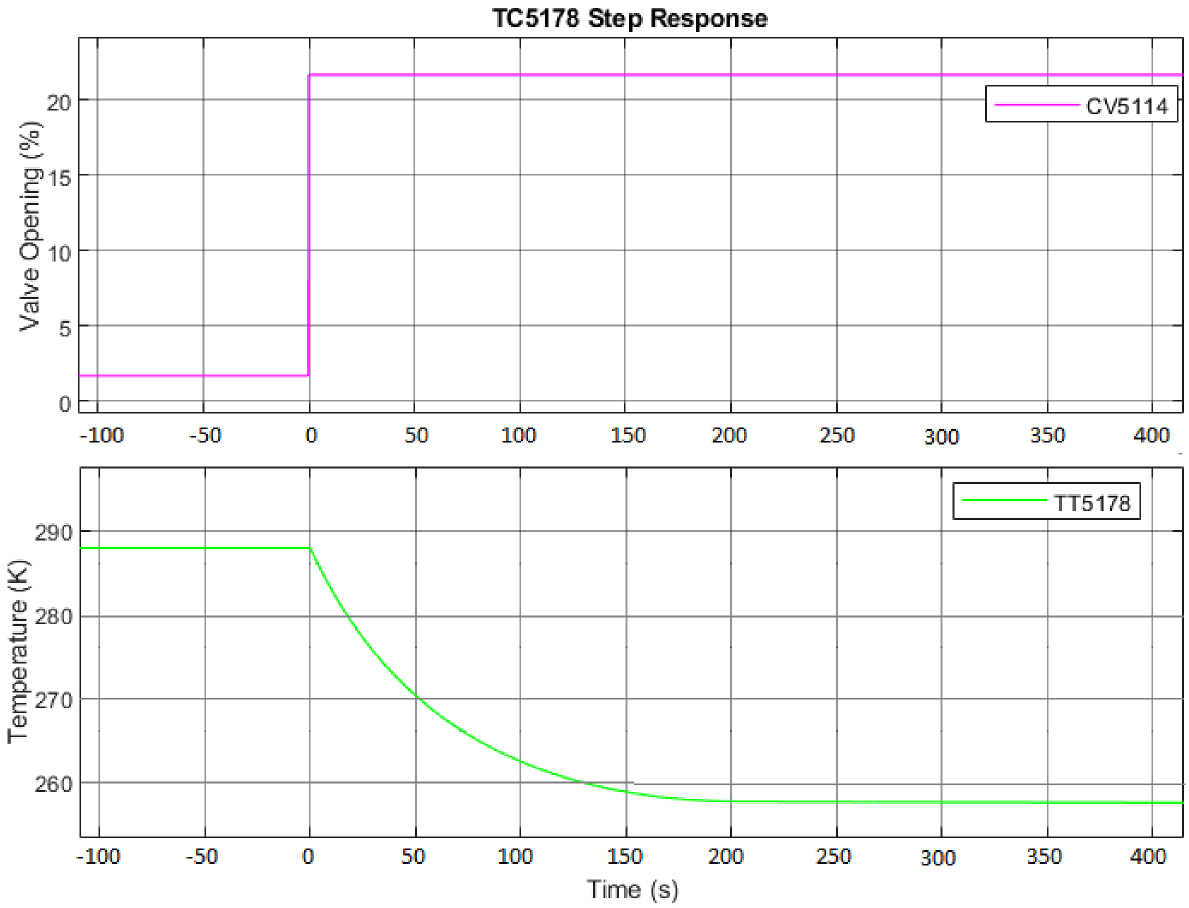


Figure 18: Step response of MP compressor inlet temperature controller TC5178

With a change of valve opening from 1.7 % to 21.7 %, the interstage temperature decreases from 14.85 °C (288 K) to -15.15 °C (258 K). The process gain is therefore as follows:

$$K = \frac{-15.15 - 14.85}{21.7 - 1.7}$$

$$K = -1.5\,°C/\%$$

After decreasing by 63 % of the total gain, the temperature is -5.25 °C (267.9 K). This temperature is reached approximately 69.2 seconds after the step. Therefore T=69.2 s.

For this first-order control loop, the transfer function is given by:

$$G\_TC5178(s) = \frac{-1.5}{69.2s + 1}\,°C/\%$$

6.4 Simulink Controller Design

Since the control loops all interact with each other, it is important to define a hierarchy of which controllers need to have the fastest, smoothest responses. The most important is the saturation temperature at the inlet of the LP compressor (STC5170) as this determines the minimum cooling temperature of the system. Second is the saturation temperature at the inlet of the MP compressor (STC5180), then the transcritical pressure (PC5002), followed by the accumulator pressure (PC5004) and lastly the interstage cooling (TC5178). The interstage cooling is the lowest in the hierarchy as it provides supplementary cooling where there is already a water-cooling system.

The controllers are designed in Matlab's control system designer using the root locus tuning tool.

6.4.1 Detailed Design of the LP compressor saturation temperature controller STC5170

Since the saturation temperature at the inlet of the LP compressor determines the minimum cooling temperature of the system, it is important that the controller has a fast response with very little overshoot and oscillation. The desired settling time of less than 60 seconds and maximum overshoot of 20% are shown on the root locus in Figure 19.

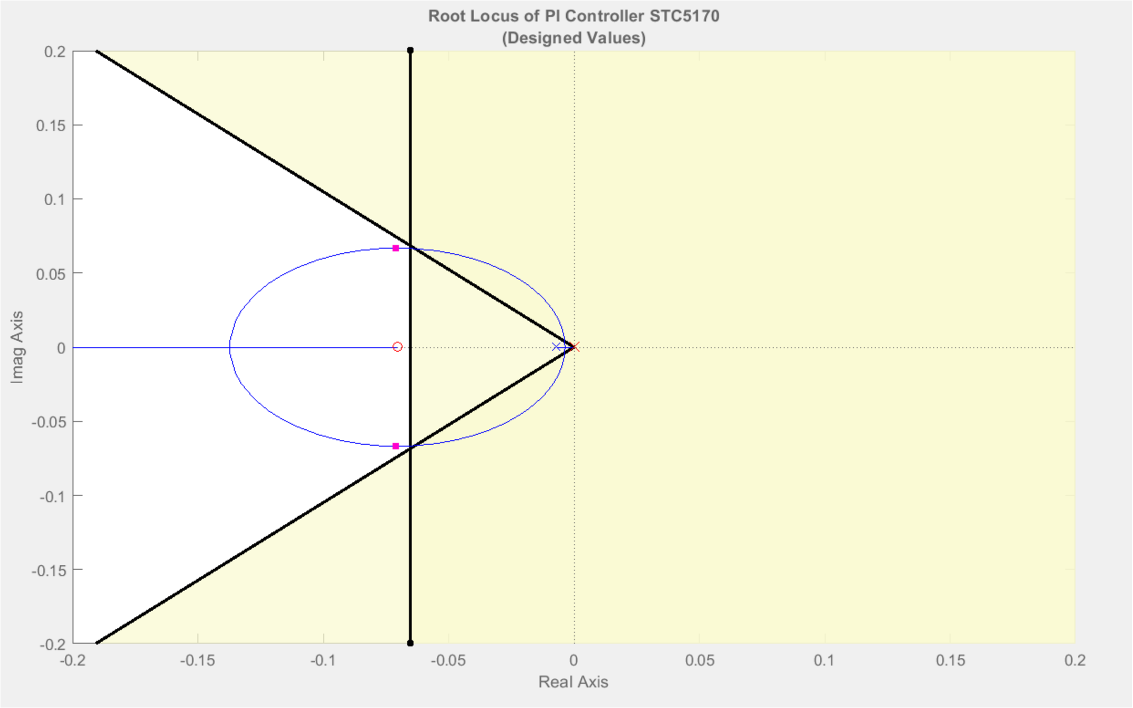


Figure 19: Root locus of STC5170 controller design

Placing a pole at 0 and a zero at -0.07, the gain of the controller is tuned so that the system response falls within the desired area. The designed controller transfer function is:

$$g\_STC5170(s) = 0.545\frac{1 + 14s}{s}$$

The step response of the system with this control loop is shown in Figure 20.

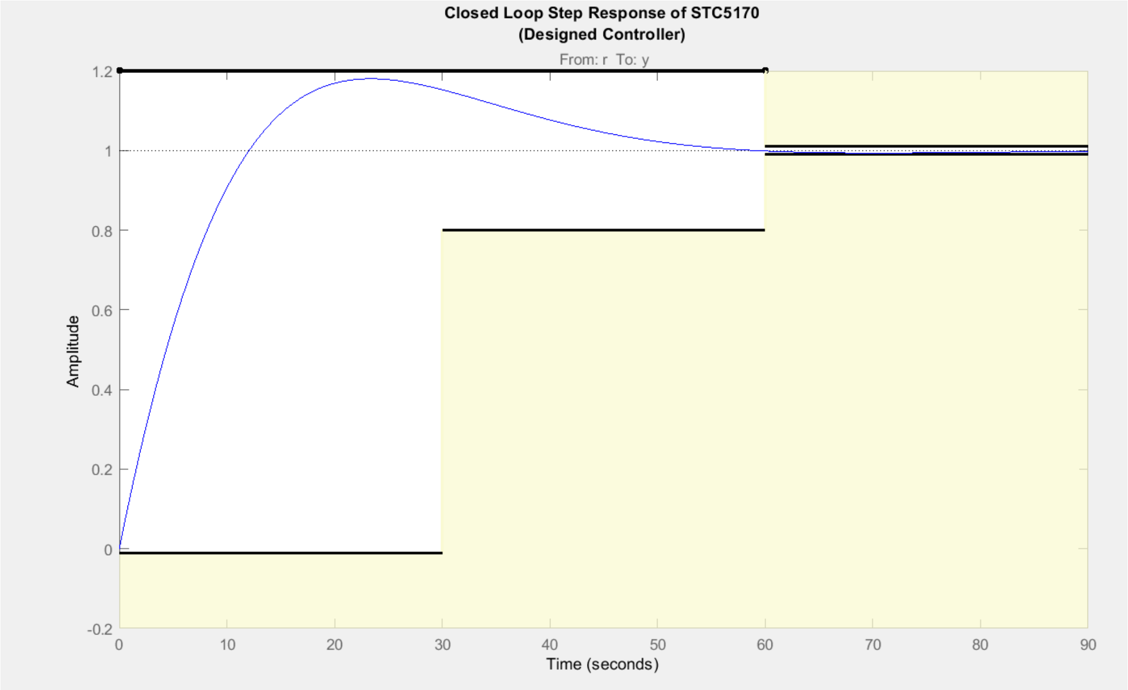


Figure 20: Closed loop step response of STC5170

From the step response above, the system has an overshoot of slightly less than 20% with no oscillation and settles in 60 seconds. This response fits nicely within the design requirements.

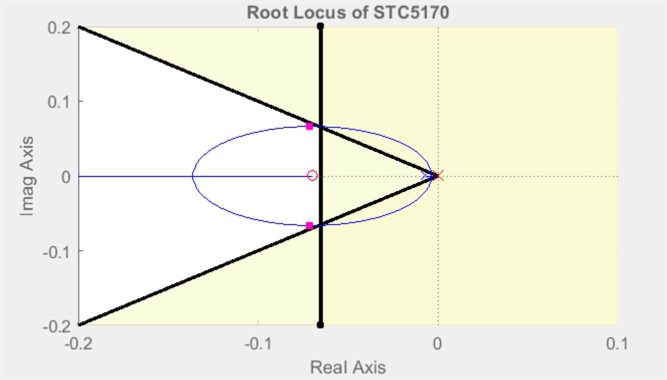
6.4.2 Summary of all controllers designed

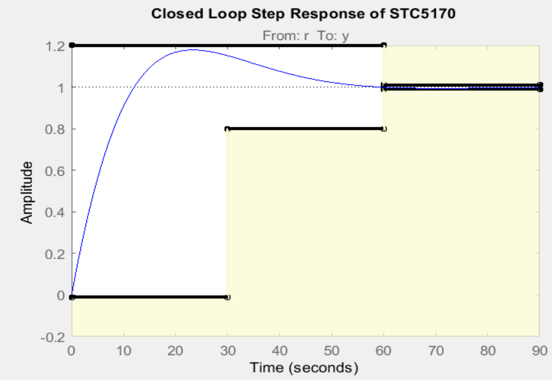
The remaining 4 controllers are designed with the same process as above and the system models, design specifications and final controllers are summarised in the table below.

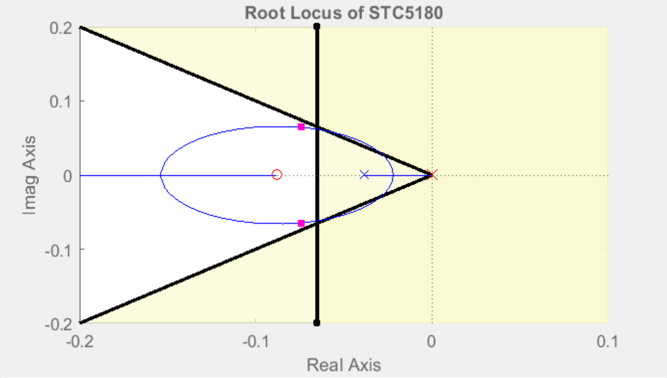
Table 11: Summary of controllers and design specifications

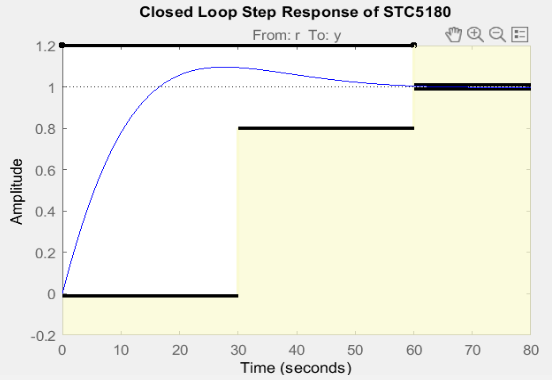
Controller Name	System Model	Design Specifications	Designed Controller
STC5170	$\frac{2.48}{141.7s+1}\ °C/\%$	Settling time: 60 s Maximum overshoot: 20 %	$0.545\frac{1+14s}{s}$
STC5180	$\frac{0.143}{25.85s+1}\ °C/\%$	Settling time: 60 s Maximum overshoot: 20 %	$1.75\frac{1+11s}{s}$
PC5002	$\frac{-0.104}{7.3s+1}\ MPa/\%$	Settling time: 120 s Maximum overshoot: 15 %	$-0.38\frac{1+3.1s}{s}$
PC5004	$\frac{-0.0118}{162s+1}\ MPa/\%$	Settling time: 60 s Maximum overshoot: 20 %	$-150.2\frac{1+13s}{s}$
TC5178	$\frac{-1.5}{69.2s+1}\ °C/\%$	Settling time: 60 s Maximum overshoot: 20 %	$-0.5\frac{1+12s}{s}$

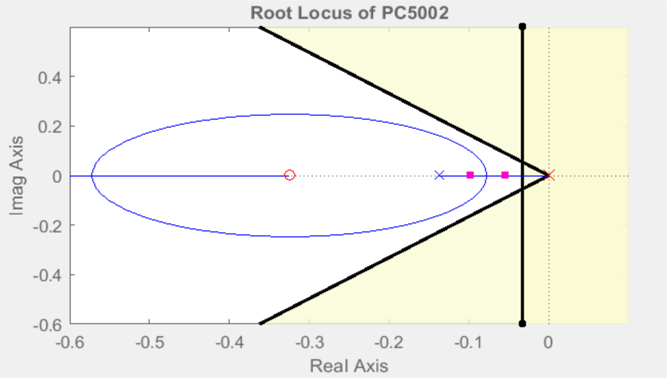
The root locus and step response for each of the above controllers are shown in the figure below along with their respective design specifications.

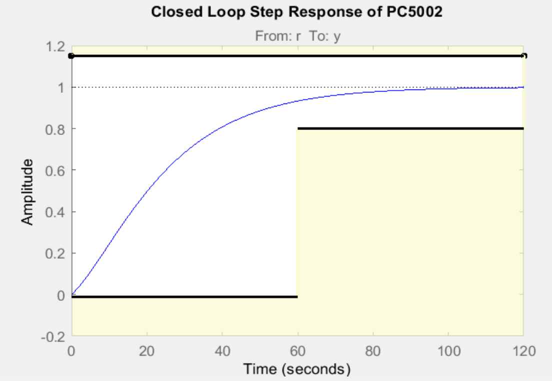

Root Locus of STC5170
Imag Axis
Real Axis
0.2
0.1
0
-0.1
-0.2
-0.2
-0.1
0
0.1

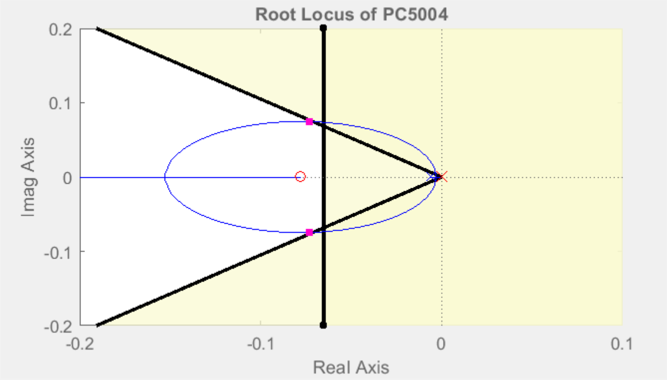

Closed Loop Step Response of STC5170
From: r To: y
Amplitude
Time (seconds)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
10
20
30
40
50
60
70
80
90

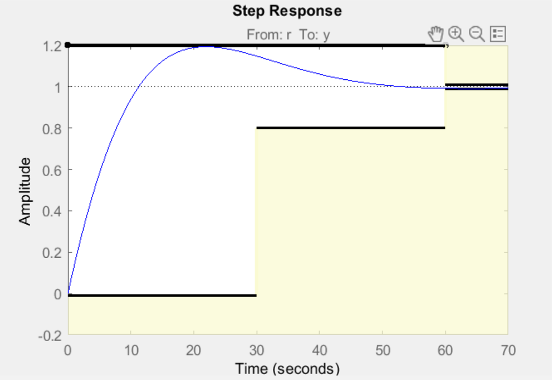

Root Locus of STC5180
Imag Axis
Real Axis
0.2
0.1
0
-0.1
-0.2
-0.2
-0.1
0
0.1


Closed Loop Step Response of STC5180
From: r To: y
Amplitude
Time (seconds)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
10
20
30
40
50
60
70
80


Root Locus of PC5002
Imag Axis
Real Axis
0.4
0.2
0
-0.2
-0.4
-0.6
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0


Closed Loop Step Response of PC5002
From: r To: y
Amplitude
Time (seconds)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
20
40
60
80
100
120


Root Locus of PC5004
Imag Axis
Real Axis
0.2
0.1
0
-0.1
-0.2
-0.2
-0.1
0
0.1


Step Response
From: r To: y
Amplitude
Time (seconds)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
10
20
30
40
50
60
70

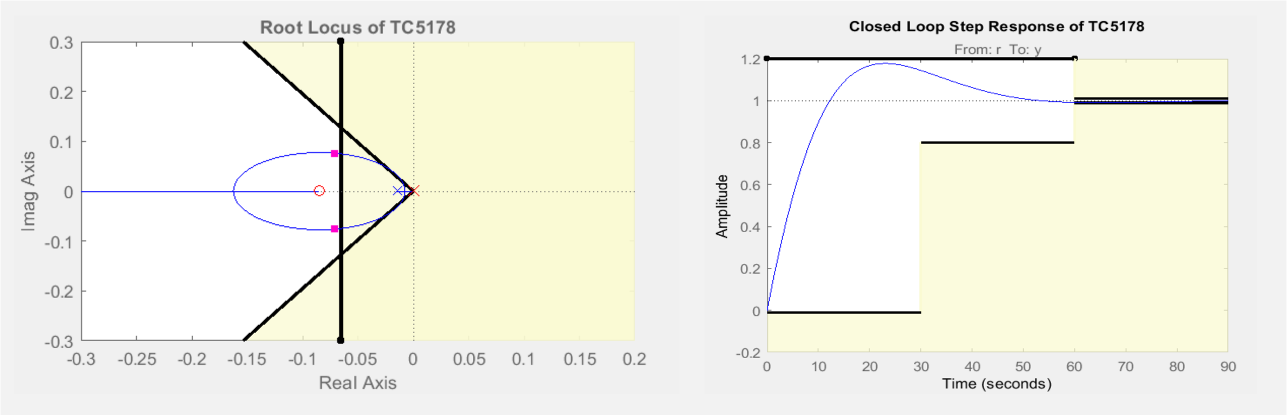


Figure 21: Root locus and step response for all designed controllers

7. Analysis of Controller Performance

The controllers designed in Section 6.4 are implemented in the Simulink model to observe their behaviour with changes in load, interaction between controllers and disturbances in the water-cooling systems. This was achieved in one run, starting with no load. This steps up to full load after 10000 seconds and returns to no load at 15000 seconds. At 20000 seconds, there is 10 °C increase in the water-cooling system.

The availability of the system to run tests is extremely limited, so the only available test data with the most recent control parameters is a step down from full load to no load. This can be compared to the simulated load step down to analyse the performance of the designed controllers in comparison to the manually tuned system.

7.1 Analysis of designed controllers implemented in Simulink

The full model was run with the designed control parameters. The load starts at 0%, increases to 100% at t=10000s and decreases back to 0% at t=15000s. At t=20000s, there is a temperature disturbance of +10°C on the water-cooling system. The response of each controller is shown in the following figures.

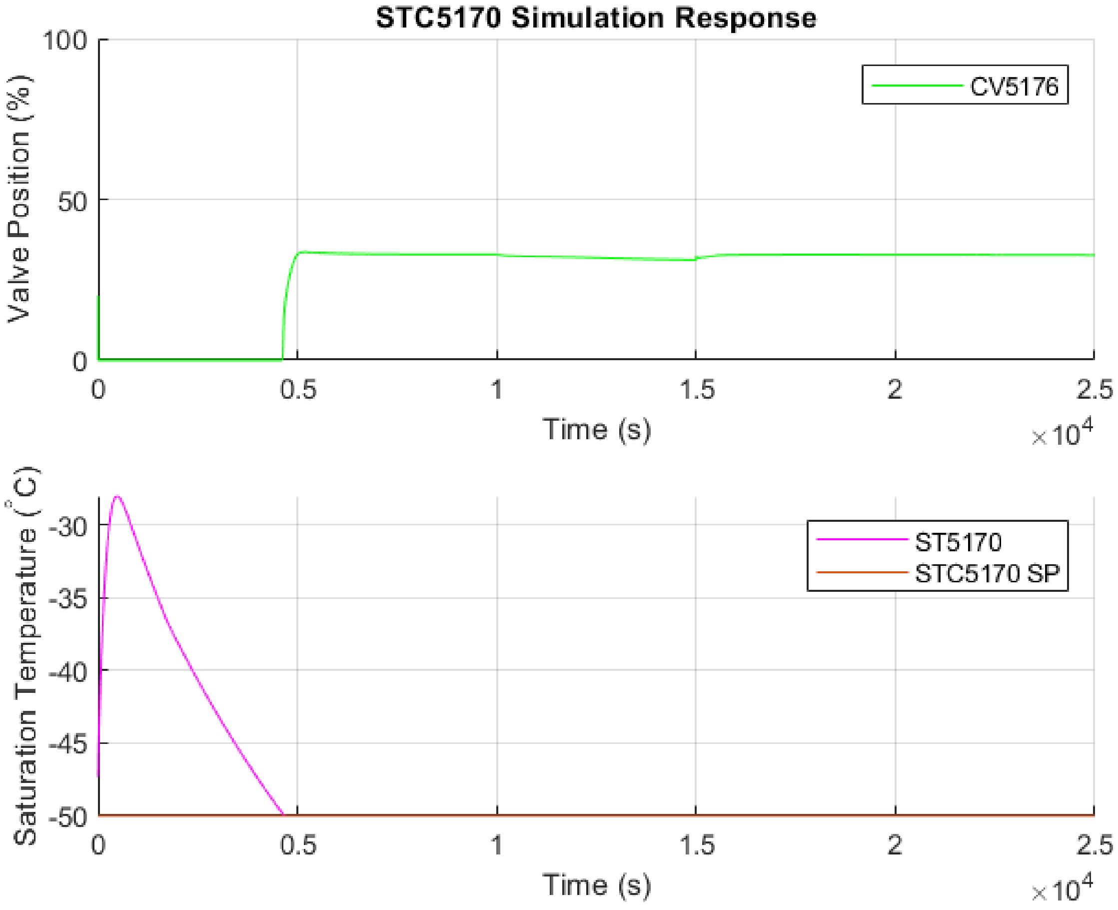


Figure 22: Simulated response of STC5170 to disturbances and variations in load

The system transients die down within 5000 seconds and the saturation temperature at the inlet of the compressor remains stable at -50 °C. When the load is introduced at the 10000 second mark, the valve closes slightly but the saturation temperature has no perceivable deviation or oscillation. The same is true after 15000 seconds, when the load is removed, and the valve opens up slightly. There is no perceivable effect on this control loop at 20000 seconds when the water-cooling temperature experiences a 10 °C disturbance. The control loop shows a fast response with good disturbance rejection and set point tracking.

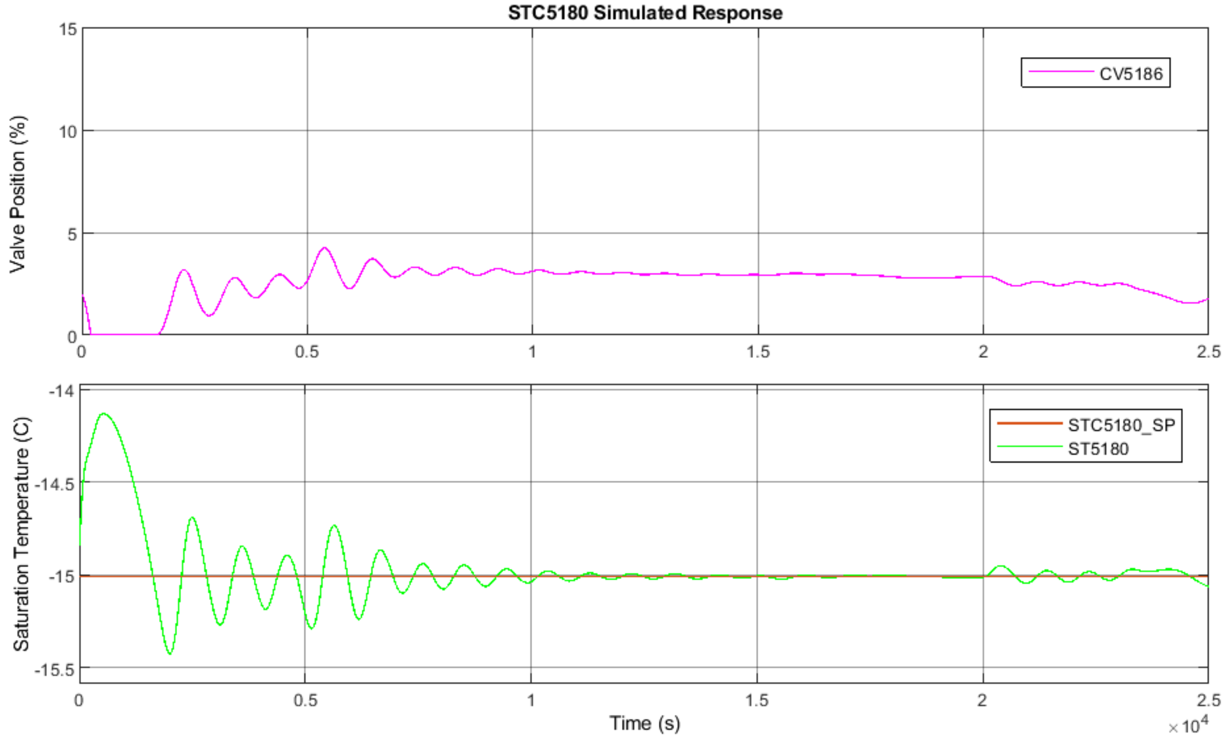


Figure 23: Simulated response of STC5180 to disturbances and variations in load

It takes slightly longer for the transients to die down in STC5180 than STC5170. The saturation temperature oscillates around the set point until approximately 10000 seconds. When the load is introduced at 10000 seconds, the oscillations die down and remain small after the load is removed at 15000 seconds. However, the saturation temperature begins to oscillate again after the water-cooling disturbance at 20000 seconds. While the controller is oscillatory, the valve oscillations are within 1% and the saturation temperature oscillates by ±0.5 °C. This level of oscillation is acceptable, especially since the controller is able to track the set point with no offset. It is more important for this controller to be reasonably close to the set point than it is to be stable and without oscillation. The impact of the water-cooling disturbance is quite small in terms of both saturation temperature oscillation and valve oscillations. Since the saturation temperature remains close to the set point throughout the disturbance and oscillation, this response is acceptable.

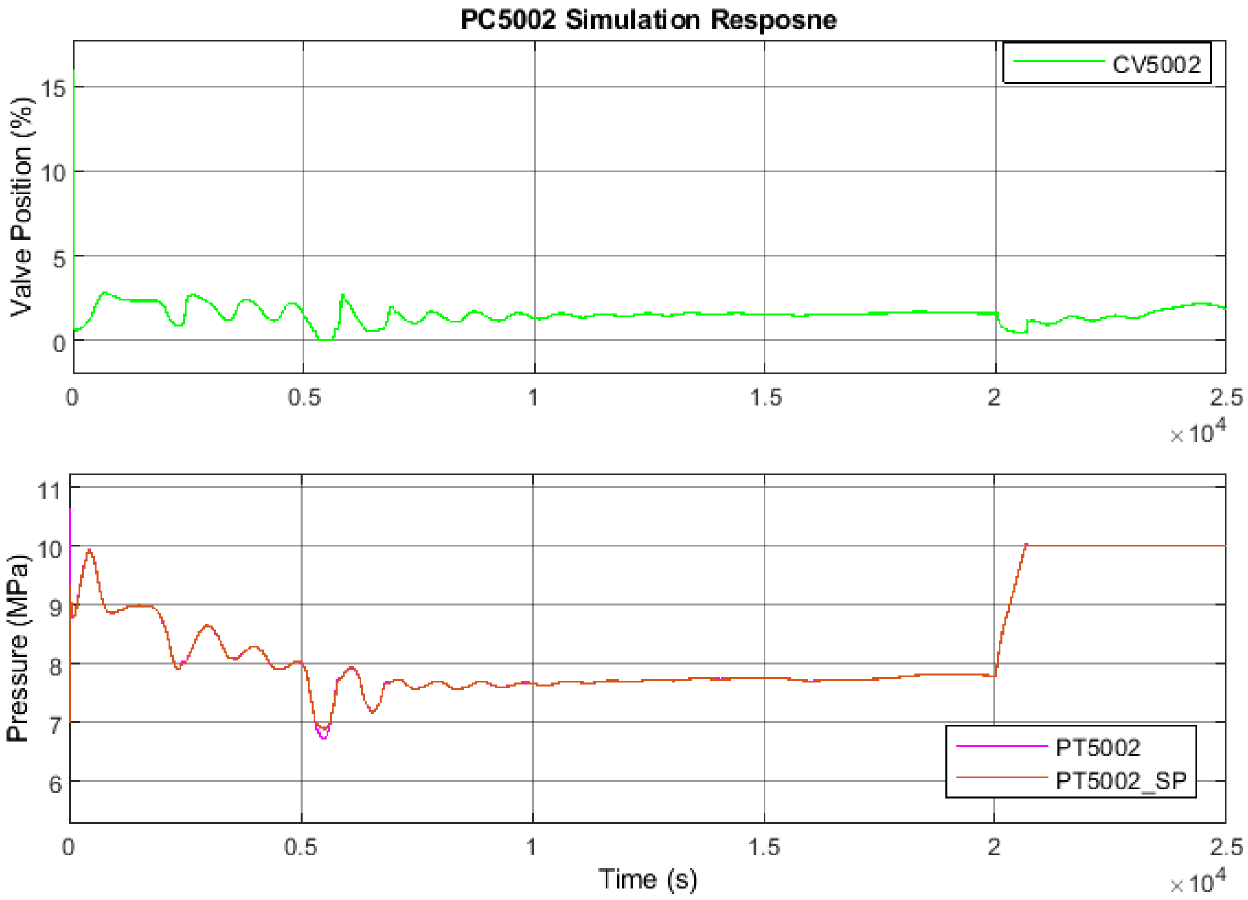


Figure 24: Simulated response of PC5002 to disturbances and variations in load

The transcritical pressure is more difficult to analyse due to the dynamic set point. The set point takes approximately 10000 seconds to reach stability. However, the pressure does track the set point through all of these changes with little perceivable error. When the load is added at 10000 seconds, the set point is unaffected, and the pressure continues to track the set point with no offset. The same is true of the pressure when the load is removed at 15000 seconds. At 20000 seconds, when the water-cooling disturbance is added, the set point increases to 10 MPa in approximately 600 seconds. This is because the pressure set point is directly related to the temperature at the outlet of the common unit water cooler (HX5002). The actuator begins to oscillate but maintains the set point well with no overshoot or oscillation. The controller performs well with load changes and seems to handle input disturbances reasonably well.

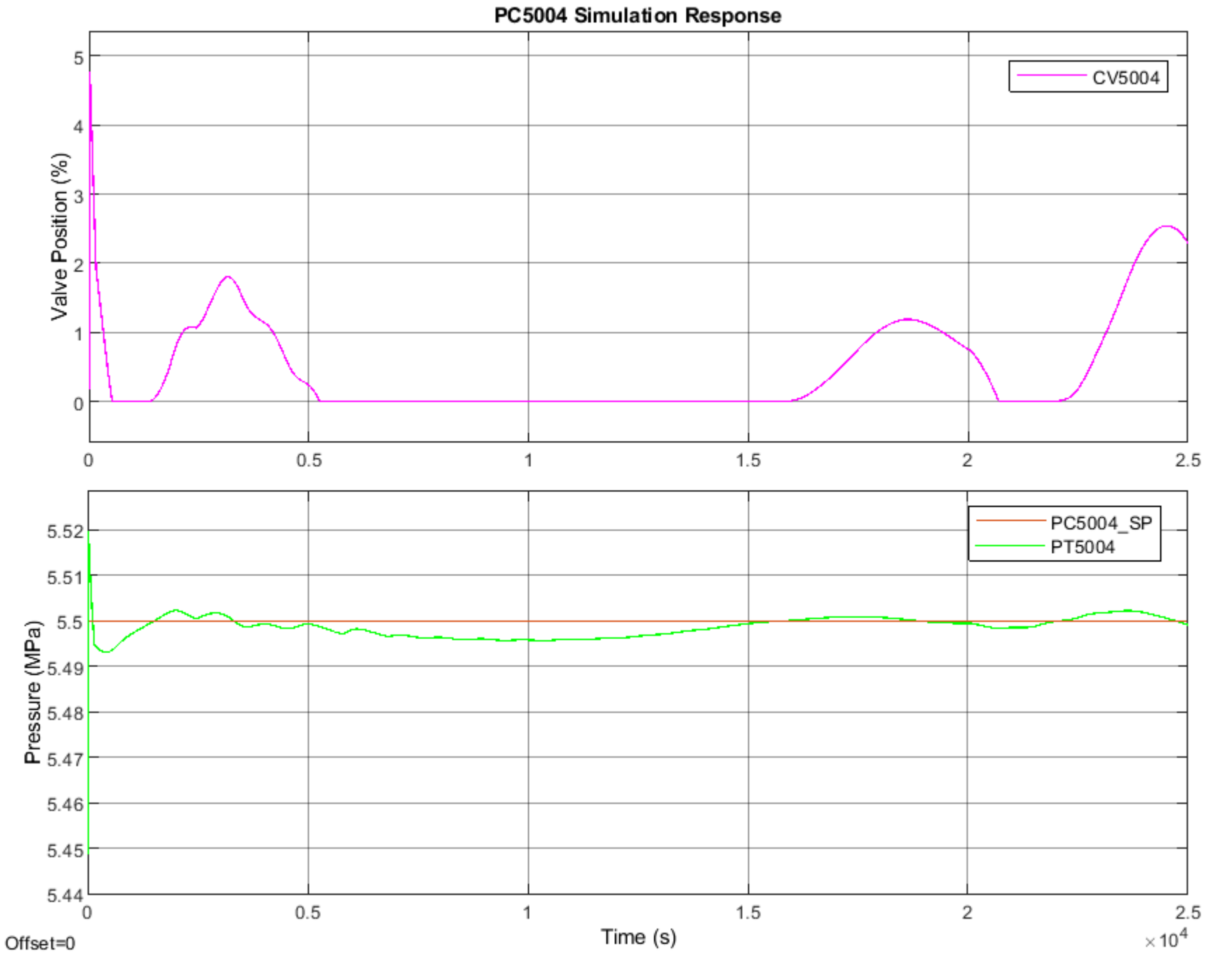


Figure 25: Simulated response of PC5004 to disturbances and variations in load

The accumulator pressure (PT5004) is directly affected by the transcritical pressure (PT5002). The effect of the transcritical pressure fluctuations at the start of the simulation can be seen in the accumulator pressure above. However, the controller does well to regulate the accumulator pressure when it gets too high. It is important to note that this controller cannot directly increase the pressure. It can only decrease the pressure by releasing gas into the compressor interstage section.

When the load is introduced at 10000 seconds, the pressure is below the set point so there is no immediate control action although the pressure does begin to increase slowly. However, when the load is removed at 15000 seconds, the pressure has already risen slightly above the set point and the controller is able to open the valve and bring the pressure back down to 5.5 MPa with only a slight oscillation. After the water-cooling disturbance at 20000 seconds, the pressure rises again, and the controller is able to bring it back to the set point. Although the valve fluctuations look large in the figure above, it is dramatized by the scale. The valve opens slowly and is able to regulate the pressure with only small changes in the opening percentage. This behaviour is satisfactory as the main goal of this controller is to prevent too high pressure in the accumulator vessel.

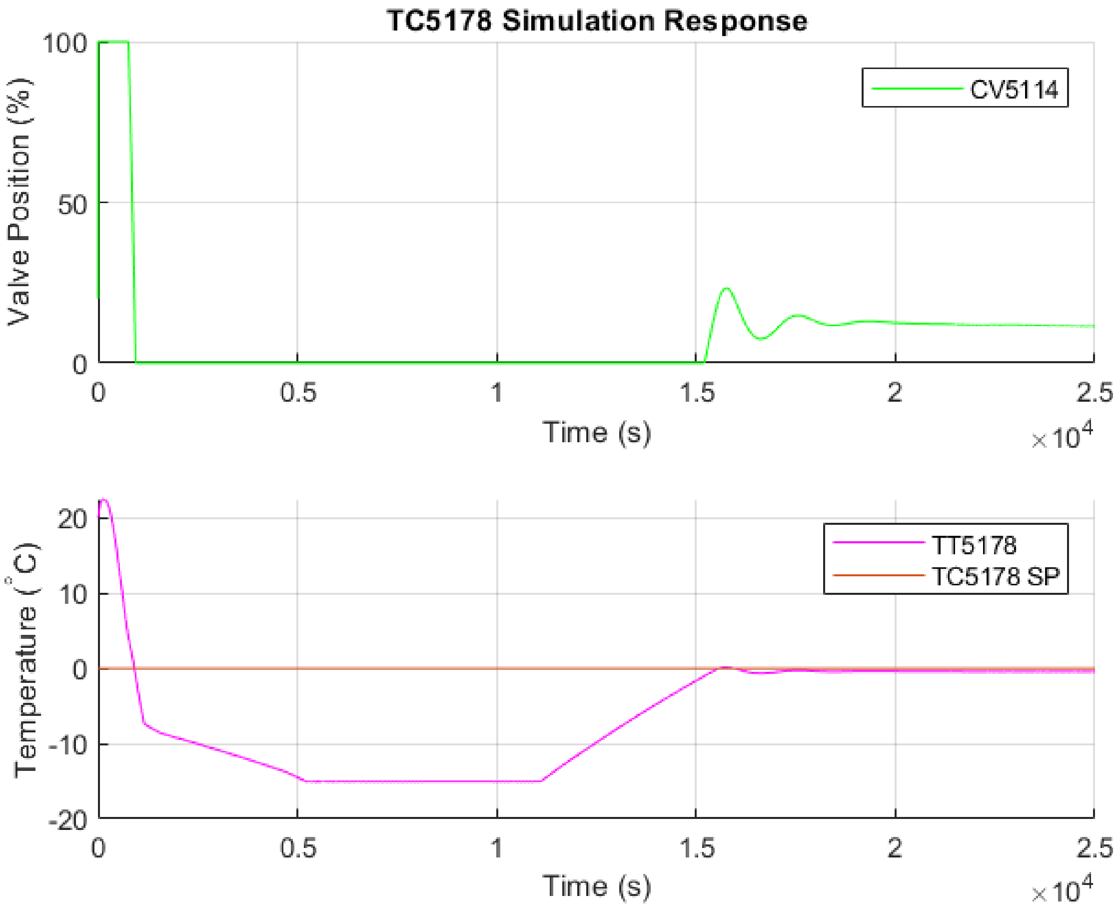


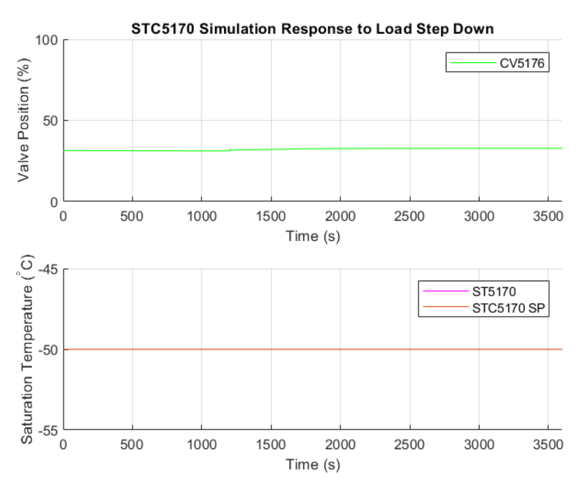
Figure 26: Simulated response of TC5178 to disturbances and variations in load

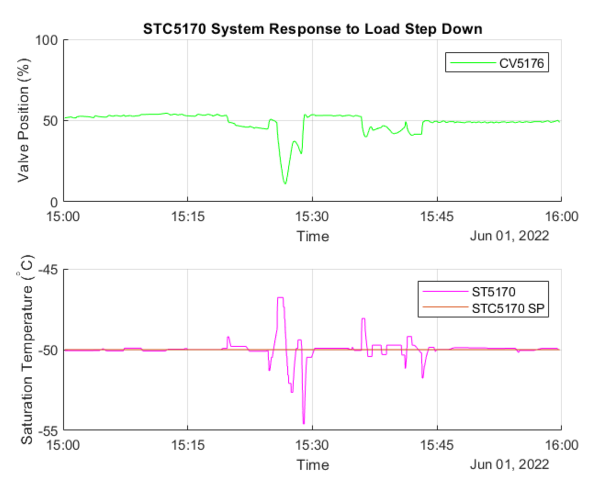
Similar to the accumulator pressure controller, the liquid injection controller can only decrease the interstage temperature. It cannot directly increase this temperature. During start up the interstage temperature is lower than the set point and the liquid injection valve remains closed. After the load is introduced at 10000 seconds, the temperature begins to increase. However, it is only after the load is removed that the interstage temperature is high enough for the liquid injection valve to begin regulating. The response has a very slow oscillation of ±1 °C which settles down after approximately 3000 seconds. There is no effect seen by the disturbance in the water-cooling system.

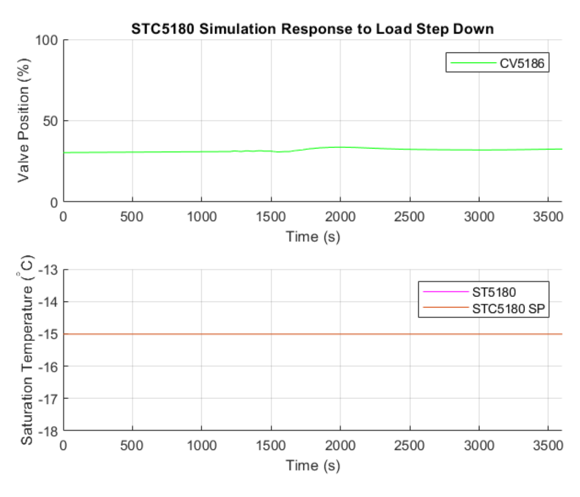
The main goal of this controller is to avoid the interstage pressure drifting too high. In this respect, the controller performs very well and does a good job of rejecting temperature disturbances from the water-cooling system. Because the water system and liquid injection both work to cool the interstage fluid, it is important that the liquid injection controller is able to maintain the set point when the water cooling cannot be relied upon.

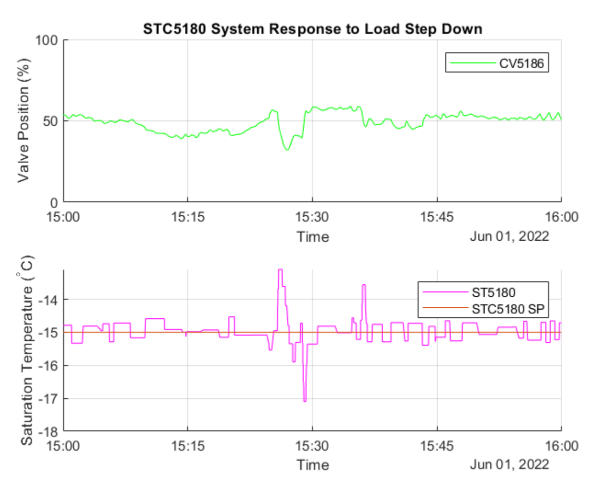
7.2 Comparison of designed controllers in Simulink and manually tuned system controllers

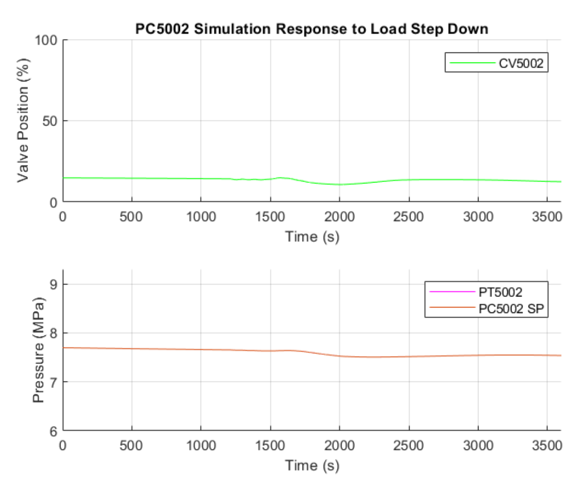
The physical system is manually tuned by an experienced operator and is tested by rapidly changing from full load to no load. The same conditions are implemented in the Simulink model which makes use of the control parameters designed in Section 6.4. The results are shown in Figure 27 below.


STC5170 Simulation Response to Load Step Down
Valve Position (%)
100
50
0
CV5176
0
500
1000
1500
2000
2500
3000
3500
Time (s)
Saturation Temperature (°C)
-45
-50
-55
ST5170
STC5170 SP
Time (s)


STC5170 System Response to Load Step Down
Valve Position (%)
100
50
0
CV5176
15:00
15:15
15:30
15:45
16:00
Time
Jun 01, 2022
Saturation Temperature (°C)
-45
-50
-55
ST5170
STC5170 SP
Time
Jun 01, 2022


STC5180 Simulation Response to Load Step Down
Valve Position (%)
100
50
0
CV5186
0
500
1000
1500
2000
2500
3000
3500
Time (s)
Saturation Temperature (°C)
-13
-14
-15
-16
-17
-18
ST5180
STC5180 SP
Time (s)


STC5180 System Response to Load Step Down
Valve Position (%)
100
50
0
CV5186
15:00
15:15
15:30
15:45
16:00
Time
Jun 01, 2022
Saturation Temperature (°C)
-14
-15
-16
-17
-18
ST5180
STC5180 SP
Time
Jun 01, 2022


PC5002 Simulation Response to Load Step Down
Valve Position (%)
100
50
0
CV5002
0
500
1000
1500
2000
2500
3000
3500
Time (s)
Pressure (MPa)
9
8
7
6
PT5002
PC5002 SP
Time (s)

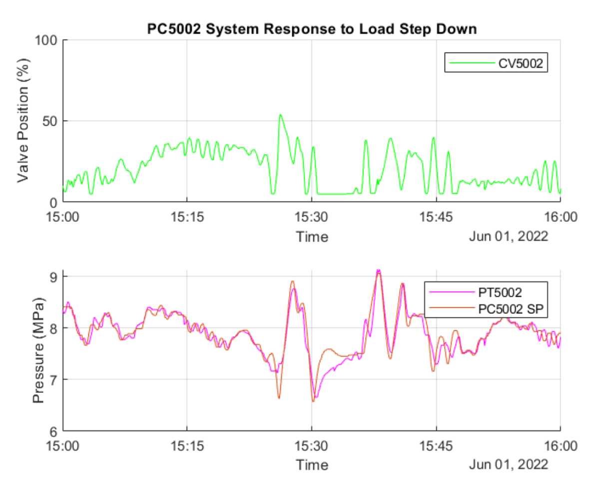

PC5002 System Response to Load Step Down
Valve Position (%)
100
50
0
CV5002
15:00
15:15
15:30
15:45
16:00
Time
Jun 01, 2022
Pressure (MPa)
9
8
7
6
PT5002
PC5002 SP
Time
Jun 01, 2022

Figure 27: Response of designed controllers in simulation (left) and manually tuned controllers in the physical system (right) in response to a step down in load

In both cases, the load changes from 100 % to 0 % 20 minutes (1200 seconds) after the start of the test.

For STC5170, the physical system starts off quite stable. After the load change STC5170 experiences an oscillation of ±5 °C for approximately 10 minutes before settling back at the set point. Comparatively, the simulated controller has a small change in valve position, but no oscillation or disturbance is visible on the saturation temperature. The oscillations in the physical system are likely due to the compressor reacting to the change in differential pressure across it.

In the physical system, STC5180 experiences a constant oscillation of ±0.5 °C. This is likely due to the controller having too aggressive parameters. After the load change, the oscillation increases to ±2 °C before returning to ±0.5 °C around 10 minutes later. The simulated controller shows very stable conditions before the load change, after which the valve opens but there is no significant change in the saturation temperature.

The transcritical pressure controller has a dynamic setpoint which is based on the transcritical temperature. In the physical system, PC5002 tracks the set point quite closely until the load change. At this point, there is a large fluctuation in set point and the controller is not quite fast enough to track these changes. In the worst case, the pressure is approximately 0.7 MPa below the setpoint. However, after 10 minutes the controller resumes its smooth tracking of the dynamic set point. Comparatively, the simulated setpoint is much more stable and the pressure tacks this without oscillation or offset. When the load is removed, the setpoint decreases and the valve oscillates slightly, but there is no deviation or oscillation seen on the transcritical pressure. The difference in stability of the dynamic set point in the simulation versus the real system can possibly be attributed to transcritical temperature fluctuations caused by instabilities in the water cooling just before the accumulator. This water cooling is provided by an external service at CERN and has been known to be quite unreliable and is often shut off without any indication or warning.

The regulation of the accumulator pressure (PC5004) in the physical system fluctuates by ±0.1 MPa with full load. After the load change, the pressure spikes by 0.8 MPa and settles back into its regular fluctuations within 20 minutes. During the entirety of this test, the simulated controller output remains at 0 %. The accumulator pressure oscillates very slightly 0.01 MPa below the setpoint. Even after the load change, the pressure remains below the set point and the controller output remains at 0 %. The oscillations in pressure in the physical system could be due to a combination of the oscillating MP compressor saturation temperature and the unstable nature of the water-cooling system.

The liquid injection (TC5178) on the physical system is quite oscillatory when operating with load, fluctuating by ±12 °C. Once the load is removed, there is one more large temperature spike from -10 °C to 10 °C. The oscillation then changes from large, slow changes to smaller, quicker oscillations of ±4 °C. Similarly, the simulated controller performs better after the load is removed. However, the initial offset is much smaller than that of the physical system. The worst-case offset is -5 °C from the set point and after the load is removed, the controller oscillates 0.2 °C above and 0.6 °C below the setpoint. The frequency of these oscillations is much slower than those in the physical system.

In all cases, the valve opening in the simulation is close to that of the real system. This is a good indication that the simulated system exhibits a good, comparable behaviour to reality. However, all simulated controllers are much more stable than their physical counterparts. This could be due to several factors. The first is the performance of the controllers themselves. These have been carefully designed and tested to give quick, stable, and reliable control. Additionally, the smoother behaviour of the simulation could be in part due to simplifications which have been made such as the removal of the oil system and the replacement of the gas- and water-cooling circuits with direct heat flow sources. Since the oil separators work to remove oil from the outlet of the compressors and recirculate it back to the compressors, there is an effect on the pressure at both the inlet and outlet of the compressors. This is likely to have some effect on the saturation temperature controllers and could account for the more oscillatory behaviour of the physical system. However, adding the oil system to the simulation would add a level of complexity to the problem that would take more time than is available to implement.

While these results give some good insight into the usefulness of the simulation, there would need to be much more testing performed in order to fully understand the differences in behaviour between the simulation and physical system. This has unfortunately not been possible due to the extremely limited testing time available for the physical system.

8. Conclusions

The transcritical R744 primary cooling system marks a number of firsts at CERN. The two stage transcritical CO_2 cycle has never been used as a primary chiller for detector cooling at CERN. Because the entire process is new, preparing the functional analysis was a highly beneficial task in terms of gaining a deep understanding of how the system should operate under a multitude of conditions. The preparation of alarms was also a good exercise in challenging the concept of the system and finding ways in which the system could fail. These lessons were further developed in the process of I/O commissioning and logic checking, as this provided a hands-on experience with the electrical, control, and thermodynamic elements which make up the system.

A major benefit that CERN has in preparing its control systems is the UAB tool for automatic PLC code generation. This allowed for rapid development of programs as most logic and functions are pre-developed and can be easily multiplied throughout the system. Not only does this make the process of programming much quicker, but it also reduces the likelihood of errors in the program caused by typing errors or other small mistakes.

The application of redundant PLCs greatly reduces the likelihood of system-wide failure. Although the chance of PLC failure is low, the reliability of detector cooling is of extreme importance. It is therefore of the highest importance that the risk of failure be reduced as much as possible. Through testing of different failure scenarios, it is clear that there needs to be multiple points of failure in the PLC communication network for this to result in a total system failure. This shows that the application of PLC redundancy protects against multiple failure scenarios and ensures that the system can operate despite these failures occurring.

This project has gained multiple benefits from the development of a simulated model of the system. The first main benefit is the understanding and first-hand experience of the thermodynamic principles involved. The simulation provided a risk-free space to experiment with the system and grapple with the key concepts without fear of accident or injury. Additionally, once the model was verified and accurately represented the physical system, the controllers and actuators could be tuned much more quickly and without the limitation of alarms. The simulation can run for the equivalent of several hours in a matter of minutes, making testing much quicker and more efficient. There is also much more data available in the simulation that may not be available in the physical system due to lack of sensors and instrumentation. It is not feasible to have sensors at every point in the system for every kind of signal, but this is not a limitation in simulation. It is therefore possible to understand the dynamics of the system in much more detail than would be possible with the sensors provided in the physical system.

Overall, the designed controllers perform better than those manually tuned in the physical system, with the exception of PC5004 which cannot be analysed in the given test conditions. However, it is highly possible that the simulation is missing several non-negligible sources of noise and disturbance. These include possible fluctuations in compressor speed, unpredictable temperature and flowrate in the water-cooling system, and pressure changes due to the oil separation system.

9. Recommendations for Future Research

From the testing of the Schneider M580 redundant PLCs, it is noted that the system could benefit from powering each PLC from a separate source, ideally with UPS or battery backup on at least one. This would further decrease the probability of losing both PLCs at the same time and ensure further reliability of the system.

Additionally, it is recommended to run further tests on the physical system to have more use-cases to compare to the simulation. For example, it would be beneficial to see the system response to various load changes, from 0 % to 100 % and with smaller steps in between. It would also be interesting to implement the designed controllers in the physical system to provide a 1:1 comparison of the simulation and physical system response.

Lastly, it is recommended to spend more time running tests and analysing various points of noise or disturbance in the system. This could then be implemented in the model to improve the accuracy and reliability of the simulation. Once this is completed, it would be highly beneficial to incorporate the slice stepper into the model to take into account the transient behaviour at start-up and at the transitions between steps. This can then be expanded further to include more than one slice, which will provide an understanding of the slice start-up behaviour, switching between active slices, and the interaction and behaviour of multi-slice operation. This understanding will provide a much-needed insight into the performance and behaviour of the modular slices which will be implemented in future iteration of the primary R744 chiller. Additionally, it is recommended to investigate the effects of the oil system disturbances and possibly include this in the model if the impact of these disturbances is found to be significant. This further development of the system simulation is currently being worked on by another student at CERN as part of a PhD project.

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11. Appendix A – CERN naming conventions

The naming convention in the below table summarises both the equipment prefix and device tag used to identify components within each system. This is useful when discussing systems with a broader view of CERN and its many installations. However, this naming convention is only used within the CO_2 cooling group for the multiple cooling systems maintained by the group.

System naming			
1st Digit	C	Cooling	Functionality (letter)
2nd Digit	S	Surface	Installation (letter)
	U	Underground	
3rd Digit	1	ATLAS, Point 1	Experiment
	2	Alice, Point 2	
	5	CMS, Point 5	
	8	LHCb, Point 8	
	0	Meyrin Area	
4th Digit	a	System A	System (letter)
	b	DEMO B153	
	c		
	d		
	e		
	…		
	x		
	y		
	z		
5th Digit	_		Underscore
6th Digit	A	Accumulator	System type
	B	Back-up chiller	
	C	Chiller	
	D	Dummy Load	

	M P S T 0, 1, 2, …, 9	Manifold CO2 Plant Surface storage Transfer line Electrical and Control cabinet	
7th Digit	0, 1, 2, …, 9	Number of system (mechanical: e.g., number of plant, number of manifold, etc.)	Number of system type
	a, b, c, …, z	Number of system linked to electrical and control cabinets	
8th Digit	_		Underscore
9th and 10th Digits	GP	Gas pump (compressor)	Component/variable letters
	TT	Temperature Transmitter	
	PT	Pressure Transmitter	
	CV	Control valve (any actuator)	
	EH	Electrical heater	
	EV	Electrical operated valve (shut-off)	

	ST	Saturation temperature	
	SP	Saturation pressure	
	SH	Super heating	
11th Digit	0	Common to more subsystems	Circuit (letter)
	1	Oil system	
	2	Water/air cooling	
	3		
	4		
	5	Chiller	
	6		
	7		
	8		
	9		
12th Digit	0	Common	Subsystem
	1	Slice 1	
	2	Slice 2	
13th and 14th Digits	10		State point (number)
	20		
	99		

12. Appendix B – Actuator Safety Positions

Unit/act.	Description	Safety Position
SLICE1	SLICE 1 PCO	OFF
SLICE2	SLICE 2 PCO	OFF
CV5002	Transcritical cycle control valve	Open
PC5002	Transcritical cycle pressure controller	Reg OFF
PC5004b	Low pressure R5004 controller	Reg OFF
CV2004	Water circuit valve	Closed
TC5002	Transcritical cycle temperature controller	Reg OFF
PC5004	Storage vessel pressure controller (Flash gas)	Reg OFF
CV5110	Flash gas injection valve – SLICE1	10% open
CV5210	Flash gas injection valve – SLICE1	10% open
EV5106	Flash gas valve	Closed
EV5112	Liquid supply	Closed
EV5166	Suction gas valve	Closed
EV5196	Discharge gas valve	Closed
EV5178	Drain valve	Open
EH1171_ON	LP heater	Off
GP5171	LP compressor	Off
STC5170b	LP compressor speed saturation temperature controller	Off
STC5170	Split range saturation temperature controller	Off
CV5176	LP hot gas bypass	Open
STC5170a	LP hot gas bypass saturation temperature controller	Off
EH1181_ON	MP heater	Off

Unit/act.	Description	Safety Position
GP5181	MP compressor	Off
STC5180b	MP compressor speed saturation temperature controller	Off
STC5180	Split range saturation temperature controller	Off
CV5186	MP hot gas bypass	Open
STC5180a	MP hot gas bypass saturation temperature controller	Off
CV5192	Air cooled gas cooler three-way valve	CLOSED to HX5194, OPEN between MP compressor and discharge line
TC5196	3way valve outlet temperature controller	Off
HX5194	Air cooled gas cooler	Off
TC5194	Air cooled gas cooler outlet temperature controller	Off
CV5114	Liquid injection valve	10% Open
TC5178	Liquid injection controller	Off
CV5110	Flash gas injection valve	Closed
EV1171	LP oil supply valve	Closed
EV1181	MP oil supply valve	Closed
EV1189	Coarse filter emptying valves	Closed
EV1191	Fine filter emptying valves	Closed
CV2176	Water cooled gas cooler circuit valve	Closed
TC5174	Water cooled gas cooler temperature controller	Off

13. Appendix C – I/O Testing Procedures and Acceptance Test Protocols

13.1 IO Commissioning

The I/O commissioning involves testing each input to and output from the PLC to ensure that the correct device is connected to the correct channel, and that the signal corresponds to how we expect the system to behave. This needs to be done for all analog inputs, analog outputs, digital inputs and digital outputs.

13.1.1 Analog input test procedure

There are 6 types of analog inputs in this system. The test procedures and troubleshooting methods for each one are detailed in Table 12.

Table 12: Testing procedure and troubleshooting methods for analog input signals

Device type	**Test procedure**	**Trouble shooting**
PT100 temperature sensor reading	• Test connection by disconnecting the sensor from the electrical terminal and checking to see if the corresponding signal is lost in SCADA. • Test the signal value by exposing the sensor to room temperature and making sure the value in SCADA matched this temperature. Then warm the sensor with your hand and observe the temperature increase	• If the wrong signal is lost when disconnecting the sensor, check that the wiring is correct, and that the sensor is connected to the correct analog input channel • If the temperature reading does not make sense, check that the sensor is correctly wired and that the signal converter has the correct configuration
Pressure sensor reading	• Disconnect the sensor from the electrical terminal and check to see if the corresponding signal is lost in SCADA	• Check that the sensor is correctly wired and connected to the correct input channel
Control valve position feedback	• Compare requested valve position with movement of the position indicator on the actuator	• Check wiring connection and signal converter configuration (where relevant)
Compressor speed feedback	• Test connection by forcing the inverter output to 10mA • The actual signal value cannot be tested without running the compressor	• Check the inverter configuration • Make sure the inverter output channel supports the type of signal you want to use (some support both

		analog and digital but some only support one of the two)
Compressor power feedback	- Test connection by forcing the inverter output to 10mA - The actual signal value cannot be tested without running the compressor	- Check the inverter configuration - Make sure the inverter output channel supports the type of signal you want to use (some support both analog and digital but some only support one of the two)
Cabinet DC current measurement	- Tested by comparing reading value with clamp multimeter	- Check connection to the analog input card

If the analog inputs produce the correct response for the tests described, then these inputs can be signed off and said to be working properly. If the signals do not respond as expected and the troubleshooting methods are not able to solve the issue, it is possible that there is a problem with either the device itself or the PLC input channel.

13.1.2 Analog output test procedure

There are 3 types of analog outputs in this system. The test procedures and troubleshooting methods for each one are detailed in Table 13.

Table 13: Testing procedure and troubleshooting methods for analog output signals

Device type	**Test Procedure**	**Trouble shooting**
Control valve position request	- Send position request from SCADA and observe actual valve position (either from external handle or digital display)	- If the handle/indicator does not move at all, make sure that there is nothing in the way that would prevent the valve from turning - Check the wiring connection to the valve - Check the valve's input signal configuration (where relevant)
Compressor speed request	- Compare command value from SCADA to value appearing on inverter display (note, this test is carried out without the compressor connected)	- Check the wiring to the analog input of the inverter - Check that the input has been correctly configured on the inverter
Air-cooled gas cooler speed request	- Change command signal and observe speed changes visually	- Check powering of the fan - Check the configuration of signal converters

If the analog outputs produce the correct response on the device for the tests described, then these outputs can be signed off and said to be working properly. If the devices do not respond as expected and the troubleshooting methods are not able to solve the issue, it is possible that there is a problem with either the device itself or the PLC output channel.

13.1.3 Digital input test procedure

Table 14: Testing procedure and troubleshooting methods for digital input signals

Device type	**Test procedure**	
Phase monitoring relay	• Test connection by disconnecting signal wire from the phase monitoring relay and check that the corresponding signal is lost. • Test signal by removing one phase from the relay input and observe an error signal sent to the PLC.	• Check wiring to digital input card. • Check relay configuration.
Power supply OK feedback	• Test connection by disconnecting signal wire from power supply. • Test signal by witching off device.	• Check wiring to digital input card.
Circuit breaker feedback	• Test connection by disconnecting signal wire from auxiliary switch. • Test signal by turning circuit breaker off and on.	• Check wiring to digital input card.
Redundancy module OK feedback	• Test connection by removing signal wire from the device. • Test signal by turning off one power supply and observing error signal sent to the PLC.	• Check wiring to digital input card.
Emergency stop relay feedback	• Test connection by removing signal wire from the device. • Test signal by triggering an emergency stop (by pressing an emergency stop button).	• Check wiring to digital input card. • Check that safety relay input is correctly wired
Valve OK feedback	• Test connection and signal by disconnecting the valve and observing error signal in PLC.	• Check wiring to digital input card.

		• Check valve error detection or valve configuration settings
Inverter OK feedback	• Test connection by removing signal wire from inverter. • Test signal by simulating an error on the inverter and observing the error signal in the PLC.	• Check wiring to digital input card. • Check inverter configuration.
Compressor ON feedback from inverter	• Test connection by removing signal wire from inverter. • Test signal by simulating an OK signal on the inverter and observing the corresponding signal in the PLC.	• Check wiring to digital input card. • Check inverter configuration.
Level switch	• Test connection by removing signal wire from the switch. • Test signal by filling the vessel above the switching point and observing the signal change in the PLC.	• Check wiring to digital input card. • Check that level switch is not stuck.
Valve end switches	• Test connection by removing signal wire from the switch. • Test signal by opening (or closing) the valve to the switching point and observing the signal change in the PLC.	• Check wiring to digital input card. • Check that valve internal end switches are correctly configured.
Pressure switch	• Test connection by removing signal wire from the switch. • Test the signal by pressurising above the switching point and observing the signal change in PLC. This should only be done during a system pressure test.	• Check wiring to digital input card.

Air cooled gas cooler OK	• Test connection by removing signal wire from the gas cooler. • Test signal by turning on the cooler and observing the signal in the PLC.	• Check wiring to digital input card. • Check the powering of the gas cooler.

If the digital inputs have the correct response in the PLC for the tests described, then these inputs can be signed off and said to be working properly. If the devices do not respond as expected and the troubleshooting methods are not able to solve the issue, it is possible that there is a problem with either the device itself or the PLC input channel.

13.1.4 Digital output test procedure

There are 5 types of digital outputs in this system. The test procedures and troubleshooting methods for each one are detailed in Table 15.

Table 15: Testing procedure and troubleshooting methods for digital output signals

Device type	**Test procedure**	**Trouble shooting**
Cabinet LEDs	• Force digital output signal from SCADA and observe the LED response.	• Check the wiring to the LED • Use a multimeter to check the output from the PLC.
Safety relay reset	• Send the ON signal after the safety relay is triggered by an emergency stop button. Observe the safety relay error signal disappear.	• Check wiring from the digital output card.
Output relays	• Force digital output signal and observe relay response (indicated by a small LED on the relay).	• Check wiring from the digital output card. • Check the power supply to the relay.
Compressor start request	• Measure voltage on the inverter contacts.	• Check wiring from digital output card. • Check inverter configuration.
Electric valves (shut-off)	• Check that valve activates when digital signal is sent (movement in the valve can be felt by resting a hand on the actuator when the signal is sent).	• Check wiring from digital output card. • Check valve powering
Gas cooler on request	• Activate on request and observe the fan turning on.	• Check wiring from digital output card. • Check fan powering.

If the digital outputs have the correct response on the device for the tests described, then these outputs can be signed off and said to be working properly. If the devices do not respond as expected and the troubleshooting methods are not able to solve the issue, it is possible that there is a problem with either the device itself or the PLC output channel.

13.1.5 *Actuator test procedure*

There are 6 types of actuators in this system. The test procedures and troubleshooting methods are detailed in Table 16.

Table 16: Testing procedure and troubleshooting methods for actuators

Device type	**Test procedure**	**Trouble shooting**
Electric valves (shut-off)	• Test with pressure inside. After opening the pressure on both sides of the valve should equalize. • Observe the movement of the handle/indicator or feel for the vibration of the valve if there is no position indicator.	• Check valve powering. • Make sure there is nothing blocking the valve (ice, etc.).
Heaters	• Test with a thermal camera that the temperature increases when power is applied.	• Check heater powering.
Control valves	• Test with pressure inside. After opening the valve the pressure on both sides should equalize. • Observe the movement of the handle/indicator.	• Check valve powering. • Make sure there is nothing blocking the valve.
Control valves for water cooling	• Observe the movement of the handle/indicator. • Test with water circuit connected and observe the changes on the temperature sensors on the inlet and outlet.	• Check valve powering. • Make sure there is nothing blocking the valve. • Check that water cooling is available.
Air-cooled gas coolers	• Activate gas cooler and observe fan movement.	• Check fan powering.
Compressors	• Activate the compressor and observe the pressure at the outlet increase.	• Check inverter configuration. • Check compressor powering.

13.2 Calculated variable and logic check

In addition to ensuring that the input and output signals are correct, it is also necessary to check that all the internal calculations and logic within the PLC behave as they should. The calculated variables are analog input real values, and the controllers fall under the regulation section of the system commissioning file.

13.2.1 Analog input real test procedure

There are several common calculations which are used throughout the system, but there are also many calculations that are more complex and specific to one actuator, variable or subsystem. The general method for testing these calculations is to change the values of the input parameters and check if the value calculated in the PLC matches the value calculated externally (whether by hand or using a different software). This requires close reference to the functional analysis to ensure that the calculation and its behaviour is fully understood and thoroughly tested. However, there are also many simple calculations that are repeated throughout the system. These have been summarised in Table 17 along with a simple description on their test procedure.

Table 17: Testing procedure and troubleshooting methods for common AIR calculations

Calculation type	Test procedure
Saturation temperature	• Use standard, known values for CO_2. Two such pairs are: - PT=10 bar, ST=-40.1°C - PT=60 bar, ST=22°C
Superheating	• Superheating = temperature – saturation temperature
Subcooling	• Subcooling = saturation temperature – temperature
Differential pressure	• $DP = PT_1 - PT_2$
Transcritical pressure	• TP = PT – 73.8 bar
Timers	• Check the time increments and ensure that the value of the timer corresponds to the amount of time elapsed • Check that the reset function successfully resets the timer to zero
Counters	• Check that the counter increments every time the input condition is triggered • Check that the counter decrements after the designated amount of time has passed • Check that the counter is reset to zero with the reset function

13.2.2 Regulations test procedure

Regulations are tested by forcing the measured value above and below the set point and observing that the control action behaves as expected. For example, with PC5004, the accumulator pressure PT5004 is forced above the set point (5.5 MPa) and the flash gas valve CV5110 should open. When PT5004 is forced below the set point, CV5110 should close.

13.3 Alarms test

Alarms are used to indicate when the system is functioning in an unexpected or dangerous manner. Depending on the severity and impact of the behaviour, the corresponding alarm can have different actions.

Warning – alerts the operator to the issue. No action is taken automatically by the system. It is up to the operator to investigate the issue and respond if appropriate or necessary.

Full stop interlock – forces the PCO and all children PCOs to full stop position. The operator needs to acknowledge the alarm and allow restart before the PCO can move out of its full-stop state.

Start interlock – stops the PCO and prevents it from starting until the alarm causing the start interlock is removed.

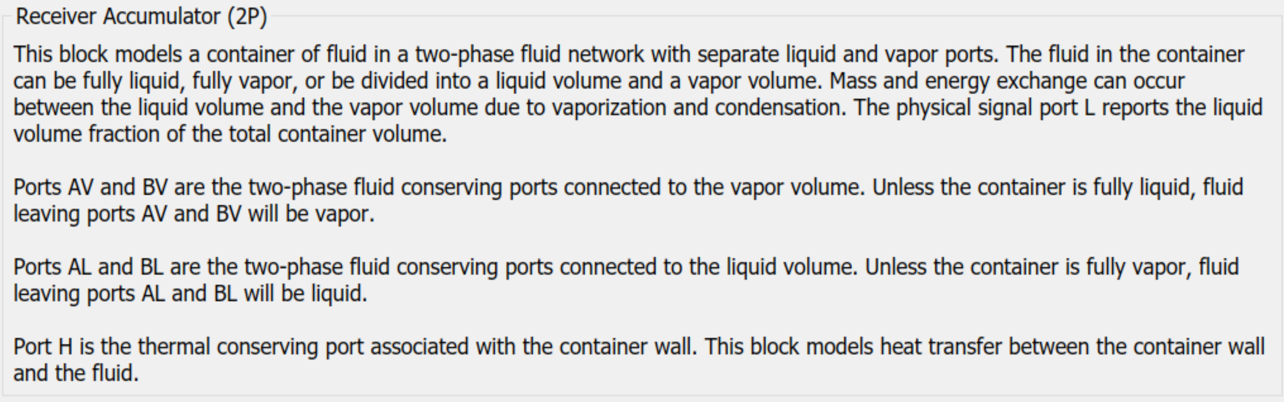
For each alarm in the system, the triggering conditions are simulated (either by forcing a value in the PLC or manipulating the physical system) and the alarm activation and action is observed. The alarm signal should be activated in the PLC and the correct actuators or PCOs should respond accordingly (displaying a warning or moving to the safety position depending on the alarm type).

14. Appendix D – Actuator and component model details

This appendix includes more detail relating to how the components and actuators have been modelled.

14.1 Accumulator Model

The accumulator model block is a standard 2 phase Simulink block. It has 2 inlet ports and 2 outlet ports for liquid and vapor flow. The block description is given in Figure 28 below.



Receiver Accumulator (2P)

This block models a container of fluid in a two-phase fluid network with separate liquid and vapor ports. The fluid in the container can be fully liquid, fully vapor, or be divided into a liquid volume and a vapor volume. Mass and energy exchange can occur between the liquid volume and the vapor volume due to vaporization and condensation. The physical signal port L reports the liquid volume fraction of the total container volume.

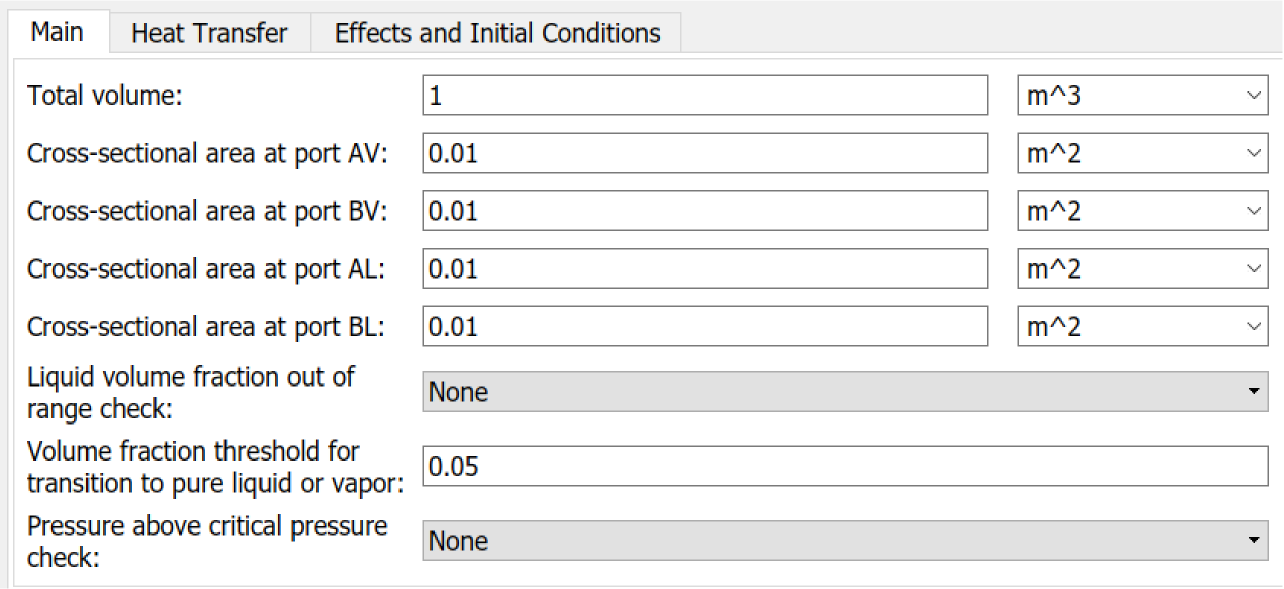
Ports AV and BV are the two-phase fluid conserving ports connected to the vapor volume. Unless the container is fully liquid, fluid leaving ports AV and BV will be vapor.

Ports AL and BL are the two-phase fluid conserving ports connected to the liquid volume. Unless the container is fully vapor, fluid leaving ports AL and BL will be liquid.

Port H is the thermal conserving port associated with the container wall. This block models heat transfer between the container wall and the fluid.

Figure 28: Accumulator block description

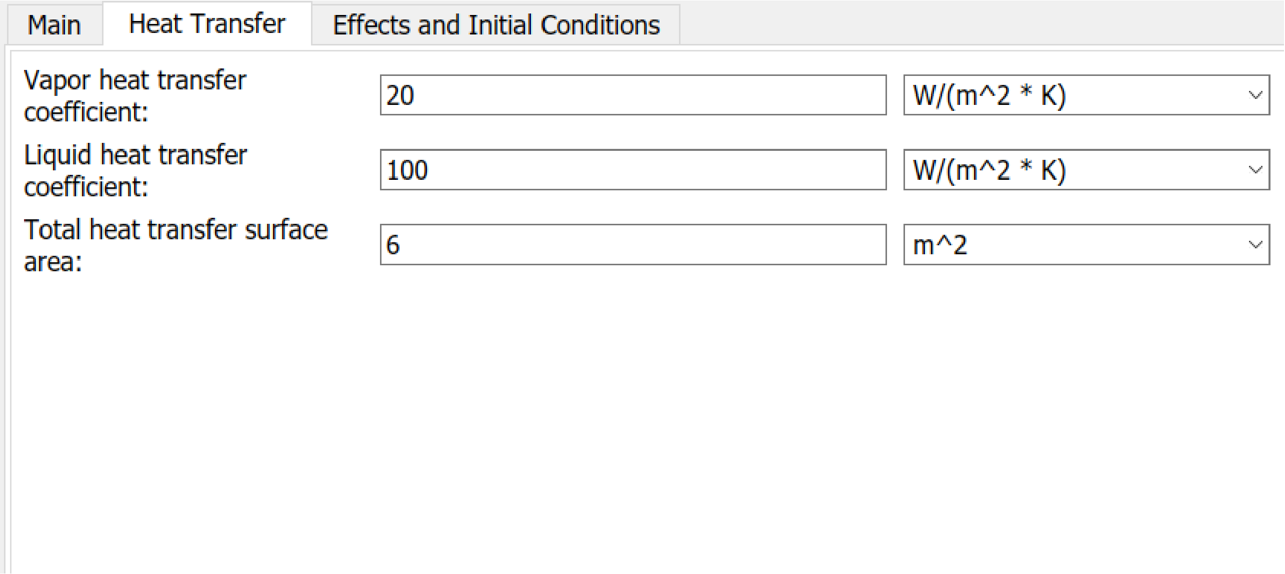
The main parameters, shown in Figure 29, describe the size of the vessel as well as the dimensions for the inlet and outlet piping.



Total volume: 1 m^3
Cross-sectional area at port AV: 0.01 m^2
Cross-sectional area at port BV: 0.01 m^2
Cross-sectional area at port AL: 0.01 m^2
Cross-sectional area at port BL: 0.01 m^2
Liquid volume fraction out of range check: None
Volume fraction threshold for transition to pure liquid or vapor: 0.05
Pressure above critical pressure check: None

Figure 29: Accumulator block main parameters

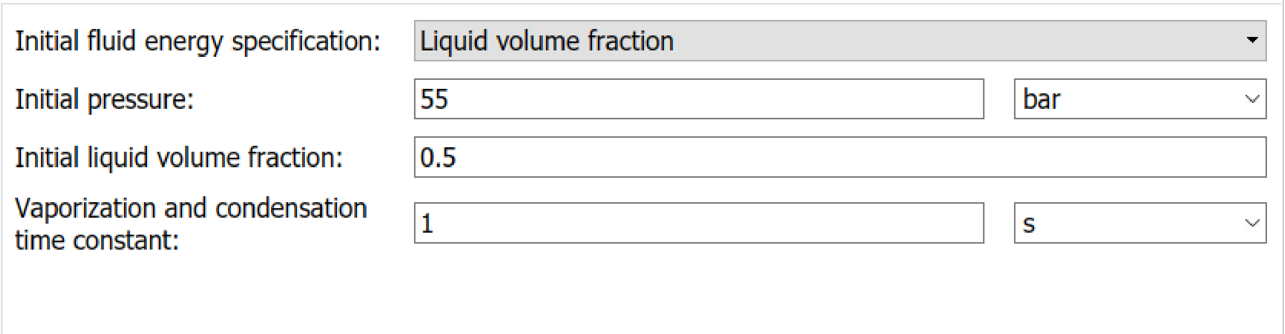
In Figure 30 there are the accumulator parameters related to heat transfer. These include the heat transfer coefficients of the liquid and gas components as well as the surface area between them. In this case, it would be the cross-sectional area of the vessel since the liquid sits at the bottom and the gas on top.



Vapor heat transfer coefficient:	20	W/(m^2 * K)
Liquid heat transfer coefficient:	100	W/(m^2 * K)
Total heat transfer surface area:	6	m^2

Figure 30: Accumulator block heat transfer parameters

The final accumulator parameters define the initial conditions of the unit. These are shown in Figure 31 below.



Initial fluid energy specification:	Liquid volume fraction	
Initial pressure:	55	bar
Initial liquid volume fraction:	0.5	
Vaporization and condensation time constant:	1	s

Figure 31: Accumulator block effects and initial conditions

14.2 Compressor Model

The compressor model is made up of a controlled mass flow rate source connected to the compressor map and frequency input. This is shown below in Figure 32.

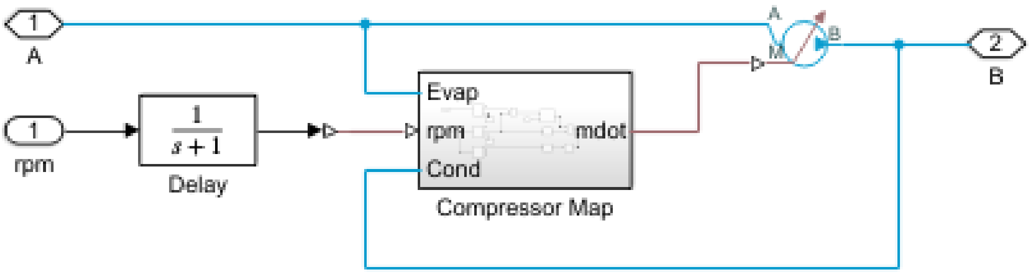
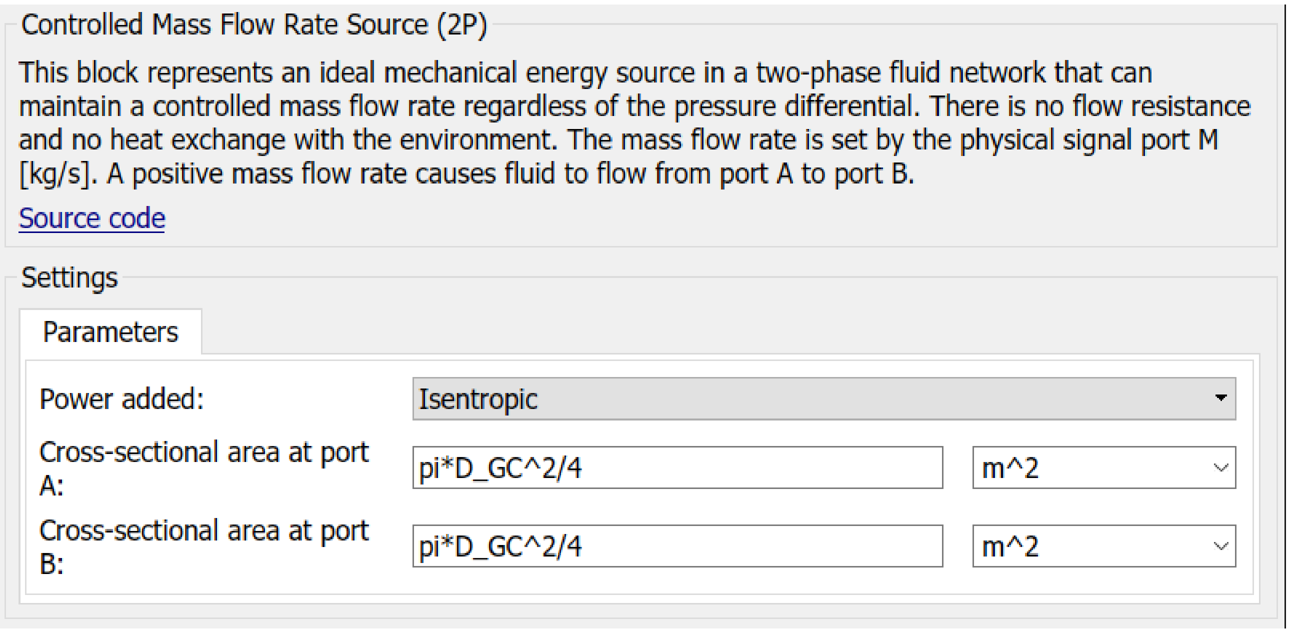


Figure 32: Compressor block model

The controlled mass flow rate source is a standard Simulink block which provides a specified mass flow rate depending on the block's input signal. The description and parameters of this block are seen in Figure 33. This block requires the cross-sectional area of the inlet and outlet ports be specified.



Controlled Mass Flow Rate Source (2P)

This block represents an ideal mechanical energy source in a two-phase fluid network that can maintain a controlled mass flow rate regardless of the pressure differential. There is no flow resistance and no heat exchange with the environment. The mass flow rate is set by the physical signal port M [kg/s]. A positive mass flow rate causes fluid to flow from port A to port B.

Source code

Settings

Parameters

Power added:	Isentropic	
Cross-sectional area at port A:	pi*D_GC^2/4	m^2
Cross-sectional area at port B:	pi*D_GC^2/4	m^2

Figure 33: Controlled mass flow rate source block

The compressor map determines the mass flow rate of the compressor, which is sent to the input of the controlled mass flow rate source. This mass flow rate reads in the pressure at the outlet of the compressor and the temperature and pressure at the inlet. This information is used with the compressor map lookup table (specific to each individual compressor) to determine the mass flow rate. This is illustrated in Figure 34 below.

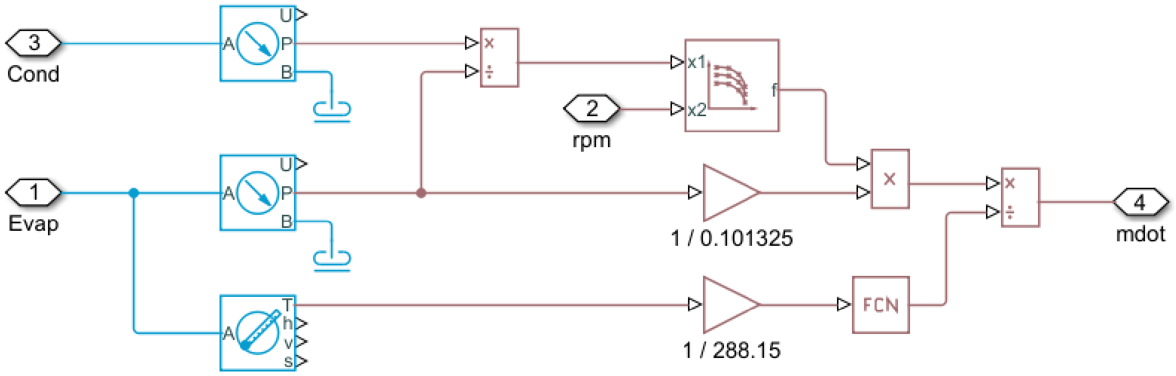
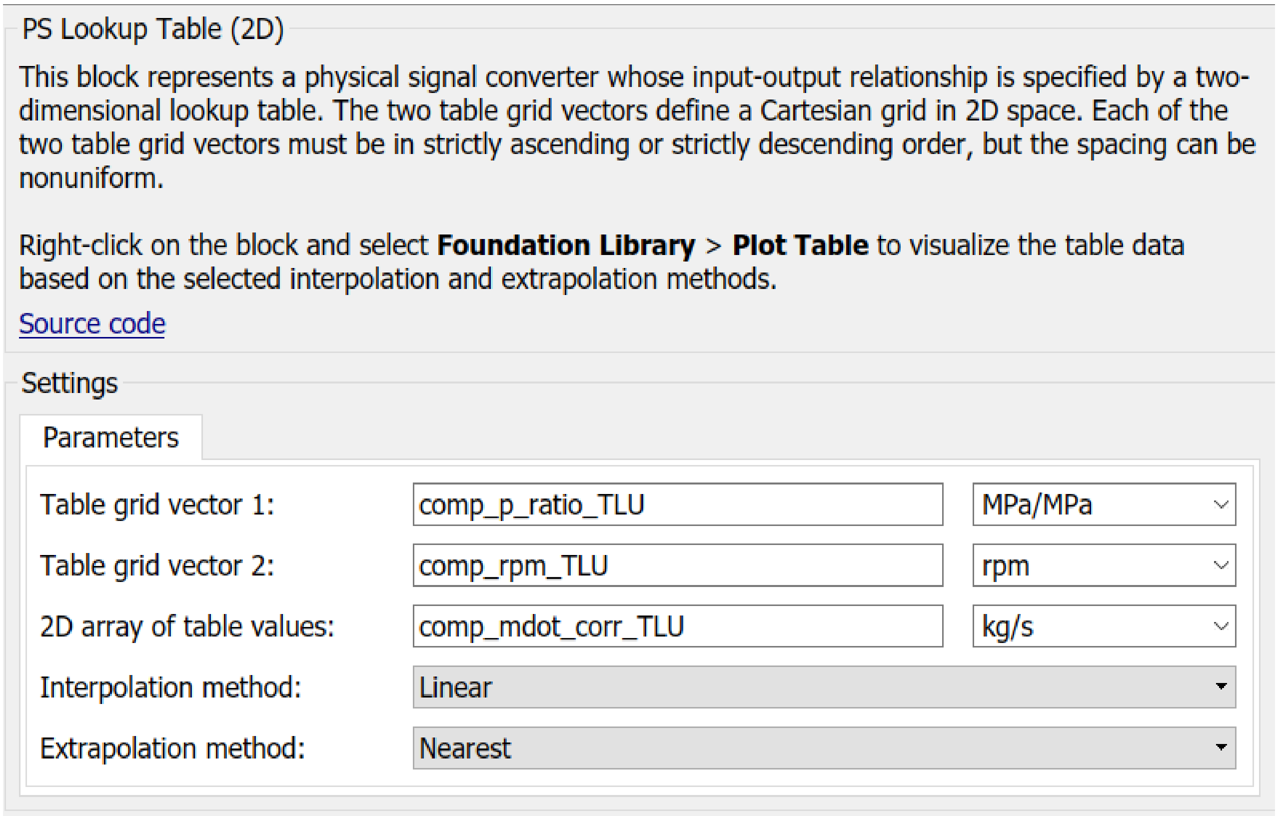


Figure 34: Compressor map block

The compressor map of each compressor is specified in a look up table that is read in by the Simulink PS Lookup Table block shown in Figure 35.



PS Lookup Table (2D)

This block represents a physical signal converter whose input-output relationship is specified by a two-dimensional lookup table. The two table grid vectors define a Cartesian grid in 2D space. Each of the two table grid vectors must be in strictly ascending or strictly descending order, but the spacing can be nonuniform.

Right-click on the block and select **Foundation Library** > **Plot Table** to visualize the table data based on the selected interpolation and extrapolation methods.

Source code

Settings

Parameters

Table grid vector 1: comp_p_ratio_TLU MPa/MPa

Table grid vector 2: comp_rpm_TLU rpm

2D array of table values: comp_mdot_corr_TLU kg/s

Interpolation method: Linear

Extrapolation method: Nearest

Figure 35: Simulink standard PS lookup table block

14.3 Valve Model

The valve model consists of a flow restriction and function block which calculates the restriction area based on the valve opening percent. The block is shown in Figure 36 below.

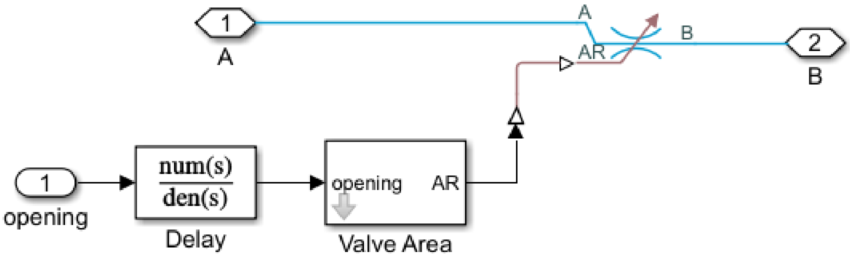


Figure 36: Valve model block

The position request (port 1: 'opening') is first put through a transfer function of $\frac{1}{0.1s+1}$ which introduces a 0.5 second delay to opening steps. This delay models the response time of the valve actuator. The calculation of the valve restriction area takes the opening percentage to be a percentage of the total valve diameter. This then calculates the cross-sectional area, to a maximum of 90% diameter to account for the fact that even a fully open valve introduces some restriction. This function block is shown in Figure 37.

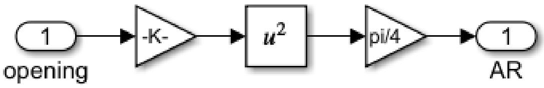
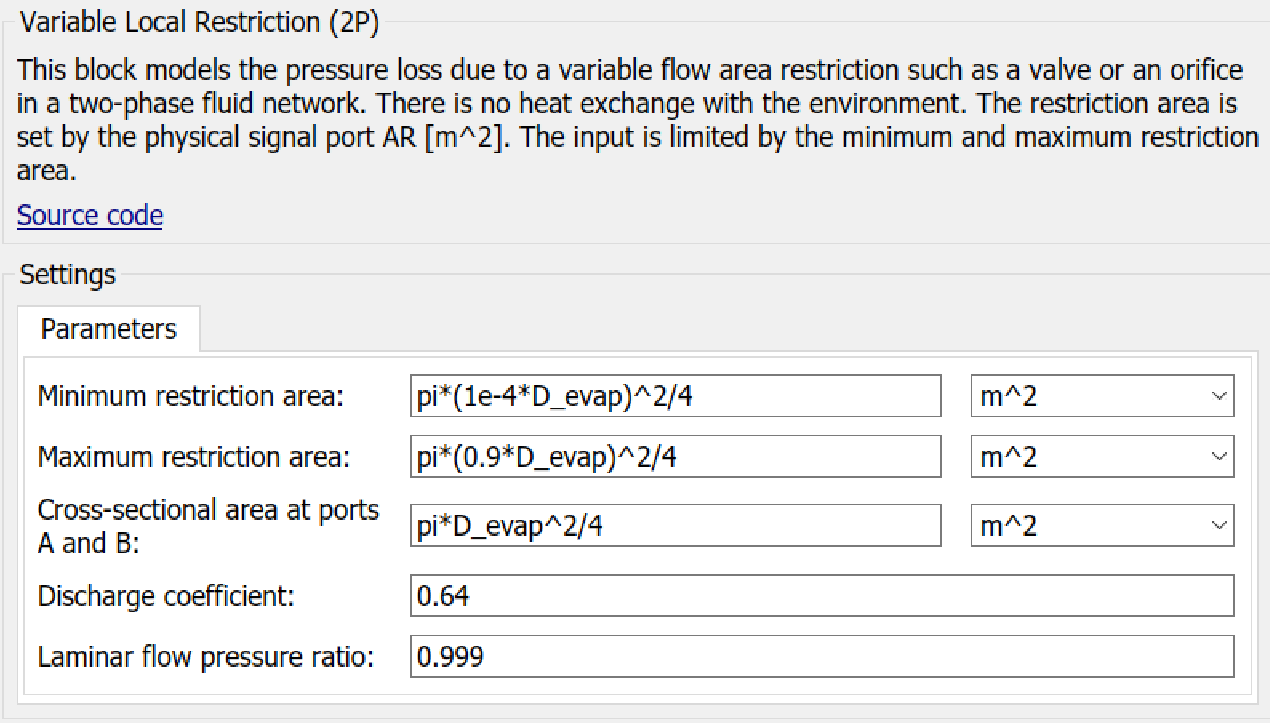


Figure 37: Valve area calculation function block

The valve area is then fed to the flow restriction block which is a standard Simulink block. This block models the pressure drop based on a given restriction area. A detailed look at this model block can be seen in Figure 38.


Variable Local Restriction (2P)

This block models the pressure loss due to a variable flow area restriction such as a valve or an orifice in a two-phase fluid network. There is no heat exchange with the environment. The restriction area is set by the physical signal port AR [m^2]. The input is limited by the minimum and maximum restriction area.

Source code

Settings

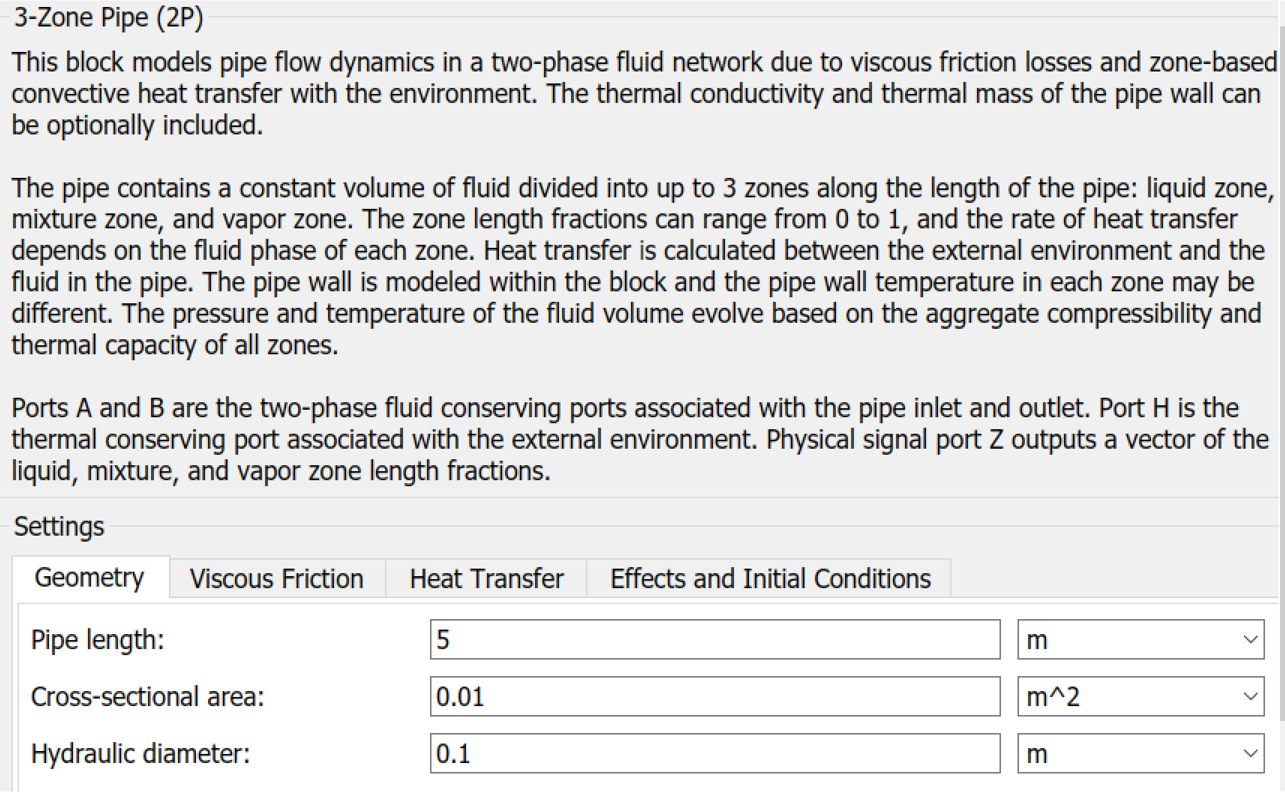
Parameters

Minimum restriction area:	pi*(1e-4*D_evap)^2/4	m^2
Maximum restriction area:	pi*(0.9*D_evap)^2/4	m^2
Cross-sectional area at ports A and B:	pi*D_evap^2/4	m^2
Discharge coefficient:	0.64	
Laminar flow pressure ratio:	0.999	

Figure 38: Simulink standard variable local restriction block

14.4 Pipe Model

Simulink has a standard 3-zone pipe block for 2 phase fluids. It models the dynamics of the 2-phase flow through a pipe of specified diameter and length with the option of modelling heat transfer with the environment. Its description and some of its parameters are included in Figure 39.


3-Zone Pipe (2P)

This block models pipe flow dynamics in a two-phase fluid network due to viscous friction losses and zone-based convective heat transfer with the environment. The thermal conductivity and thermal mass of the pipe wall can be optionally included.

The pipe contains a constant volume of fluid divided into up to 3 zones along the length of the pipe: liquid zone, mixture zone, and vapor zone. The zone length fractions can range from 0 to 1, and the rate of heat transfer depends on the fluid phase of each zone. Heat transfer is calculated between the external environment and the fluid in the pipe. The pipe wall is modeled within the block and the pipe wall temperature in each zone may be different. The pressure and temperature of the fluid volume evolve based on the aggregate compressibility and thermal capacity of all zones.

Ports A and B are the two-phase fluid conserving ports associated with the pipe inlet and outlet. Port H is the thermal conserving port associated with the external environment. Physical signal port Z outputs a vector of the liquid, mixture, and vapor zone length fractions.

Settings

Pipe length: 5 m

Cross-sectional area: 0.01 m^2

Hydraulic diameter: 0.1 m

Figure 39: Simulink standard 3-zone pipe block

14.5 Heat Exchanger Model

The heat exchanger is modelled as 2 separated piped with heat transfer between them. This is depicted in Figure 40. It makes use of the 3-zone pipe described in Section 14.4.

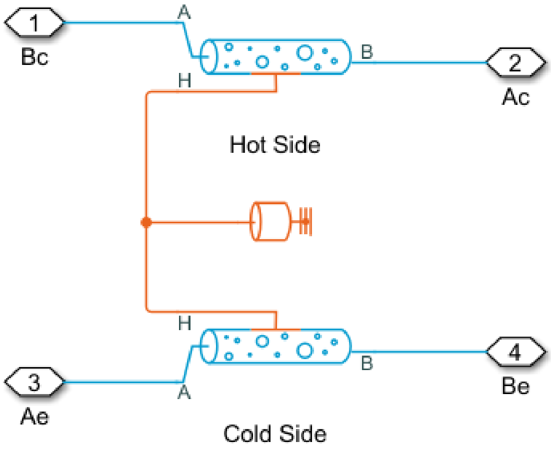
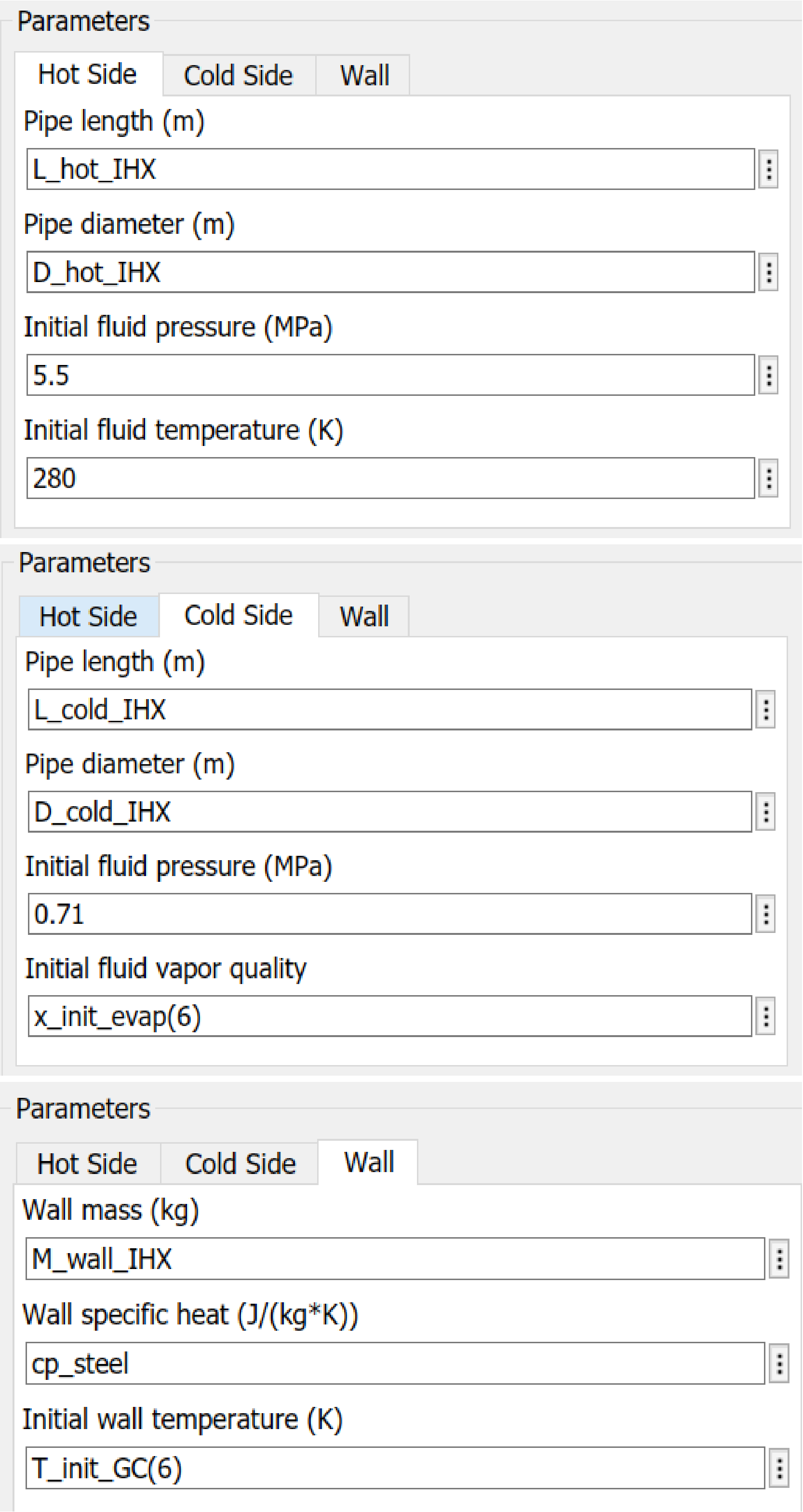


Figure 40: Heat exchanger model

This block requires information about the piping geometry as well as the heat transfer properties of the piping walls. The parameters required are shown in Figure 41.



Pipe length (m): L_hot_IHX

Pipe diameter (m): D_hot_IHX

Initial fluid pressure (MPa): 5.5

Initial fluid temperature (K): 280

Pipe length (m): L_cold_IHX

Pipe diameter (m): D_cold_IHX

Initial fluid pressure (MPa): 0.71

Initial fluid vapor quality: x_init_evap(6)

Wall mass (kg): M_wall_IHX

Wall specific heat (J/(kg*K)): cp_steel

Initial wall temperature (K): T_init_GC(6)

Figure 41: Heat exchanger model parameters

14.6 Gas Cooler Model

The gas cooler is made up of a series of 3-zone pipes with heat exchange through convection with an external source. In the case of the air-cooled gas cooler, the heat source is the environment. In the case of the water-cooled gas cooler, the external heat source is the water-cooling system (modelled as a constant temperature for simplicity). This model is illustrated in Figure 42 below.

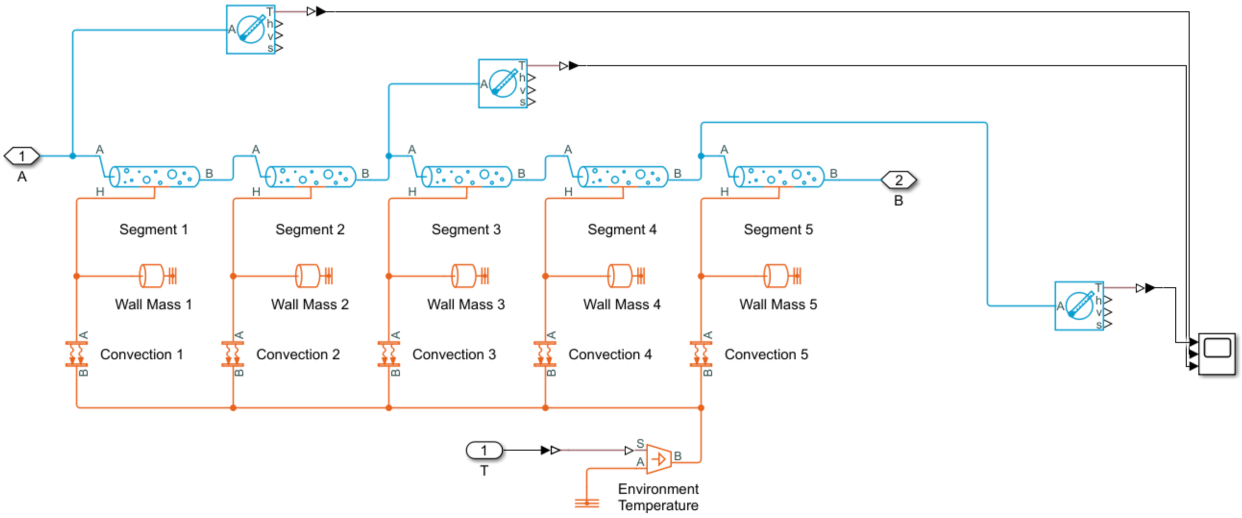
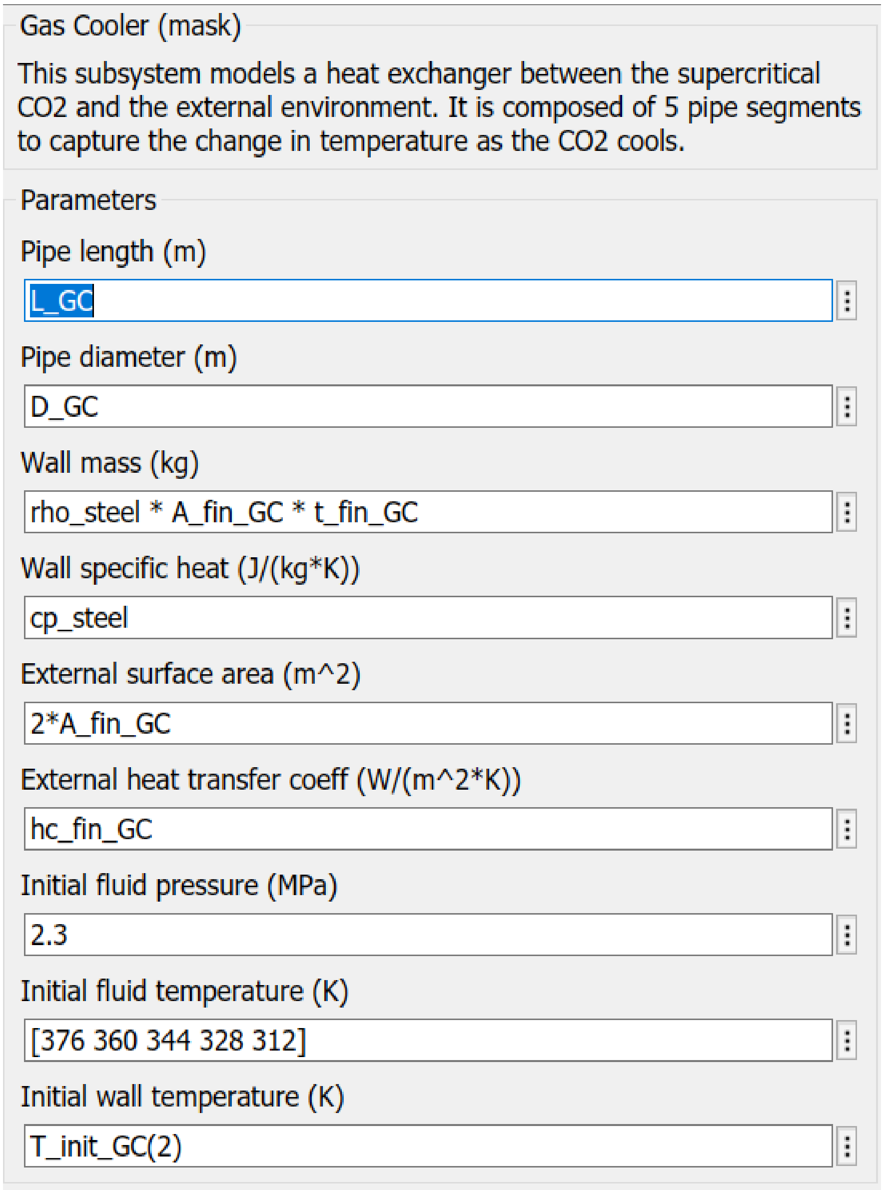


Figure 42: Gas cooler model

The gas cooler block requires a number of values to be specified such as the pipe length, pipe diameter, the temperature and pressure of the fluid, as well as the heat transfer properties of the pipe walls. These parameters are shown in more detail in Figure 43.



Gas Cooler (mask)

This subsystem models a heat exchanger between the supercritical CO2 and the external environment. It is composed of 5 pipe segments to capture the change in temperature as the CO2 cools.

Parameters

Pipe length (m)

L_GC

Pipe diameter (m)

D_GC

Wall mass (kg)

rho_steel * A_fin_GC * t_fin_GC

Wall specific heat (J/(kg*K))

cp_steel

External surface area (m^2)

2*A_fin_GC

External heat transfer coeff (W/(m^2*K))

hc_fin_GC

Initial fluid pressure (MPa)

2.3

Initial fluid temperature (K)

[376 360 344 328 312]

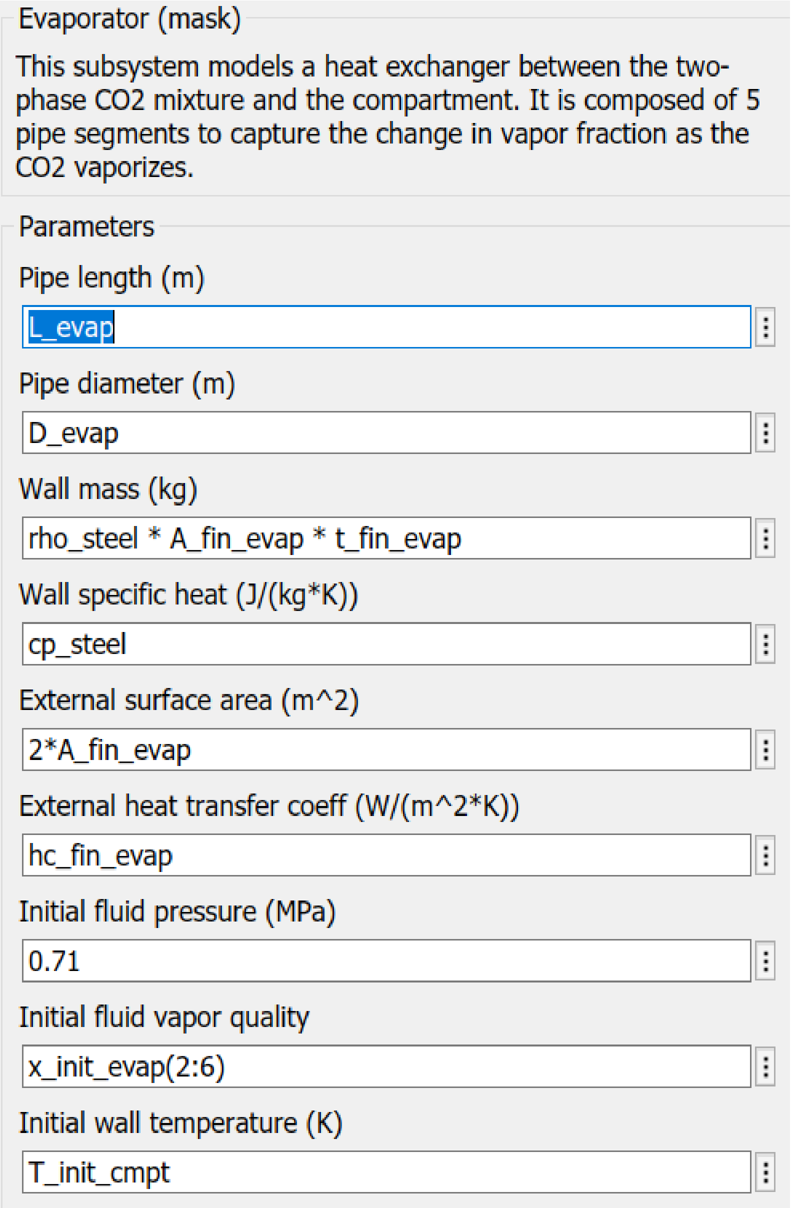
Initial wall temperature (K)

T_init_GC(2)

Figure 43: Gas cooler model parameters

14.7 Evaporator

The evaporator is modelled much like a gas cooler with the heat exchange between the piping and the system load. Figure 44 shows the description of the evaporator block along with its parameters which are much the same as those of the gas cooler.



Evaporator (mask)

This subsystem models a heat exchanger between the two-phase CO2 mixture and the compartment. It is composed of 5 pipe segments to capture the change in vapor fraction as the CO2 vaporizes.

Parameters

Pipe length (m): L_evap

Pipe diameter (m): D_evap

Wall mass (kg): rho_steel * A_fin_evap * t_fin_evap

Wall specific heat (J/(kg*K)): cp_steel

External surface area (m^2): 2*A_fin_evap

External heat transfer coeff (W/(m^2*K)): hc_fin_evap

Initial fluid pressure (MPa): 0.71

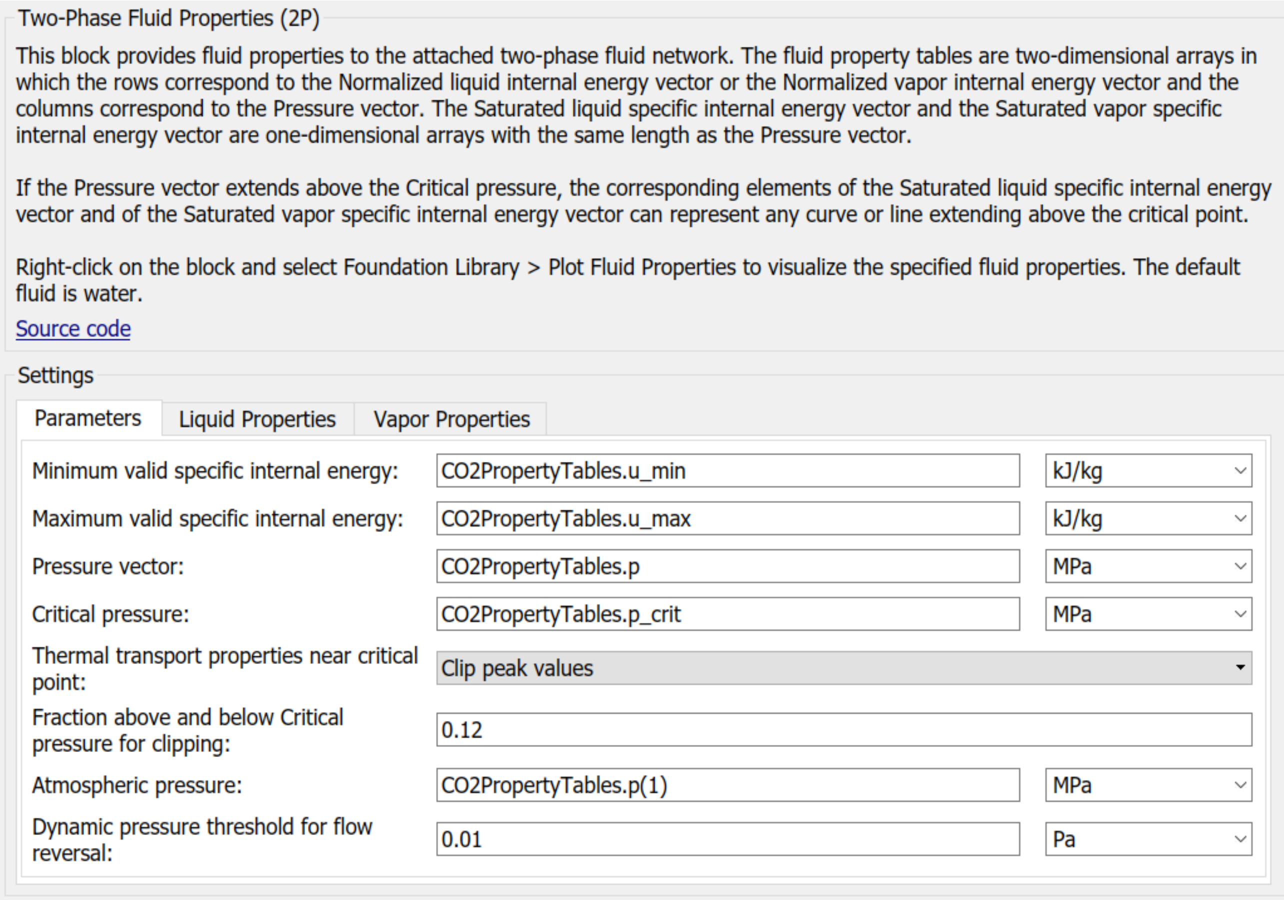
Initial fluid vapor quality: x_init_evap(2:6)

Initial wall temperature (K): T_init_cmpt

Figure 44: Evaporator model parameters

14.8 Fluid Property Model

Finally, but arguably most importantly, is the model of the 2-phase fluid properties. Simulink has a standard fluid properties block which reads in data such as the critical temperature, the critical pressure, the saturation curve as well as a lookup table of temperature, pressure and specific internal energy. The block's description and some of the block properties are seen in Figure 45 below.


Two-Phase Fluid Properties (2P)

This block provides fluid properties to the attached two-phase fluid network. The fluid property tables are two-dimensional arrays in which the rows correspond to the Normalized liquid internal energy vector or the Normalized vapor internal energy vector and the columns correspond to the Pressure vector. The Saturated liquid specific internal energy vector and the Saturated vapor specific internal energy vector are one-dimensional arrays with the same length as the Pressure vector.

If the Pressure vector extends above the Critical pressure, the corresponding elements of the Saturated liquid specific internal energy vector and of the Saturated vapor specific internal energy vector can represent any curve or line extending above the critical point.

Right-click on the block and select Foundation Library > Plot Fluid Properties to visualize the specified fluid properties. The default fluid is water.

Source code

Settings

Minimum valid specific internal energy:	CO2PropertyTables.u_min	kJ/kg
Maximum valid specific internal energy:	CO2PropertyTables.u_max	kJ/kg
Pressure vector:	CO2PropertyTables.p	MPa
Critical pressure:	CO2PropertyTables.p_crit	MPa
Thermal transport properties near critical point:	Clip peak values	
Fraction above and below Critical pressure for clipping:	0.12	
Atmospheric pressure:	CO2PropertyTables.p(1)	MPa
Dynamic pressure threshold for flow reversal:	0.01	Pa

Figure 45: Simulink standard 2-phase fluid properties block