Abstract

This project consists of the development and validation of a numerical model to simulate transient responses of the ALBA's synchrotron cooling system. In particular, the work aims at studying the pumping system start-up and stop in order to detect possible problems that can lead to piping failures.

The project focus on the hydrodynamic response of the cooling system, which is part of the activities integrated in a stability and reliability plan promoted by CELLS (Consortium for the Exploitation of the Synchrotron Light Laboratory).

Flowmaster® is the 1D thermo-fluid simulation software that has been used to model the cooling system to detect dangerous pressure peaks and flow oscillations when operation conditions of the pumping stations are suddenly changed.

The first part of this project has been involved in learning and familiarizing with Flowmaster® program in order to perform correctly the simulations. Simple models have been designed to understand and learn the properties and the response influence of the components and model set-up.

The second part has involved the simulations of the actual cooling system. A model available from preliminary studies has been modified to take into account compressibility effects by replacing and adding the adequate components. In addition, it has also been necessary to create scripts and to introduce and make changes in the PID controllers in order to simulate the real ALBA synchrotron pumping system startup/stop procedures.

The normal start-up maneuver of the pumping system has been simulated and the fluid dynamic response has been analyzed. The results indicate the generation of significant pressure rises. To mitigate them, changes to the PID controller parameters have been proposed that improve the transient behavior reducing such peaks.

The simulation and analysis of pumps' shutdowns due to unexpected failures has served to identify the consequences on the system behavior and to prevent possible life-reduction conditions. The calculations have been carried out without and with simultaneous thermal regulation. For example, the results indicate that when the thermal regulation is on the consequences of the simultaneous shut-down of all pumps are mitigated.

Finally, the effect of air in the pipes has been analyzed during a pump shut-down and it has been confirmed that the transient pressure fluctuations predicted in the system are modified.

Summary

ETSEIB

1. Glossary

BL: Beam Lines

BO: Booster Ring

CELLS: Consortium for the Exploitation of the Synchrotron Light Laboratory.

CFD: Computational Fluid Dynamics

D02: Accumulator.

D03: Pneumatex

EA: Experimental Area

EX07: Heat exchanger

PID: Proportional-integrative-derivative controller

P07: Experimental Area pumping system

P08: Storage Ring pumping system

P09: Booster Ring pumping system.

P10: Service Area pumping system.

P11: Pumping system that brings the heated water to the heat exchangers.

PEM: It is the Budget of Material Execution. In Catalan, stand for "*Pressupost d'Execució Material"*.

PEC: It is the Contracted Operation Budget. In Catalan, stands for "*Pressupost d'Execució per contracte*".

SA: Service Area

SR: Storage Ring.

$V3V_{D02}$: Three-way valve connected to the accumulator.

$V3V_{P07}$: Three way valves of the pumping ring P07

$V3V_{P08}$: Three way valves of the pumping ring P08

$V3V_{P09}$: Three way valves of the pumping ring P09

$V3V_{P10}$: Three way valves of the pumping ring P10

2. Preface

2.1. Origin of the project

CELLS (Consortium for the Exploitation of the Synchrotron Light Laboratory) is in implementation state of a transversal project whose objective is to develop and improve the piping system that compound the ALBA's synchrotron cooling system. It is aimed at improving the reliability and stability at the following points:

- More protection against occasional failures.
- More robustness when flow rate changes.

The activities that have been taking part of this project can be organized in three groups:

1. Understanding about fluid dynamics and cooling system's thermal control.
2. Insertion of new components in the system that can reduce pressure peaks, oscillations and cavitation.
3. A more exhaustive control of the system to protect the components and reduce the reaction time when the system is down due to a failure.

2.2. Motivation

Firstly, the willingness and ambition to learn deeper in Fluid mechanics and thermodynamics while using the theoretical concepts learned at class and during this project in order to analyze real system simulations and provide solid conclusions.

Moreover, the possibility to carry out a project about one of the most advanced technical buildings in Europe and the curiosity to know more about the technology and its building making it a very interesting project.

It is expected to visit the building when the project has finalized.

2.3. Previous requirements

As a common project requirements, the objectives and ideas must be clearly identified. Some concepts and ideas about how to proceed are also helpful. Furthermore, theoretical part must be analyzed and understood in order to move to further chapters, such as building the model and simulating it.

In this project, the knowledge of the basic differential equations that hold Fluid Mechanics field is fundamental. The fluid interaction with piping components makes also the knowledge of the components, such as pumps, valves and pipes, very valuable.

As the performance of these components will be simulated at a big level of complexity due to the high number of components, therefore, it is also important to know how some components will react when they are operating. Moreover, having an idea about some of the fluidic dynamic situations (such as; water hammer, pressure peak, how pumps work in parallel, etc) that take place in piping systems are a great deal.

A knowledge of the program to be used, in this case is Flowmaster. The program simulates the events which later may need to be analyzed and comprehended, and not to forget, the creation of the model is only possible when the user knows exactly what can be made with the program.

3. Introduction

3.1. Objectives of the project

The main objective of this project is to study the start-up and stop of any pump device in the cooling system and detect if pressure variations created in transient events may lead to failures and piping components' deterioration.

It is intended to determine if normal procedure and unexpected events may lead the system to experience phenomena such as water hammer or pressure peaks. This study aims at simulating and analyzing the following transient events:

- Start-up of the cooling system (without thermal exchange).
- Unexpected stop of the cooling system (without thermal exchange).
- Unexpected stop of the cooling system (with thermal exchange).
- Stoppage of all pumps simultaneously (without thermal exchange)

To finish, it will be investigated if the presence of air in the pipes has an effect on the pressure transients by setting accumulators in strategic places.

3.2. Scope of the project

In order to achieve the results mentioned in the last chapter, different fluid models will be designed for each simulation situation. Thermic and dynamic flow fields are studied by unidimensional numeric simulations.

On the one hand, the unexpected pump stop may happen when the synchrotron's electromagnets are accelerating the particles, which means there is a thermal exchange in the cooling system and heat transfer transient simulations are required. On the other hand, when electromagnets are not working, the study without thermal exchange can be assumed.

For the different situations studied, pressure evolution will be the principal parameter analyzed as this bachelor's thesis aims at solving piping problems related to pressure change situations.

Flowmaster V7.9.0 is the tool used to model and simulate. This program reduces significantly the time and processing power required in other simulations such as CFD (Computational Fluid

Dynamics) due to the dimension of the system studied.

4. ALBA synchrotron

ALBA is a third generation Synchrotron Light facility located in Cerdanyola del Vallès. The complex is one of the twenty facilities of this type in Europe and the newest source in the Mediterranean area. It was funded in equal parts by the Spanish and the Catalonian Administration and it is managed by the Consortium for the Construction, Equipping and Exploitation of the Synchrotron Light Source (CELLS).

It is a 22870 m^2 complex of electron accelerators to produce synchrotron light, which allows the visualization of the atomic structure of matter, as well as, the study of its properties. Electrons are accelerated until a velocity which is close to the light speed, with an energy of 3 GeV and electromagnetic radiation waves, which is called synchrotron light, are emitted [2]. Alba functions as a giant microscope which allows discovering structures of matter at atomic and molecular level. The properties of the light generated allow it to penetrate into matter in an extremely selective manner, making it easier to analyze molecules and other materials.

The objective is to research, deliver and maintain methods in such a way that knowledge and added value data are pumped into the scientific and industrial communities. The goal is to contribute to the improvement in the well-being and progress of society as a whole.

Figure 4.1 ALBA's synchrotron from the air

4.1. Description of the facilities

As it can be inferred from the image below, the four principal buildings perceived are the followings: technical building, main building, offices and mechanical workshop.

The last two buildings, offices and mechanical workshop, have an important functionality in the ALBA's complex but the project is not related to them. Consequently, they will not be further discussed.

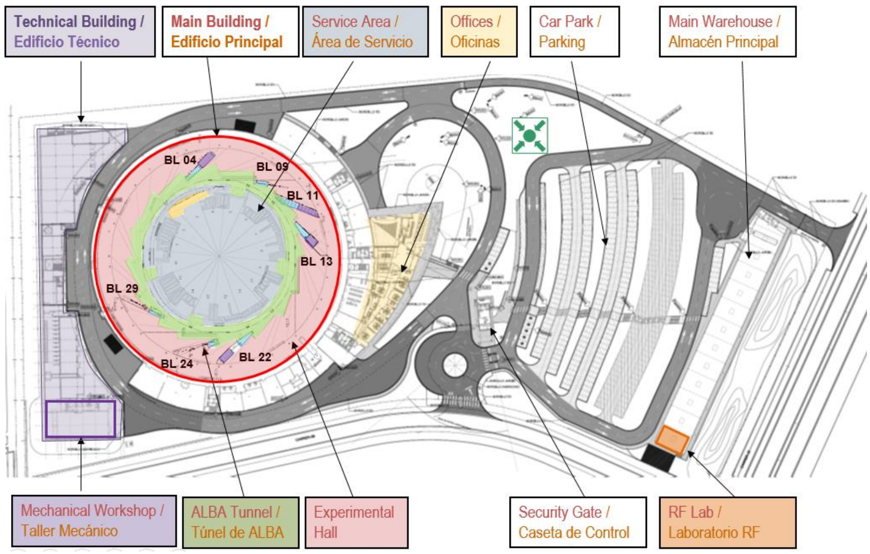


Figure 4.2 Description of the different buildings [3].

4.1.1. The main building

Within its 140 m of diameter, it holds the most relevant an important elements of the installation. The lineal accelerator accelerates in a low pressure conduit and accelerates to 100 MeV, using electric fields. Electrons are lead to the circular accelerator called Booster Ring, by a Transfer Line [4]. The Booster Ring, with its 250 m perimeter, accelerates electrons to 3 GeV using electromagnetic fields and introduce them into the Storage Ring.

In the Storage Ring, the electrons move at a constant speed and energy rate. The perimeter is 269 m and electromagnets control the direction of the particles. Inside the ring, the pressure is extremely low in order to avoid electrons changing its direction when colliding. The synchrotron light is created when the magnetic field changes the electron's direction. The light reaches Experimental Stations or Beam Lines through *Front Ends*, tangential openings, and a wall that separates the accelerator facilities to the other buildings.

The beam lines are made of steel and once the light arrives in the line, the wavelength must be selected in order to proceed with the testing and experimentation. The beam lines that are operating in ALBA synchrotron are explained in the Annex, section A.

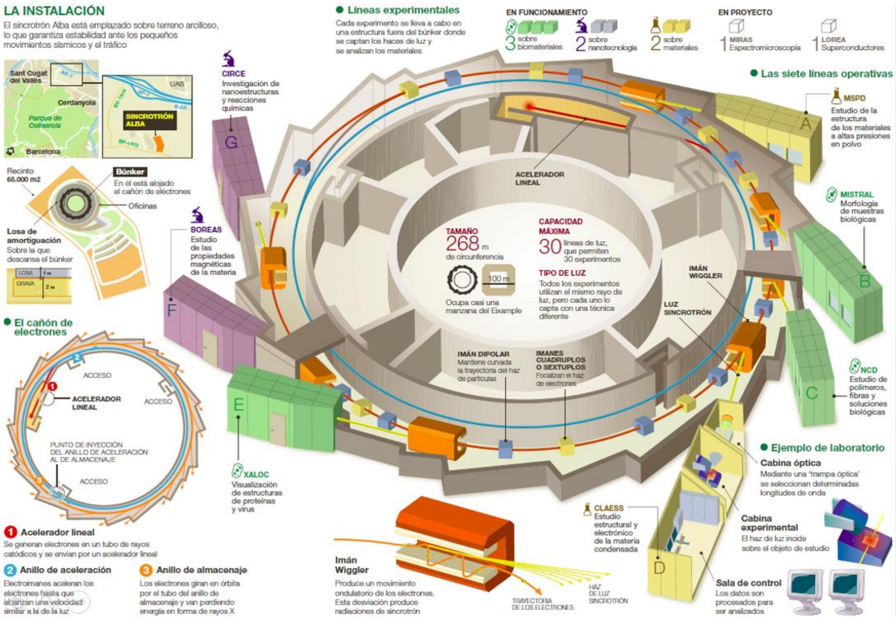


Figure 4.3 Squematic view of ALBA synchrotron

4.1.2. The technical building

The control and distribution of thermal energy is done in this building. There are few pipe installations that guarantee the distribution of cold and hot water. In order to control and regulate the temperature inside the office during summer and winter, water is set to 7 ± 0,5 ºC during summer and 50 ± 1 ºC during winter.

Deionized water, controlled at 23 ± 0,2 ºC, is used to refrigerate the magnets and rings of the facility. The water needs to be treated through softening and reverse osmosis. The subject of study of this project will be this piping system in order to detect and prevent possible damages to the piping system, and specially, in pipes and pumps [1].

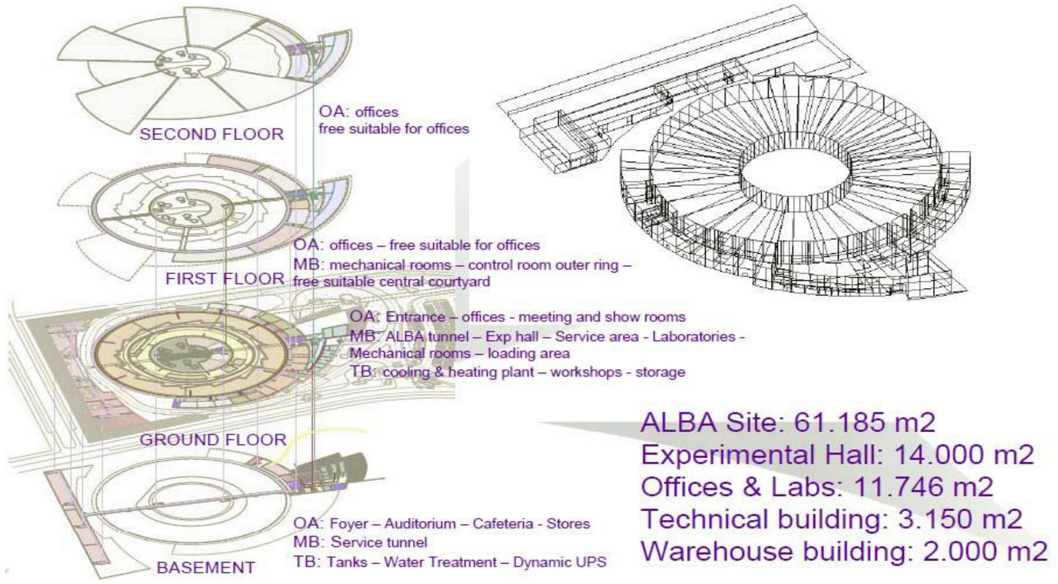


Figure 4.4 Division of the different floors [1]

5. Description of the ALBA cooling system

5.1. Functionality of the lines

The ALBA cooling system is formed by the piping installation that refrigerates the four rings. As it is previously stated, the rings are named Experimental Area (EA, group P07), Service Area (SA, group P10), Storage Ring (SR, group P08), and Booster Ring (BO, group P09).

Both the Storage and the Service Area rings operate with a pair of twin-pumps mounted in parallel and the rest with a single pump. Each pump is controlled by feedback controllers, such as PID and the rotational speed is regulated in order to guarantee a stable and controlled pressure in each piping line and avoid to reach pressures that can damage any components of the installation.

The cooling occurs after the deionized water is heated thorough the rings (consumption side, see Figure 5.1). Then, the water is collected in a common return line. In order to regulate the temperature of the water, part of the heated flow can be suctioned again to any pumping ring in order to be mixed with the cooling water temperature that is coming from the accumulator (D02). A different pump, named P11, brings the water heated to the heat exchangers (EX07), where there is heat transfer and the deionized water is cooled down. The cooled water is brought to an accumulator, a large volume element where the water can be suctioned upstream or downstream.

The accumulator upstream connection connects the accumulator with the common return line located in the pump P11. It compensates the lack or excess of flow that comes from the return line.

The accumulator downstream connection leads the cooled water to the rings' pumps. The cooled water is mixed with heated water (which comes from the common return line) in order to control the flow and the water temperature. Then, the water is suctioned by each pump.

In the following image, it is seen a simplified scheme about the lines' functionality.

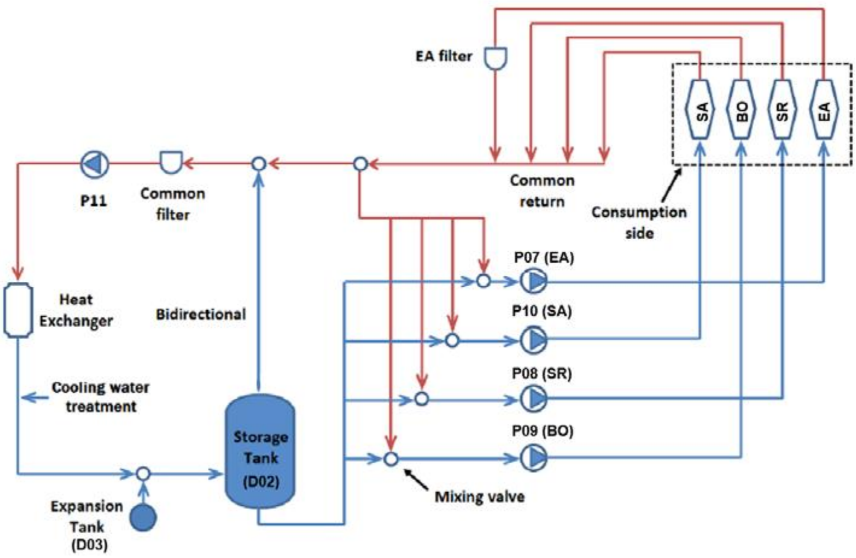


Figure 5.1 Simplified scheme of the cooling system [7].

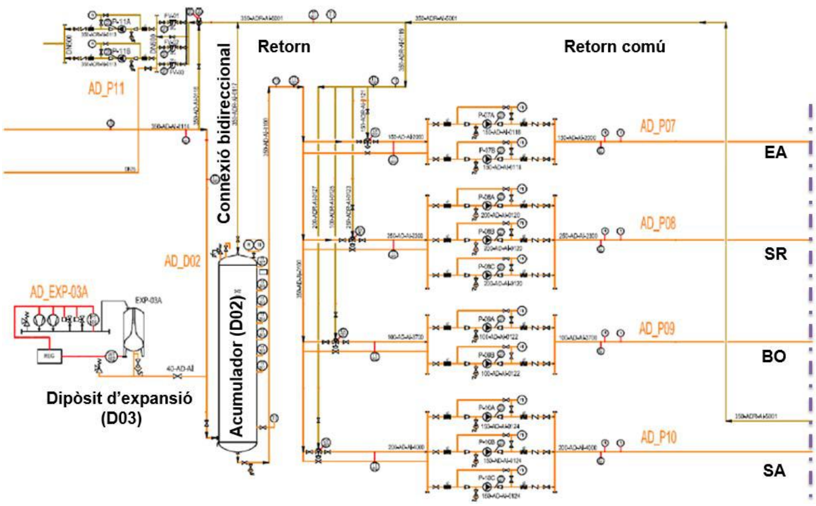


Figure 5.2 Detailed scheme of the cooling system [7]

5.2. Functionality of the components

5.2.1. Pumping system

A pump is a device that moves fluid by mechanical action. A pump does not create pressure, it only creates flow movement. Hence, the kinetic energy is transformed to pressure and this process varies depending on the pump type. Pumps can be classified into two groups according to its principle of operation: positive displacement and rotodynamic pump.

On the one hand, a positive displacement pump makes a fluid move by trapping a fixed amount and displacing the trapped volume of fluid into the discharge pipe. As this type of pumps are not used in this project, positive displacement pumps are not going to be discussed in the next chapters. On the other hand, a rotodynamic pump is a kinetic machine in which energy is continuously imparted to the pumped fluid by means of a rotating impeller or rotor.

5.2.1.1. Rotodynamic pump

Rotodynamic pump converts rotational energy, usually from a motor, to energy in a moving fluid. The main components of centrifugal pumps are the impeller, the casing and the drive shaft with gland and packing.

The liquid enters the eye of the impeller axially due to the suction created by the impeller motion. The impeller blades guide the fluid and impart momentum to the fluid, which increases the pressure of the fluid, causing the fluid to flow out. A part of the kinetic energy in the fluid is converted to pressure in the casing.

Rotodynamic pumps are usually classified as radial, mixt or axial. In Axial-flow pumps, the fluid is pushed outward or inward and move fluid axially while in Radial-flow pumps, the fluid enters along the axis or center and is accelerated by the impeller and exits radially. These pumps, Radial-flow pumps, are used in ALBA synchrotron cooling systems and they operate at higher pressures and lower flow rates than axial and mixed-flow pumps. Mixed-flow pumps function as a compromise between radial and axial-flow pumps.

In the following images, a schematic view of each type of rotodynamic pump can be viewed.

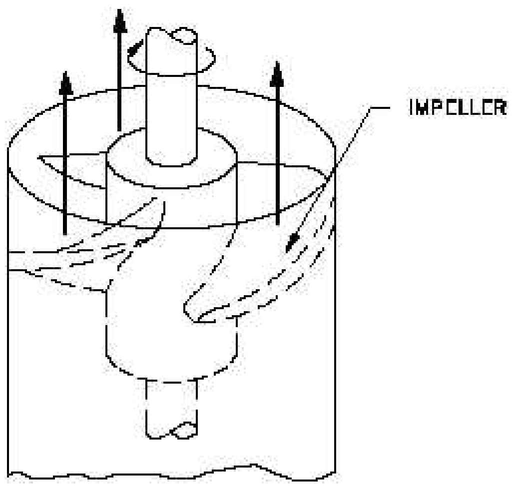


Figure 5.3 Radial Flow pump

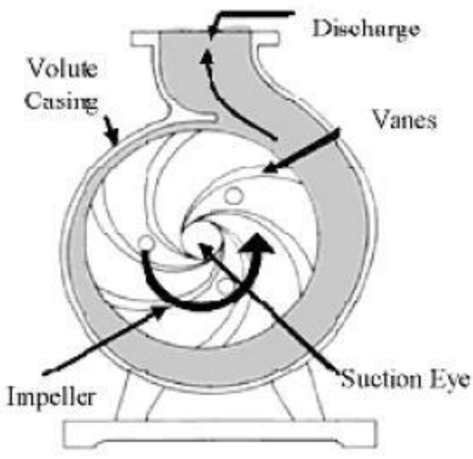


Figure 5.4 Axial Flow pump

5.2.1.2. Pumps technical descriptions

In reference of the ALBA pumping system, see below in the Figure 5.5, for each pump, the evolution of pump head vs flow and in Figure 5.6, the evolution of power vs flow. Rotational speed and suction diameter for each pump are presented in the Table 5.1.

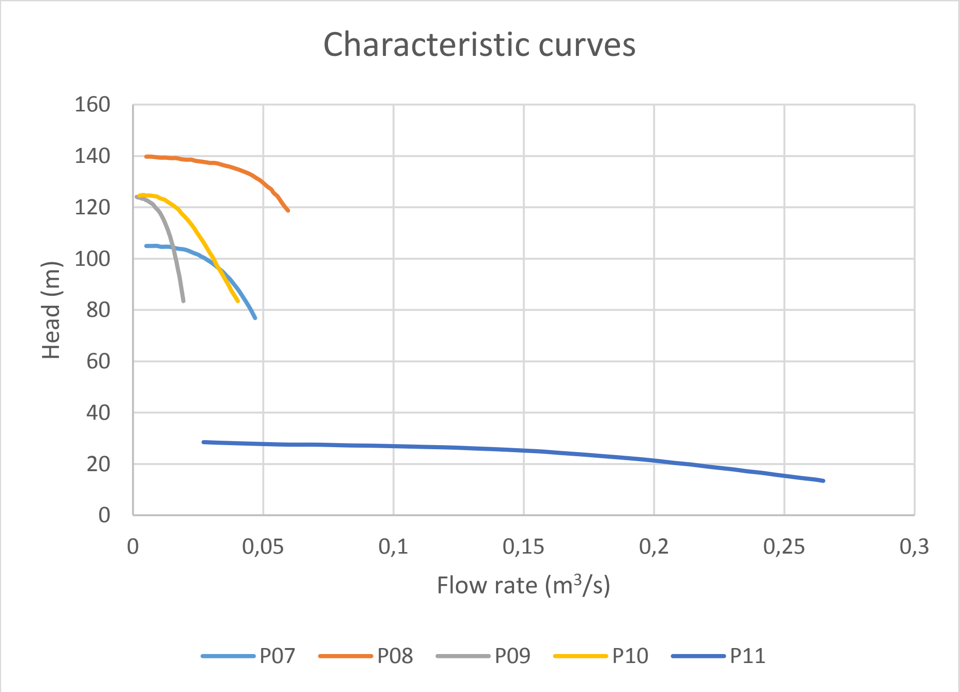


Figure 5.5 Head-Flow rate curves

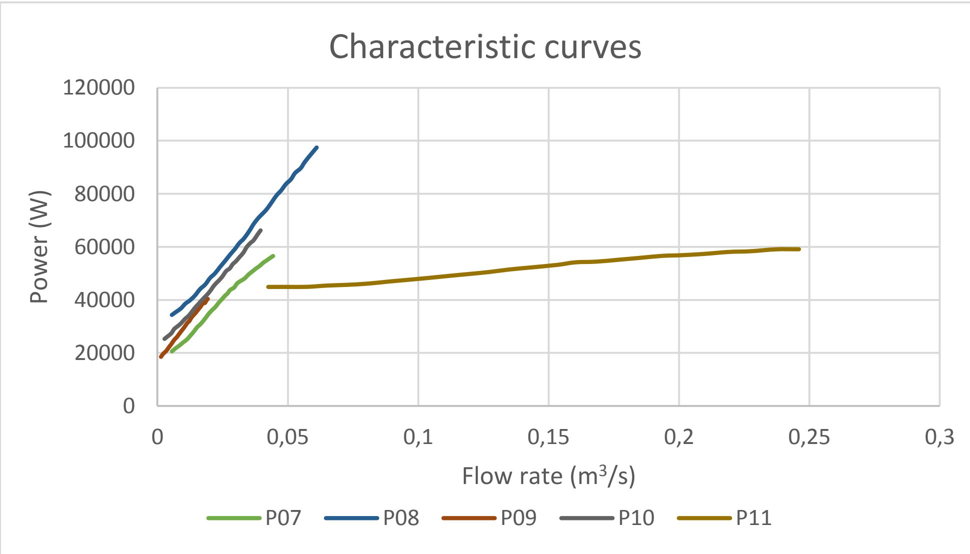


Figure 5.6 Power-Flow rate curves

Table 5.1 Rotational speed and suction diameter of the pumps

	P09	P08	P10	P07	P11
Model	NM-50/315BR	INP-80/315C	NM-65/315BR	NM-65/250B	INP-250/300C
Rotational speed [min^{-1}]	2955	2975	2975	2960	1485
Suction diameter [mm]	299	318	294	266	305,5 – 295,5

The technical data sheet for each pump has been attached into Annex, section C.

5.2.1.3. Pump and motor inertia calculation

As it has been said before, the information provided by the manufacturer is attached into Annex, section C. However, it does not contain information about pump and motor inertia. These pump properties are important as they influence in the behavior of the pump in transient states.

These properties do not have any influence in stationary simulation as rotational speed is stable. However, in order to simulate transient events, they play an important role in the response of the pump.

The previous model did not simulate transient events, consequently, these properties have been calculated in this project.

In order to calculate the values, Thorley empirical equations have been used and are the followings:

$$Inertia\ motor = 118 \cdot \left(\frac{P}{N}\right)^{1,48} \quad \text{(Eq. 5.1)}$$

$$Inertia\ pump = 1,5 \cdot 10^{7} \cdot \left(\frac{P}{N^3}\right)^{0,9556} \quad \text{(Eq. 5.2)}$$

Where

P	Brake Horsepower	Kw
N	Rotational speed	Rpm

See the results attached in the next table:

Table 5.2 Calculation of motor and pump inertia

Pump	Brake Horsepower [kW]	Rotational Speed [rpm]	Motor Inertia [Kg·m^2]	Pump Inertia [Kg·m^2]
P09 (BO)	29.0	2955	0.126	0.042
P08 (SR)	65.3	2975	0.414	0.090
P10 (SA)	53.6	2975	0.309	0.074
P07 (EA)	35.7	2960	0.171	0.051
P11 (CL)	55.6	1485	0.913	0.564

5.2.2. Pneumatex

Pneumatex, D03 in Figure 5.1, is an element of pressure maintenance and its objective is to guarantee a constant pressure of $2 \cdot 10^5$ Pa in the piping system. It is a 1,5 m^3 container with butyl bags that can control and adjust the pressure. Inside the bag, there is the water used to control the system pressure. The sensor measures the air pressure located outside the butyl bag and compares it to the set point value.

If $P_{air} < P_{set\ point}$, butyl bag compresses due to the startup of compressors. Then, water inside the bag is provided to the system in order to increase the system pressure.

If $P_{air} > P_{set\ point}$, air valve opens and air flow exits pneumatex. The pressure is reduced and the butyl bag, which is in higher pressure than the air, expands until the pressure equilibrium is reached. As a result, water from the system is swallowed inside the bag lowering the pressure of the system.

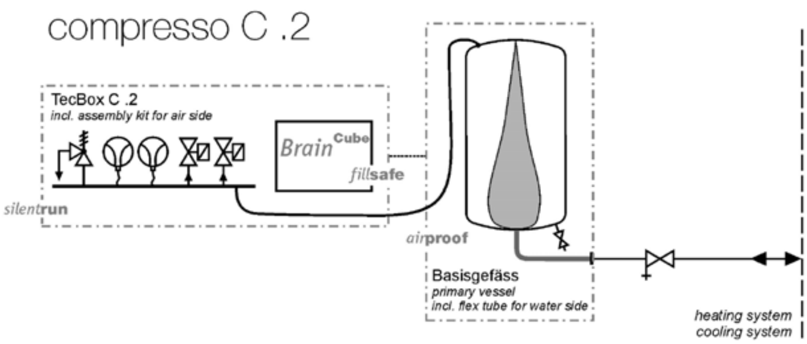


Figure 5.7 Pneumatex squeme

5.2.3. Three-way valves

The purpose of a 3-way control valve is to shut off water flow in one pipe while opening water flow in another pipe, to mix water from two different pipes into one pipe, or to separate water from one pipe into two different pipes. In ALBA system, these valves regulate the heated and refrigerated flow that will be mixed before entering a pump ring. Flow temperature is regulated by one 3-way valve in each pumping ring: $V3V_{P09}$, $V3V_{P08}$, $V3V_{P10}$ and $V3V_{P07}$. The next table shows the valves' nominal diameters.

Table 5.3 Nominal diameters of the three ways valves

	V3VP09	V3VP08	V3VP10	V3VP07
Nominal diameter (mm)	65	150	150	150

5.2.4. Pipes

The most common element of the system is the stainless steel 316L pipes from DN100-DN350. In Annex section D, more information of its dimensions is exposed.

5.3. System regulation and operational transients

5.3.1. Pressure regulation

A proportional–integral–derivative controller (PID controller) is a control loop feedback mechanism commonly used in industrial control systems.

The pressure regulation is managed by PID controllers. There is one controller for each ring as each pumping ring has a different pressure set point. PID input pressure is measured at a close point to a pump. PID output signal is a rotational speed or torque value which is connected to the inlet of the pump. Hence, the pump rotational speed or torque signals are managed by PID controllers.

Depending on the pressure, the controller sends a signal to the pump that will increase or reduce the rotational speed in order to achieve the pressure set point. Consequently, as the rotational speed varies, it has a direct proportional effect in flow rate.

See, in the next table, the pressure set point values for each pumping ring.

Table 5.4 Pressure set point for each pump in the system

Pumping ring	Set point pressure [Pa]	Set point pressure [bar]
P07	$7{,}5 \cdot 10^5$	7,5
P08	$10{,}2 \cdot 10^5$	10,2
P09	$10{,}2 \cdot 10^5$	10,2
P10	$10{,}0 \cdot 10^5$	10,0
P11	$3{,}5 \cdot 10^5$	3,5

The regulation of the PID output signal is made with scripts. See, in the figure below, the script that regulates pump P09. The script output is the signal that the PID controller will send to its pump. In this case, we want to hold at a pressure of 10,2 ± 0,01 bar. On the one hand, if pressure is above the set point value, the output signal will reduce the pump's rotational speed. On the other hand, if pressure is below the set point value, the output signal will increase the pump's rotational speed.

```
p09 = Controller.InputValue(1)
rpm09 = Controller.InputValue(2)
if Manager.Time = 0 then
Controller.OutputValue = initrpm09*3.14159/30
else
      if (abs(p09-10.2e5) > 0.01e5) then
      pratio = (10.2e5-p09)/10.2e5
      else
      pratio = 0.
      end if
Controller.OutputValue = rpm09 * (1 + 0.01*pratio)
end if
```

Figure 5.8 Pressure regulation script

5.3.2. Heat regulation

Three-way valves regulate the fluid temperature. There are two temperature set points:

- 23 ºC, when the water enters each pumping ring.
- 21 ºC, temperature of cooled water and water in accumulator.

Three-way valves control the temperature of the water before entering to each ring. The degree of valve lift (opening) may change depending on the temperature of heated and cooled water. See, below, the script used in Flowmaster's model in order to simulate and change the opening of the valve.

```
TV3VK=Controller.InputValue(1)
PosV3V=Controller.InputValue(2)
if Manager.Time = 0 then
Controller.OutputValue = initPosV3V09
else
      if (abs(TV3VK-296.15) > 0.01) then
      Tratio = (296.15-TV3VK)/296.15
      else
      Tratio = 0.
      end if
Controller.OutputValue = PosV3V * (1 - 1*Tratio)
end if
```

Figure 5.9 Heat regulation script

6. Description of water hammer

Water hammer is a familiar sound that nearly everyone has heard in their own home; slamming a faucet closed or from radiators during the water heating process. In industrial situation, this phenomena is more than just a noisy annoyance. It can lead to important problems in the piping system if water hammer has not been simulated and controlled, previously, in transient states.

Water hammer usually results from the opening and closing of valves and from pump starts and stops. It is a pressure abrupt change caused when a fluid, which is in motion, is forced to stop or suddenly, change in direction leading to a momentum change. This phenomena creates pressure waves that travel back and forth in a piping system. Consequently, it acquires great force, damaging equipment and potentially putting personnel at risk. Hence, pipelines that must transport hazardous liquids or gases are carefully designed, constructed and operated in order to avoid any catastrophe.

Transients in the piping system can cause high or low pressures. On the one hand, the problems related to excessively high pressure ($P>>>P_{atm}$), can lead to damage in pump, valves and also to pipe rupture. On the other hand, the problems related to excessively low pressure ($P<P_{atm}$) can lead to entrance of air through vacuum valves, cavitation and release of large amounts of dissolved air.

The repetitive of low-high alternative pressures can lead to vapor cavity closure and excitation of pipeline components with natural frequencies near the pressure fluctuation frequency. Consequently, there are generation of vibrations, stresses, strains and displacements that can cause a failure in any of the piping components [6].

System actions that can precipitate water hammer include:

- Fast start or shutdown of pumps
- Fast closure and opening of valves
- Power interruptions
- Check valves slamming shut on reverse flow
- Water column separation

In order to minimize the effect of water hammer there are some actions that can be done:

- Reduce the pressure by fitting a regulator.
- Lower fluid velocities.
- Control valves such as: slowly closing valves, air valves and by-pass valves.
- Good pipeline control (start and shut-down procedures).
- Regulator of the flow pressure such as, accumulators and air vessels.
- Water Hammer Arrestor, which are devices that can absorb the shock and stop the banging.
- Shorter pipe lengths.

Slowly closing valve may not be an appropriate solution if the flow must never travel in opposite direction. It is defined as $t_{critical}$ the time taken by the pressure wave to return to its original position. The length, *L*, and the pressure speed, *a*, are variables that have an effect on $t_{critical}$, $\text{Tcritical} = \frac{2L}{a}$. The pressure waves counteract the pressure in pipes when the waves move back and forth in a pipe.

- Closing time = L/a

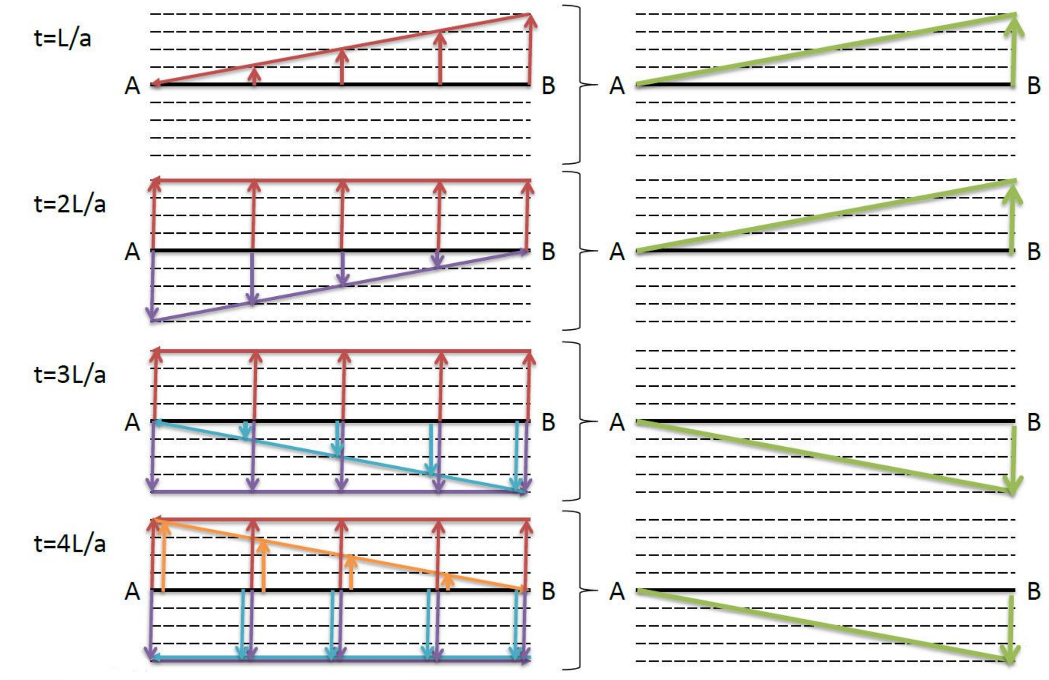


Figure 6.1 Pressure counteraction

It is also defined a $L_{critical}$, which is the half of the length travelled by the wave during the critical closing time, $\text{Lcritical} = \frac{a \cdot Tclosure}{2}$. It indicates that the pipe sections, at a given length from the reservoir L ≥ Lc, suffer a maximum and constant head increase ΔH. See the next picture as an example about how the pressure in each point of the system depends on pipe length.

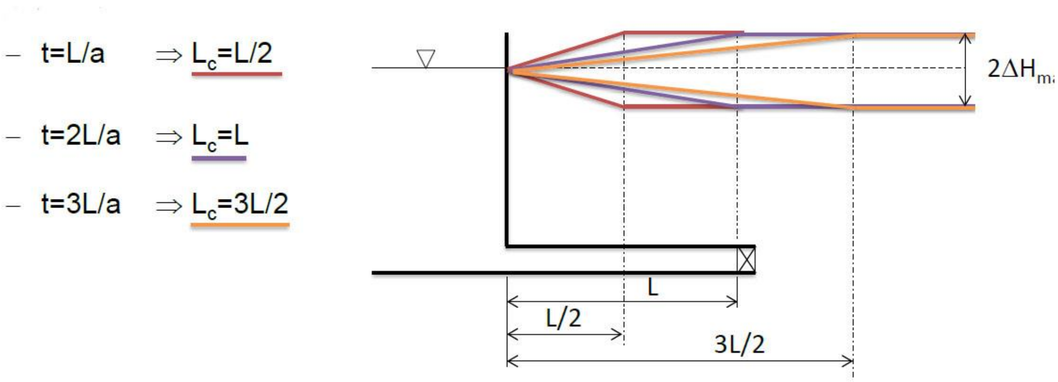


Figure 6.2 Variation of head pressure [6]

6.1. Causes of water hammer

Three different conditions are identified to provide the force that initiates water hammer. They are hydraulic, thermal and differential shock.

Hydraulic shock occurs when a valve is closed too abruptly. The closure produces a shockwave that slams into the valve and rebounds in all directions, reflecting back and forth along the length of the piping system until the energy is dissipated due to friction. There is an increase in pressure while fluid is compressed and pipe is stretched.

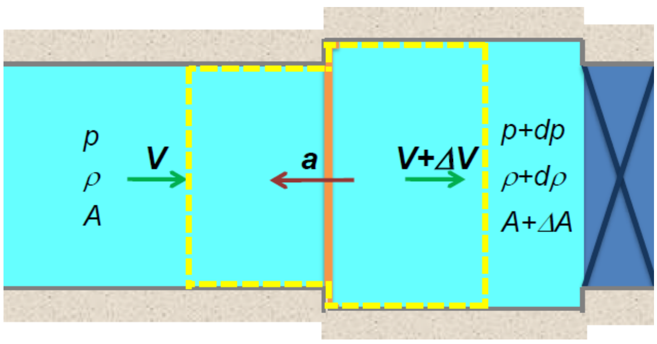


Figure 6.3 Water hammer effect [6]

Thermal shock can also initiate this phenomena. In bi-phase systems, such as, heat exchangers, steam bubbles condensate. As a steam bubble occupies much more space than the equal amount of water, water is accelerated to fill the bubbles, sending shockwaves in all directions.

Differential shock occurs when steam and condensate flow are in the same pipe, but at different velocities. In bi-phase systems, the steam is much higher than the velocity of the liquid. Steam flowing over condensate can create waves of condensate and become higher. The air flow causes the waves to block off more of the cross section of the piping until a seal is formed, closing off the pipe.

The following image gives an idea about how pressure changes can cause water hammer and the effect on the piping system. The system illustrated is very simple, it contains a valve, a pipe and a reservoir.

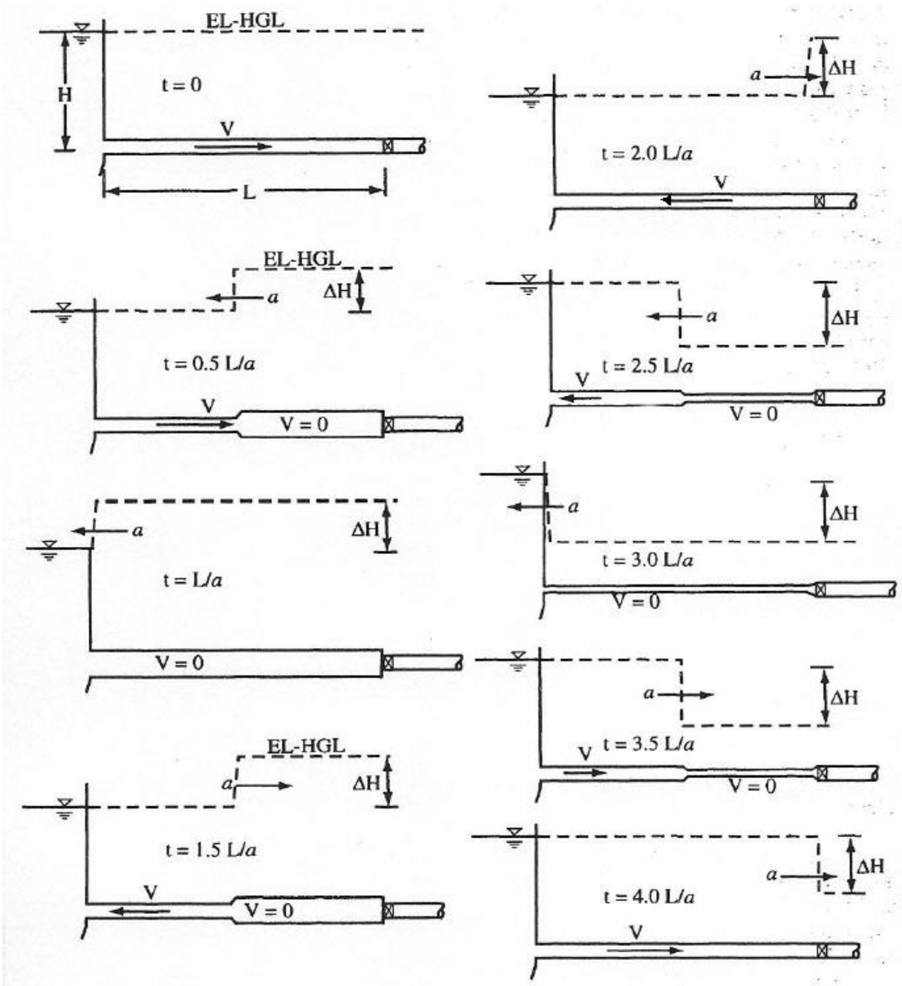


Figure 6.4 The evolution of pressure waves [6]

At the first image, a valve is opened and the fluid travels at a velocity *V* through a pipe with length *L*. The head pressure of the reservoir is *H* and it represents the steady state. The transient state starts when, suddenly, the valve closes and the fluid is forced to stop. The fluid in motion hits the closed valve and the pressure abruptly increases. A pressure wave is generated and it propagates upstream at *a* speed. The pressure change enlarges the pipe, less than < 1%, and increases the density of the fluid.

At the second image in the Figure 6.4, the wave reaches the reservoir. The flow velocity is zero but the pressure is not in equilibrium as pipe is at pressure of $\Delta H + H$ while the reservoir is at pressure of H. Consequently, it can also be seen in the rest of the images that the fluid starts to flow towards the region of lower head pressure moving back and forth through the pipe changing the pressure in each image as it is a non-equilibrium system.

Three points of the illustrated picture above has been selected, in order to study the pressure change along the time. These points are:

1. When the fluid enters the pipe.
2. At half length of the pipe.
3. Immediately before the valve

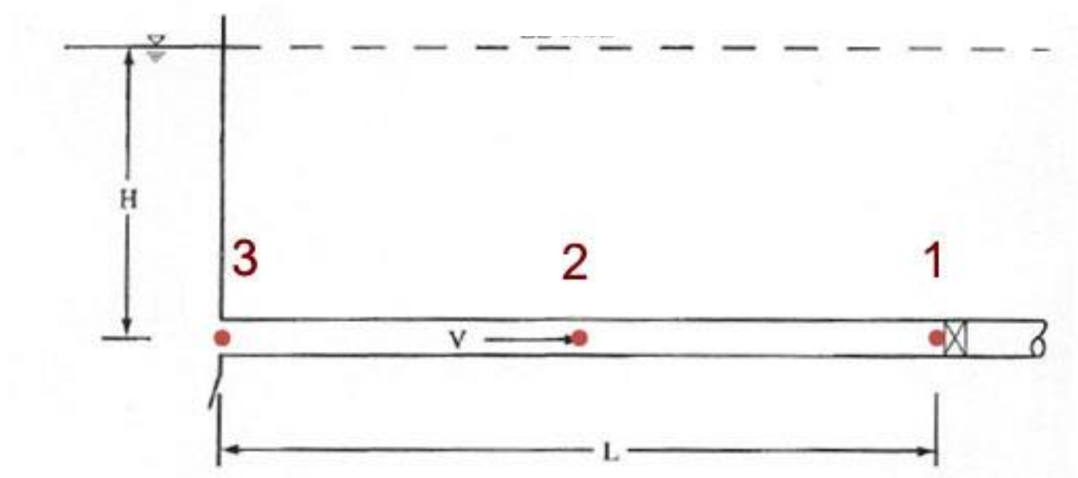


Figure 6.5 System and points studied

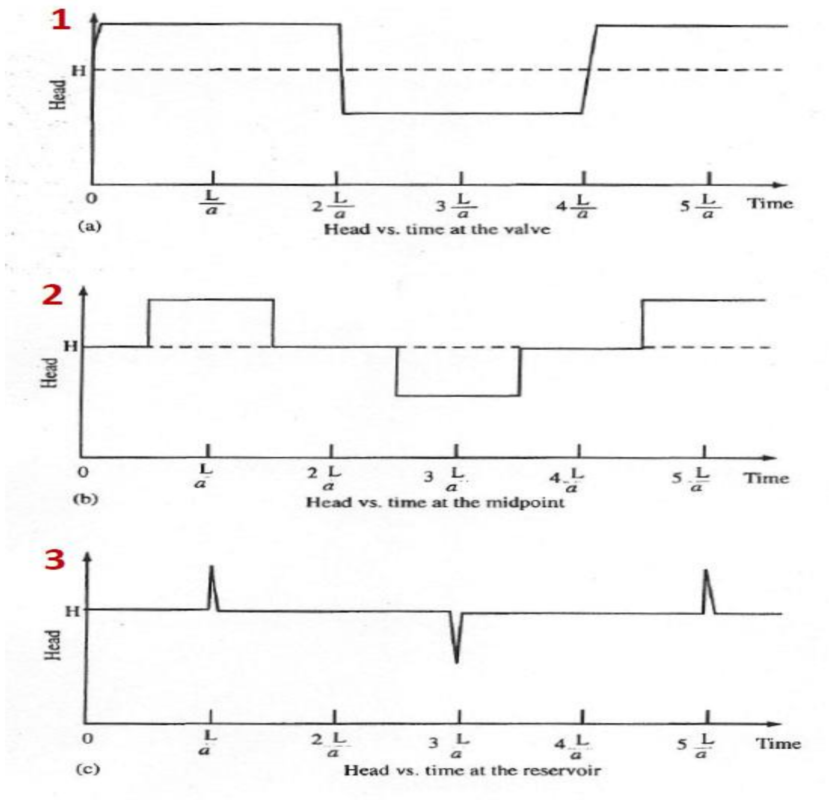


Figure 6.6 Pressure's evolution of the points selected

Valve closes at zero seconds and the closing is very fast. At 1st point, the pressure is at maximum value until the pressure wave reaches the valve again, at 2·L/a seconds where the pressure wave counteract the pressure generated for the closure of valve. At 2nd point, the pressure wave arrives at 0,5·L/a and it stays at its maximum value until the pressure wave returns and counteracts its effect. At 3rd point, as we are supposing it is a large reservoir, the effect is only a peak of pressure.

In absence of friction, this phenomena would be endless until a component breaks but in the reality, friction and other pressure losses end with the water hammer phenomena.

In order to verify that Flowmaster program holds for water hammer calculation, it has been modelled the previous system. The aim of this simulation is to replicate the phenomena of water hammer seen above and verify its behavior in Flowmaster simulation. The results that Flowmaster provides are compared with Joukowsky method, which is explain in the next chapter. The results can be seen in Annex section E.

From the simulations' results, it is validated that Flowmaster calculates phenomena such as water hammer and it is the tool used to simulate in this project.

6.2. Methods for water hammer calculation

6.2.1. Joukowsky

The maximum pressure change is given by Joukowsky equation and occurs at the location of the disturbance. According to Joukowsky equation, the opening/closing is instantaneous which does not correspond to a realistic case because valves and pumps need some time to fully open or close. Moreover, the theoretical value obtained does not take into account the following concepts that interact in real systems fluid transient simulations:

- Wave reflection
- Pipe friction losses
- Cavitation

The equation is the following:

$$\Delta p = \rho a \Delta v \qquad \text{(Eq. 6.1)}$$

Where

Δp	Magnitude of pressure change	N/m^2
ρ	Liquid density	kg/m^3
a	Waves speed	m/s
Δv	Change in flow velocity	m/s

In terms of liquid head, the previous equation is:

$$\Delta H = \frac{a}{g}\Delta v \qquad \text{(Eq. 6.2)}$$

Where

ΔH	Magnitude of head rise	meters of water column
g	Acceleration due to gravity	$9.81\ m/s^2$

The wave speed is calculated from:

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{k}+\frac{d}{tE}\right)}} \qquad \text{(Eq. 6.3)}$$

Where

k	Bulk modulus of liquid	N/m^2
d	Pipe internal diameter	m
t	Pipe thickness	m
E	Young's modulus of pipe material	N/m^2

In order to provide a more accurate pressure change value that a real system experience, Allievi or Michaud equations can be used. These formulas are a function of the closing/opening characteristic time.

6.2.2. Allievi and Michaud

Both equations takes into account the time that a valve or pump need to fully close or open, property named closing/opening characteristic time.

- Allievi:

- H = static head at the valve m of water column
- V = steady velocity at the valve m/s^2
- T = operation time (lineal) s
- L = pipe length m
- \+ C for closing, - C for opening

$$\Delta H = \frac{H}{2}(C^2 \pm C\sqrt{4 + C^2}) \quad \text{(Eq. 6.4)}$$

$$C = \frac{LV}{gHT} \quad \text{(Eq. 6.5)}$$

-Michaud:

$$\Delta H = \frac{2LV}{gT} \quad \text{(Eq. 6.6)}$$

Those equations are easy to be used in very few and simple cases. As this project faces with a complex cooling system, a simulation software is needed in order to run any test. The software used is called Flowmaster, which uses the method of characteristics in order to solve the differential equations involved in the fluidic dynamic discipline.

6.2.3. Method of characteristics

Most water hammer software packages use the method of characteristics to solve the differential equations involved. This method is based on the following equations:

Euler's equation:

$$\frac{dV}{dt} + \frac{1}{\rho}\frac{\partial p}{\partial s} + g\frac{dz}{ds} + \frac{f}{2D}V|V| = 0 \qquad \text{(Eq. 6.7)}$$

Conservation of mass equation:

$$\alpha^2\frac{\partial V}{\partial s} + g\frac{\partial H}{\partial t} = 0 \qquad \text{(Eq. 6.8)}$$

Applying initial and boundary conditions and integrating the differential equation, the resulting equations are the following equations. The following equations are a 2D example.

$$\frac{Vp - V_A}{tp} + \frac{g}{a}\frac{Hp - H_A}{tp} + \frac{f}{2D}V_A|V_A| = 0 \qquad \text{(Eq. 6.9)}$$

$$\frac{Vp - V_B}{tp} + \frac{g}{a}\frac{Hp - H_B}{tp} + \frac{f}{2D}V_B|V_B| = 0 \qquad \text{(Eq. 6.10)}$$

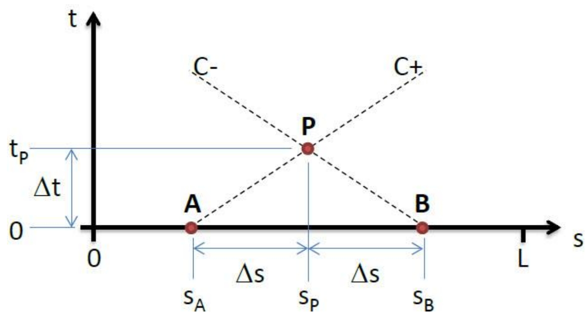


Figure 6.7: Method of characteristics

7. Description of Flowmaster model.

7.1. Initial model

The rings' models were built up from the available components in Flowmaster software. The properties of each component were selected based on the information provided by the corresponding manufacturer in the form of construction planes and technical documentation. As a result, the model was built grouping many subsystems as it is inferred from the next figure.

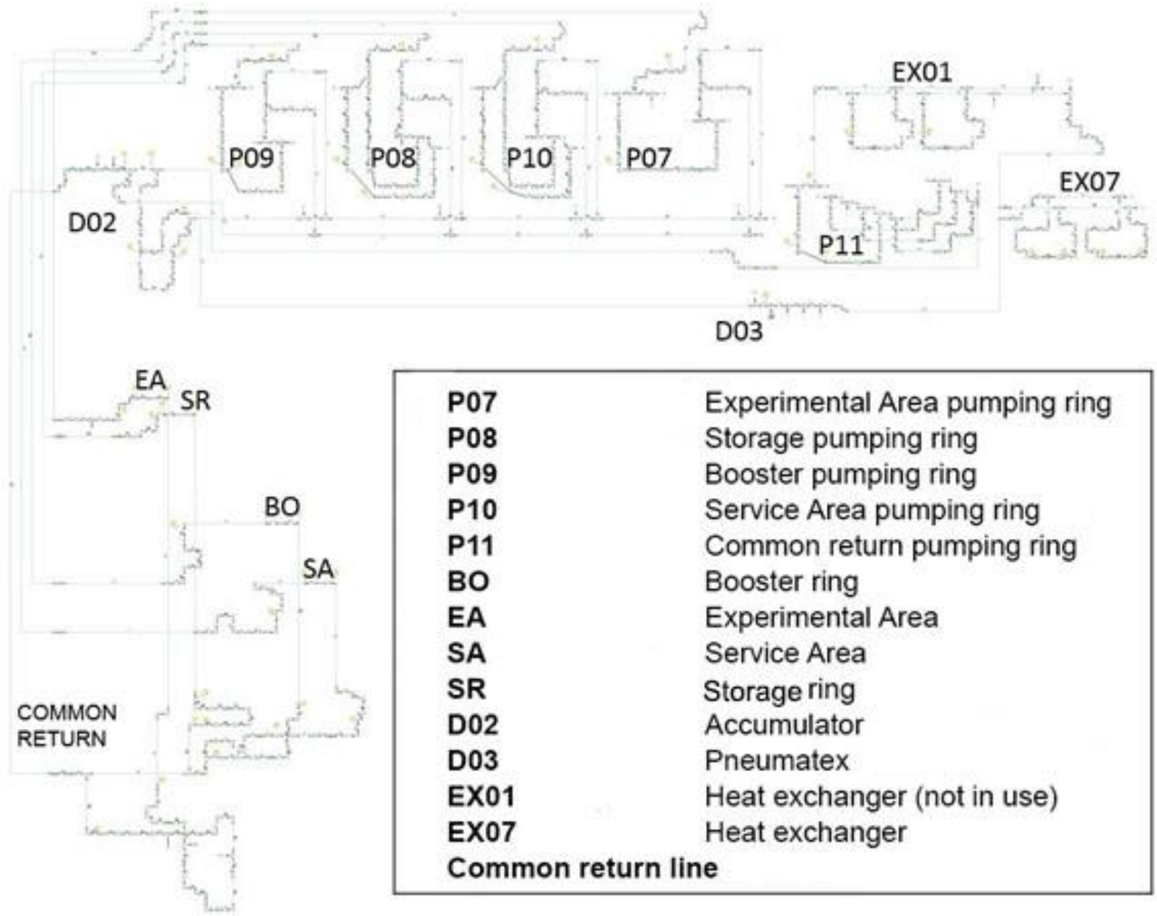


Figure 7.1 Description of all the model and its subsystems

In the present document, different names have been used to refer to the same parts of the system. For a better lecturer comprehension, a list of the names used for each part of the system are enlisted below:

- P07 pumping ring can also be referred as: P07 pumping line, pumping station and experimental area ring as P07 pumping line connects with the experimental area.

- P08 pumping ring can also be referred as: P07 pumping line, pumping station and storage ring as Storage ring is the prolongation of P07 pumping line.
- P09 pumping ring can also be referred as: P09 pumping line, pumping station and Booster ring as Booster ring is the prolongation of P09 pumping line.
- P10 pumping ring can also be referred as: P10 pumping line, pumping station and Service Area ring as Service Area ring is the prolongation of P10 pumping line.
- P11 pumping ring can also be referred as: P11 pumping line, pumping station or common return line as Common line is the prolongation of P11 pumping ring.

In Annex section F, it can be seen a figure for each pumping lines of the initial model.

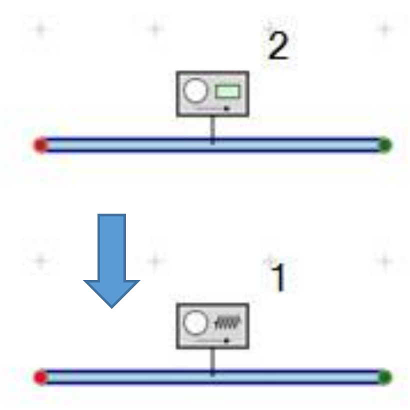
7.2. Adjusted model

Previous model was built up in order to successfully simulate stationary events of the system. The adjusted model keeps the same structure but some components were added, replaced or deleted. The adjusted model has needed some universal changes, but also, it has been adjusted for each transient state; Start and Stop.

Firstly, a research and understanding of the construction planes, attached in Annex section I, was needed in order to detect and adapt the model to transient simulations.

Although specific changes must be set for each transient state (pump start-up and shut-down), two main changes are needed in our system:

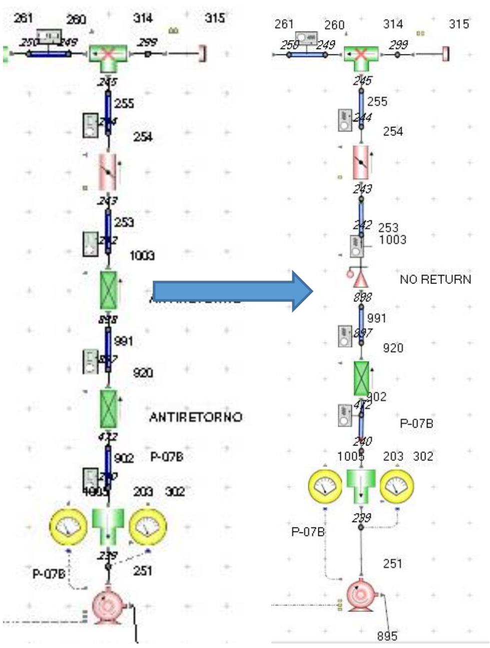
1. Pipes in the previous model were set as rigid pipes in order to simplify and assume that pipes did not compress either expand. In transient events, where water hammer can happen, the pipes may experience some geometrical changes and it is necessary to simulate with elastic pipes. In its properties, it is compulsory to set the wave speed, which is function of the pipe internal diameter, as it was seen in Chapter 0. The geometrical information of the pipes can be seen in Annex section D.
   See in the images below the pipe change and, in red colour, the properties that must be set for elastic cylindrical pipes.



Property	Value
Pipe: Cylindrical	Sub Form...
Length	Not Set
Friction Data	Sub Form...
Diameter	Not Set
Vapour Pressure	0,02062 bar
Wave Speed	Not Set
Pipe Thermal Properties	Sub Form...
Heat Transfer Data	Sub Form...
Buried Data	Sub Form...
Volumetric Flow Rate	Not Set
Pipe Profile	Not Set
Mile Post	Not Set
External Pressure v Time	Not Set
Results On/Off	1. On

Figure 7.2 Change of the type of pipe *Figure 7.3 Properties of the elastic pipes*

2. From the construction plans it can be noticed a non-return valve placed after each pump. These valves only act as a discrete loss in stationary simulations while they get closed if flow travels in opposite direction. Therefore, in order to simplify the model, in previous model, a discrete loss was placed in order to simulate the valve. The ALBA synchrotron system non-return valve is a tilting disc check valve.
   Flowmaster does not hold this type of valve. However, it holds a very similar type of valve called swing check valve which has been used to adjust the model. The information related to the valve has been obtained not only from the technical description of the valve, see Annex section G, but also was necessary to contact with the manufacturer company.



Property	Value
Valve: Swing Check	Sub Form...
Diameter	0,1615 m
Characteristic operating time	1 s
Minimum Velocity	0,6 m/s
Thermal Capacity	Sub Form...
Head Loss v Fluid Velocity	Glenfield Non-return Valve
Results On/Off	1. On

Figure 7.4 Set of the swing check valve *Figure 7.5 Properties of the swing check valve*

8. Preliminary simulations

At an early stage in this project, an validation analysis has been performed. The objective is not only getting familiar with Flowmaster program, but also studying the components and their properties that take an effect in a piping system. For this reason, it has been tested with a less complex system.

8.1. Validation of the components to be used

Firstly, it has been modeled a piping system with a pump that suctions flow from the downstream reservoir to the upstream reservoir. The fluid travels inside a piping system which also contains a swing check valve that will close its lift/gate in case the flow goes downstream. This case may happen when the pump is not active or it is in tripped mode as the nodes are not in the same altitude, see it in Figure 8.1. The components of the system are the following:

- Components 1 and 8 act as an infinite reservoir, such as a sea or lake.
- Component 3 is a pump tabular controlled. It will be used to control and send inputs to the pump. This controller controls the pump's rotational speed.
- Component 4 is a swing check valve.
- Three pipes with a length of a hundred meters each. As the objective is to check if water hammer appears in the transients simulations, pipes are defined as elastic.

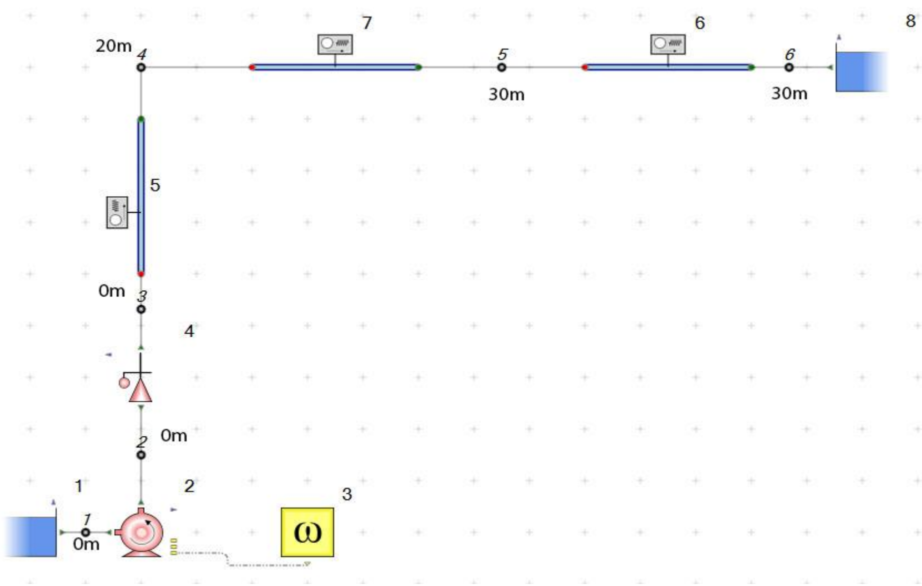


Figure 8.1 Model created

In this first round of simulation, the main interest is to model and analyze the results due to the start-up and shut-down of the pump as it will be studied in the next chapters in a more complex system.

It is supposed that water hammer and, as consequence, cavitation may appear because the system does not hold any pressure suppressor or any other device to work against pressure waves. This phenomena might appear in valve outlet when it is closed or at the pump outlet during a start-up or shut-down.

The negative effects that water hammer provide are serious and some components can minimize the power of water hammer (explained in chapter 0). That is the reason why two different properties that may cause water hammer are studied in this chapter. These properties are the following:

1. Fast/Slow pump start-up and shut-down by controlling the pump speed with a tabular controller.
2. The characteristic operating time of the swing check valve. It is the time that the valve closes its lift when the fluid travels in the opposite direction. This property is studied in the stoppage of the pump.

Once the analysis has been completed, a pressure wave suppressor (accumulator) will be placed in the system in order to detect its effect in the system.

8.2. Analysis of pump start-up

Two different pump start-up are simulated. The following figure shows the difference of the two simulations that has been called Fast and Slow start according to its pump start-up.

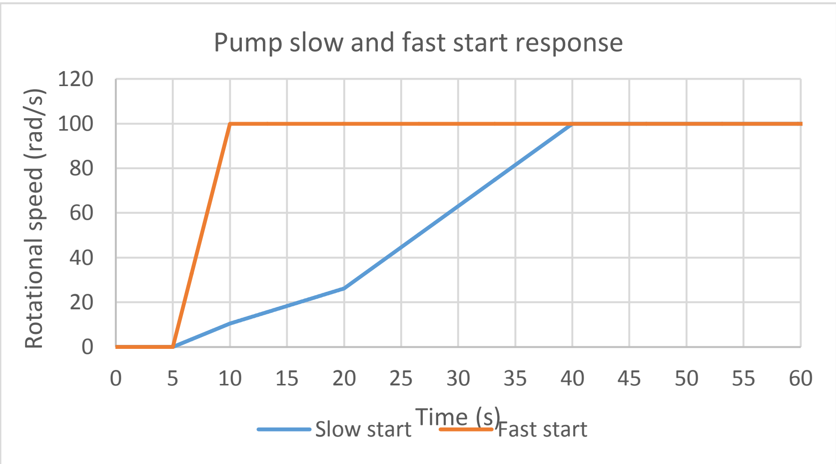


Figure 8.2 Evolution of fast and stop start

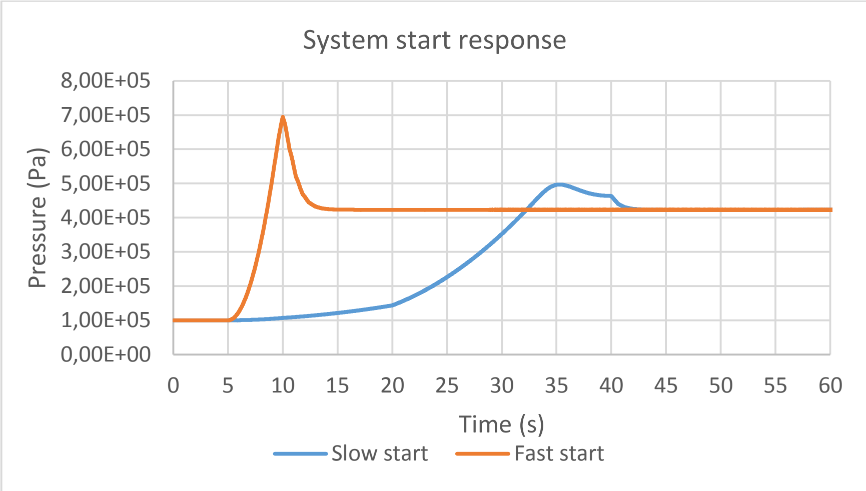


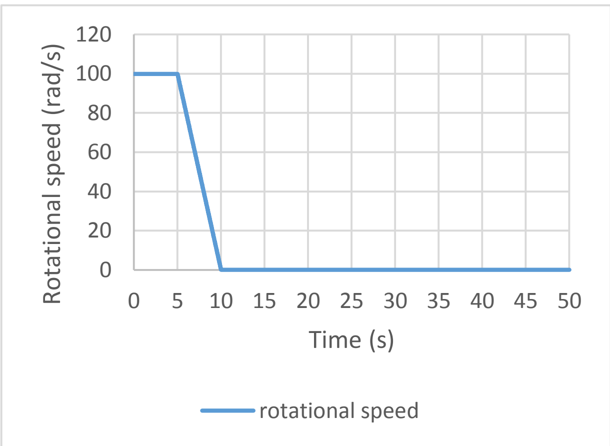
Figure 8.3 Pressure at pump outlet

Pressure peak is influenced by the acceleration of the flow and pump's inertia. At pump outlet, fast start present a pressure peak of $7 \cdot 10^5$ Pa, with 64% of overpressure, while slow start pressure peak is $5 \cdot 10^5$ Pa, with 17% of overpressure. The pressure gradient experienced in fast is more dangerous than slow start pressure gradient and reduces life-time components.

8.3. Analysis of pump shut-down

8.3.1. Sensibility to check valve operating time

The stop set by the controller is the following:



Property	Value
Pump Speed	Sub Form...
Repeat after Time Interval	Not Set
Output Quantity	34. Rotational Speed
1st Time	0 s
Pump Speed at 1st Time	954 rpm
2nd Time	5 s
Pump Speed at 2nd Time	954 rpm
3rd Time	10 s
Pump Speed at 3rd Time	0 rpm
4th Time	50 s
Pump Speed at 4th Time	0 rpm

Figure 8.5 Stop of the pump

Figure 8.4 Data set at the pump controller

The characteristic operating time of a valve is the time that it needs to close the lift in case flow changes and travels in reverse direction. The effect of the characteristic operating time can be detected comparing a very fast closure with a slow one. The slow closure will let flow to move downstream of the system for a few more time than fast closure.

- Results with $T_{characteristic}$ = 0,1s, fast closure:

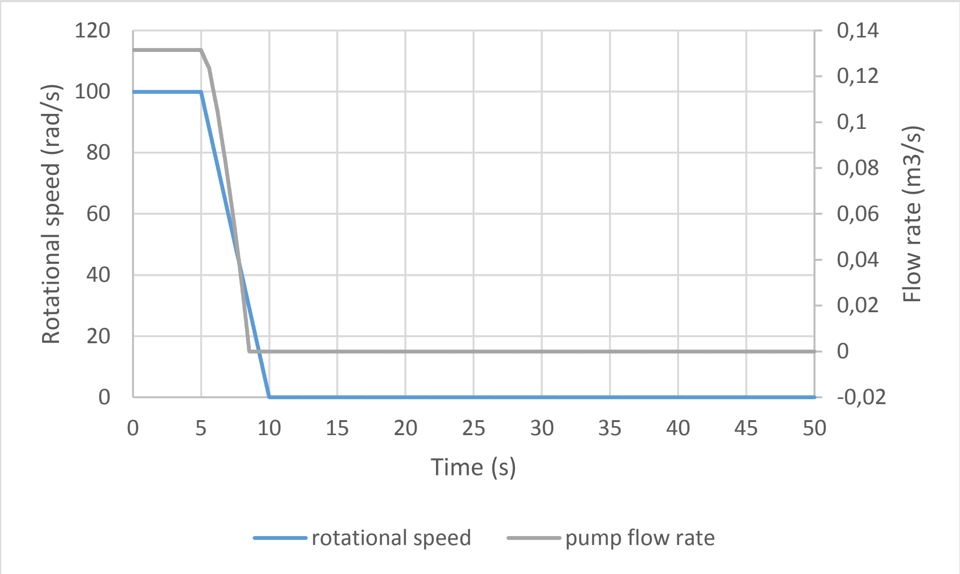


Figure 8.6 Evolution of rotational pump's speed and flow rate

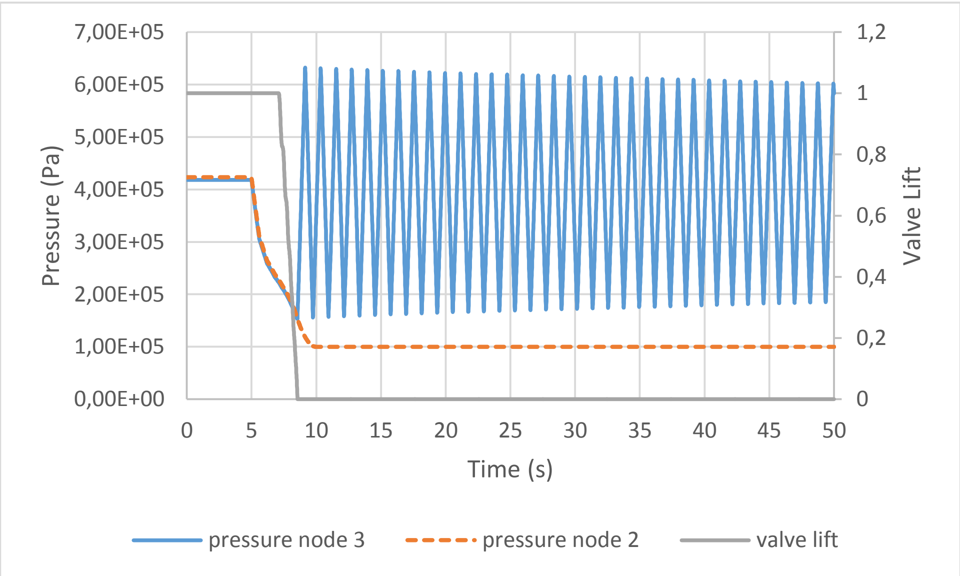


Figure 8.7 Evolution of valve lift, pressure at valve's (node 3) and pump (node 2) outlet

Rotational speed lows down at 5s until it stops. As the valve closure is really fast, the valve closure slope is vertical and water hammer is generated once the valve gets closed. Water hammer is generated at 3rd node (at valve outlet) but it does not lead to cavitation as lowest pressure is around 1,5 bar, higher than cavitation pressure. The highest pressure of the system is 6,3 bar due to the fast valve closure. The pressure at pump outlet does not experience pressure waves as the reservoir is close and minimizes the pressure impact.

- Results with $T_{characteristic}$ = 5s, slow closure:

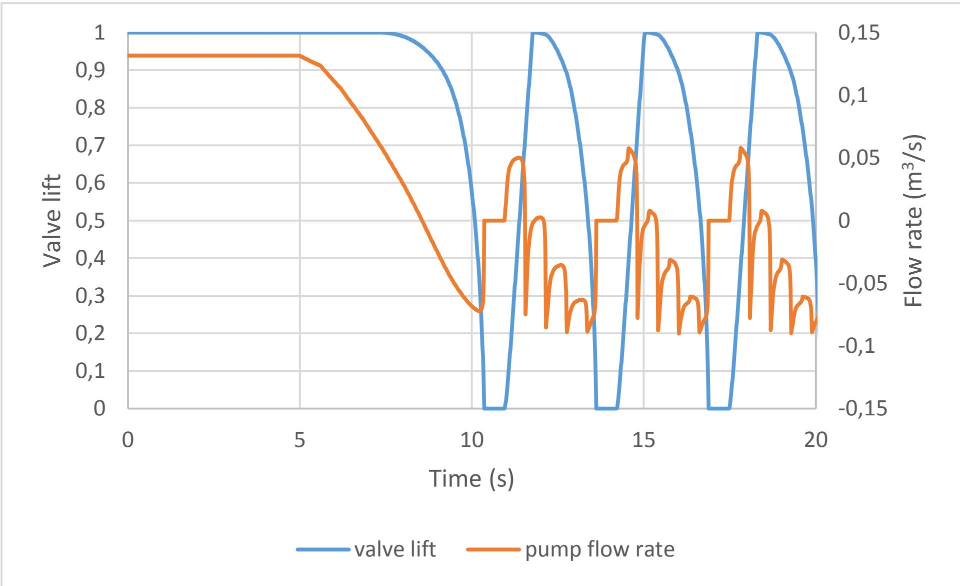


Figure 8.8 Evolution of flow rate in reference of the opening of the vale

In this case, the closure of the valve is very slow and the flow can move forth and back in the piping system. As a result, the valve lift keeps opening/closing because of the continuous changes in flow direction.

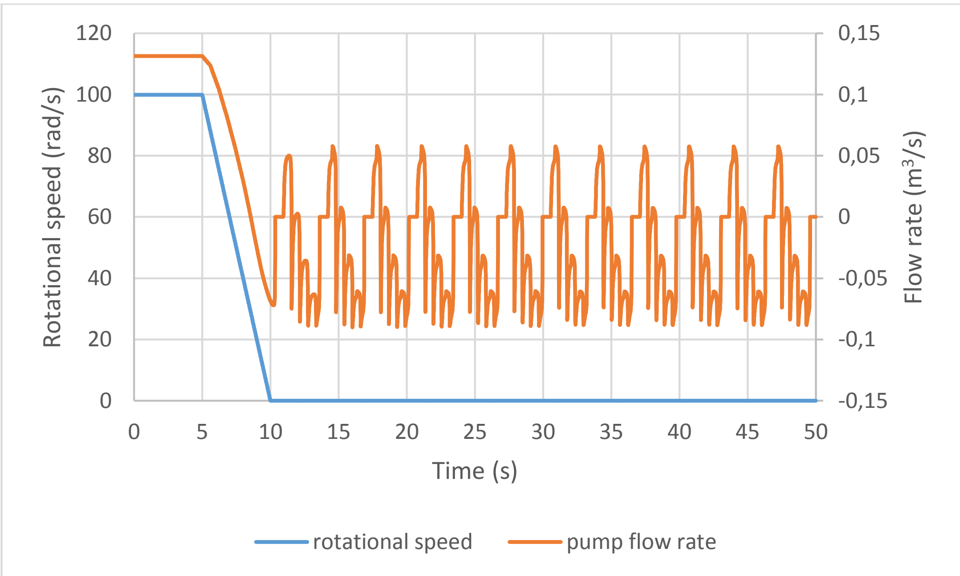


Figure 8.9 Evolution of the rotational speed and flow rate

A pressure wave propagates through all the system. The closure delay generate bigger differences in pressure than previous case, and this scenario may lead to damages in pumps and pipes. Cavitation phenomena occurs as pressure goes below 0,02062 bar (cavitation of water), as it is inferred from the following figure. Note that Flowmaster has an option to include cavitation calculations or not. In this simulation does not have into account the cavitation and, as a result, the pressure goes below the cavitation pressure.

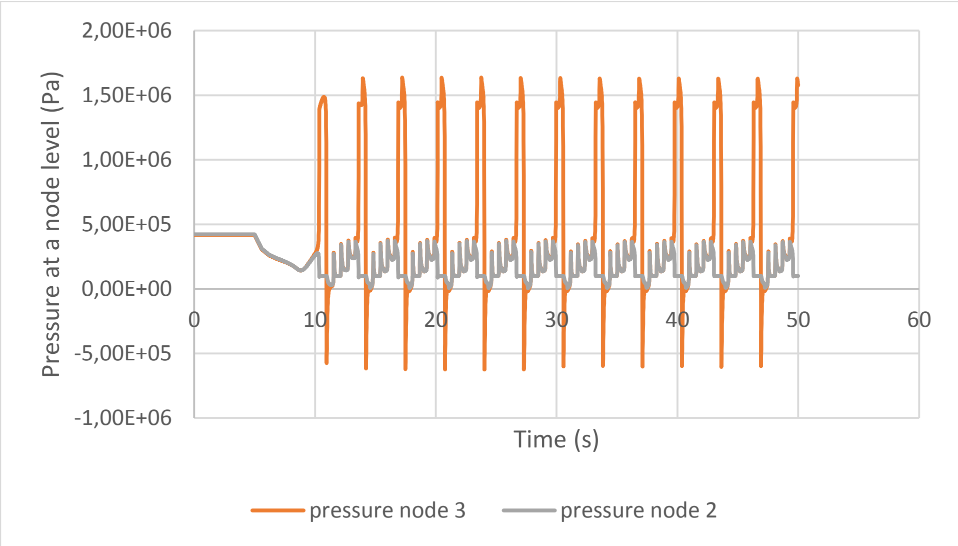


Figure 8.10 Pressure evolution in valve's and pump outlet

Once the cavitation has been detected, Auto-vaporization must be selected and fluid vapour pressure must be set as an option in the program. Note that each fluid has its own cavitation's pressure. In the following figure, auto-vaporization box has been activated.

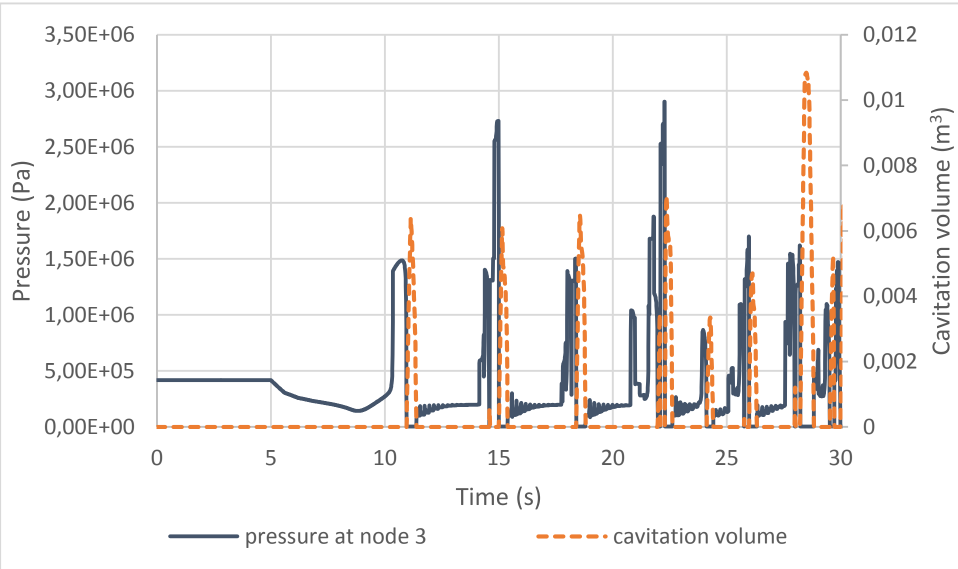


Figure 8.11 Pressure and cavitation volume evolution

With Auto-vaporization activated, pressure at valve outlet reaches $2{,}9 \cdot 10^6$ Pa and once it reaches the pressure of cavitation, air is created. The maximum cavity of generated air in the system is 0,011 m^3. This situation must be avoided at all costs. Otherwise, it can lead to serious problems in the pumps and other piping components.

8.3.1.1. Minimizing water hammer using an accumulator

In this case, an accumulator has been placed at valve outlet. Setting the characteristic operating time value as 0.1 seconds, the simulation result show that water hammer is not detected once the accumulator is placed in the system. The following graphic shows the difference in pressure by placing the accumulator (orange) or not (blue).

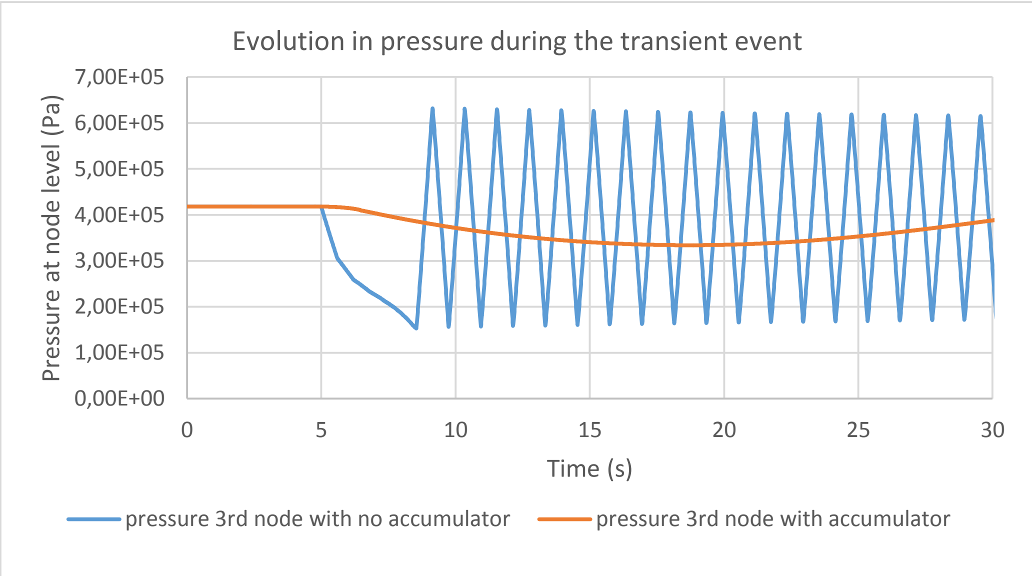


Figure 8.12 Difference in evolution pressure using or not an accumulator

8.3.2. Sensibility to pump shut-down time

In order to measure the shut-down importance, the test has been realized with the accumulator at valve outlet. The operational characteristic time has set at 1 second. With this property's value, flow does not go in reverse direction as valve closes before.

Fast and slow stops are the following:

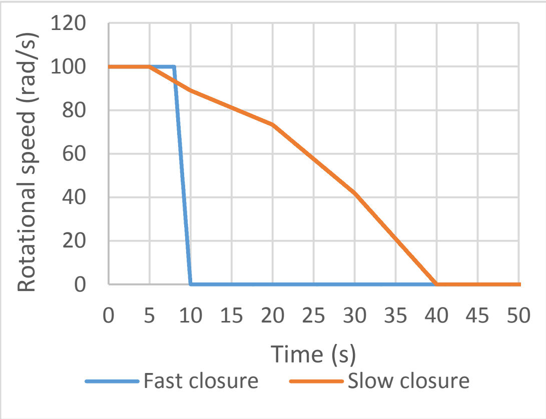


Figure 8.13 Stop of the system

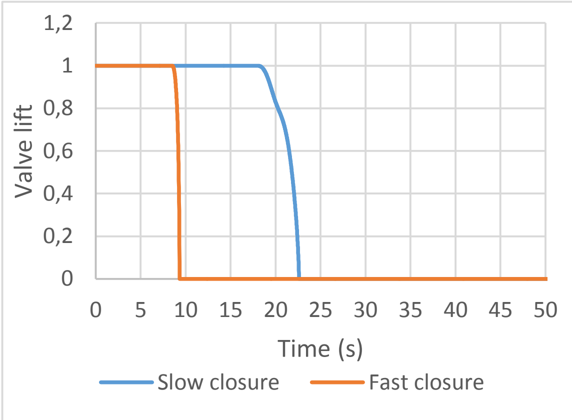


Figure 8.14 Closure of the valves

As for the pressure results, it can be seen that the pump's stop generate a pressure negative peak. In the fast closure, the slope is more significant and pressure change gradient is higher than the slope in slow closure case. The difference is consequence of the flow rate quantity. When the valve closes, the quantity of flow, in the pipe, is less in the slow closure than fast closure when the valve closes. The pressure peak for the fast closure decreases until $2{,}4 \cdot 10^6$ Pa. Along the time, transients in both cases are very similar.

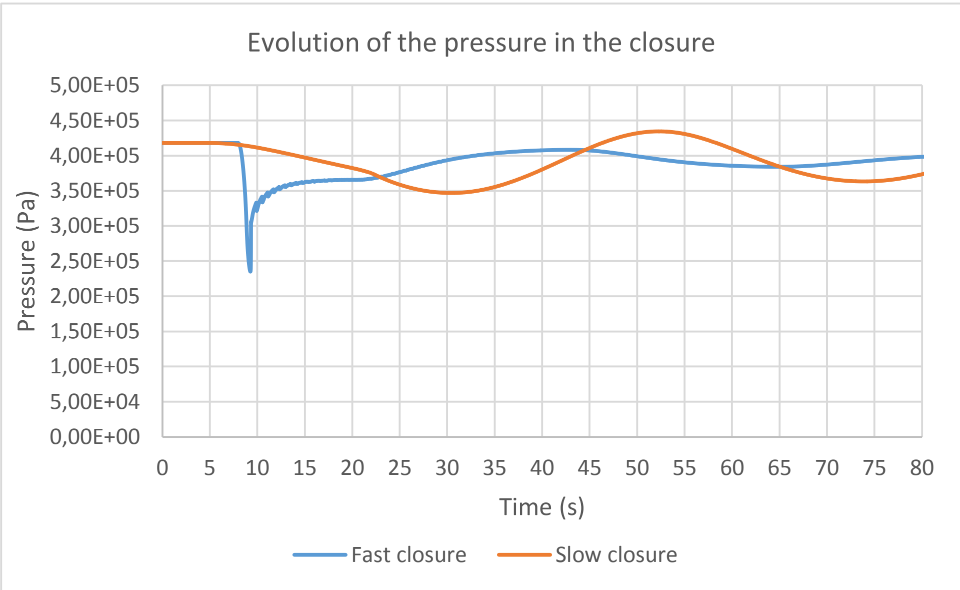


Figure 8.15 Evolution of pressure in each simulation

9. Transient simulations with the adjusted model

In this chapter, the start-up and shut-down of the pumping system is simulated. During these transient events, the pressure, which depends on the pump rotational speed, keeps changing and, consequently, flow rate also changes. The main objective of the simulation is to verify that the transient events do not present any problem.

The study is focused on detecting pressure and thermic variations that could damage components. Before proceeding to the simulations, it is necessary to adjust the model for each of the states (start-up and shut-down) that are going to be studied.

9.1. Normal start-up of the pumping system

The model simulates the real pump start. The procedure of the pumping system's start follows the order indicated in the next list:

1. Start of P11 pump
2. Start of P07 pump
3. Start of P08 pumps (both twin-pumps mounted in parallel start simultaneously)
4. Start of P09 pump
5. Start of P10 pumps (both twin-pumps mounted in parallel start simultaneously)

Steps are sequential, when a pump reaches the pressure set point, next pump is activated.

9.1.1. Model adjustments

Pump input can be rotational speed or torque. Depending on it, Flowmaster makes different types of simulations. If the input is rotational speed, Flowmaster does not apply pump properties that have an effect in transient simulations while it does if torque is selected as input. Despite this fact, previous model was set with rotational speed as pump input because it was designed to simulate stationary events.

The required adjustments made are the following:

1. Motor and pump inertia calculations. It is explained in Section 5.2.1.3.
2. Scripts that regulate the three way valves opening have been removed from the model as the start of the pumps is always made before electromagnets are activated. The opening of the three way valves has been set at 50% and the model has been reduced to a transient simulation with no heat transfer. The power exchanged in the heat

transfer have been set also to zero and the component only appears in the model as a discrete loss.

3. Changes in PID output signal:
    a) The output variable has been changed from rotational speed to torque.
    b) Maximum torque for each pump has been calculated, see Annex section C to see the values.
    c) The generation of the output value is made by a script. The variable is changed and a new script has been adjusted, using the values of maximum torque, in order to deliver to the pump the correct torque value.

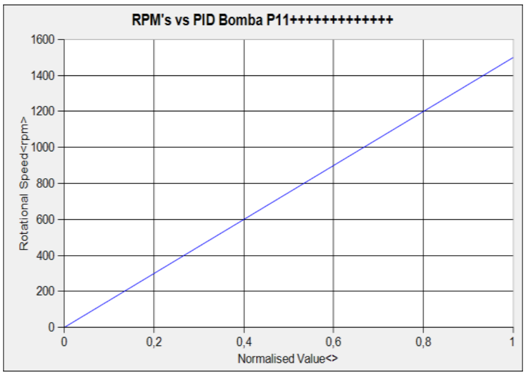


Figure 9.1 Previous script in the PID controller

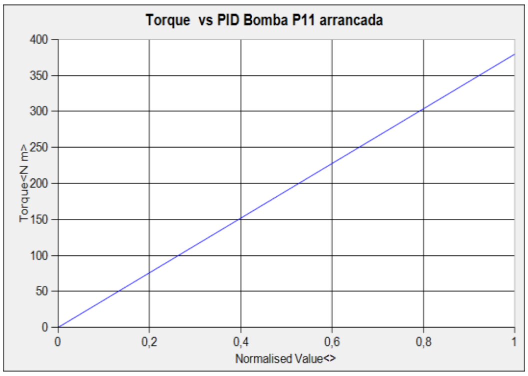


Figure 9.2 Adjusted script in the PID controlled

9.1.2. System's response of the common start-up

The start of the pumping system has been modelled and proceeded as in ALBA's synchrotron. By the simulation, it is seen that the system needs approximately 100 second to reach the stationary state. The duration needed in each pumping station to reach the pressure set point is showed in the table below.

Table 9.1 Time to reach the stationary states in the start of each pump

	P11	P07	P08	P09	P10	Total
Time to reach stationary state (s)	4	30	25	30	10	99
Time of start-up (s)	0	4	34	59	89	

See in Figure 9.3, the time that each pump starts in the simulation.

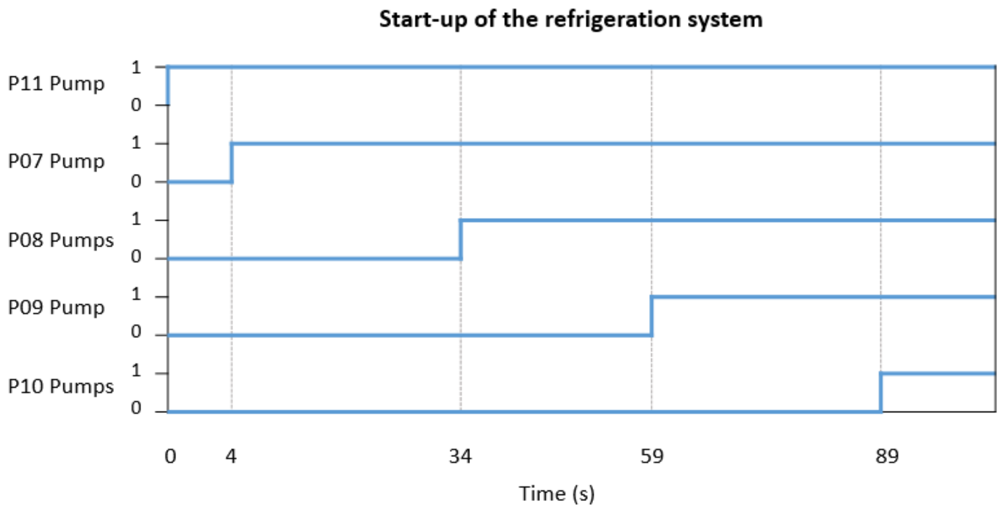


Figure 9.3 Start-up time of each pump in the simulation

As for the system start, when the pumps are started, the pressure reaches a peak, higher than the pressure set point. It happens because of inertia of the pump. When the PID controller lowers its torque signal value, the pump still has the previous acceleration and inertia, which means that it will need some time to meet the value set by the output PID signal. The Figure 9.4 shows the correlation of pump's rotational speed and PID output signal.

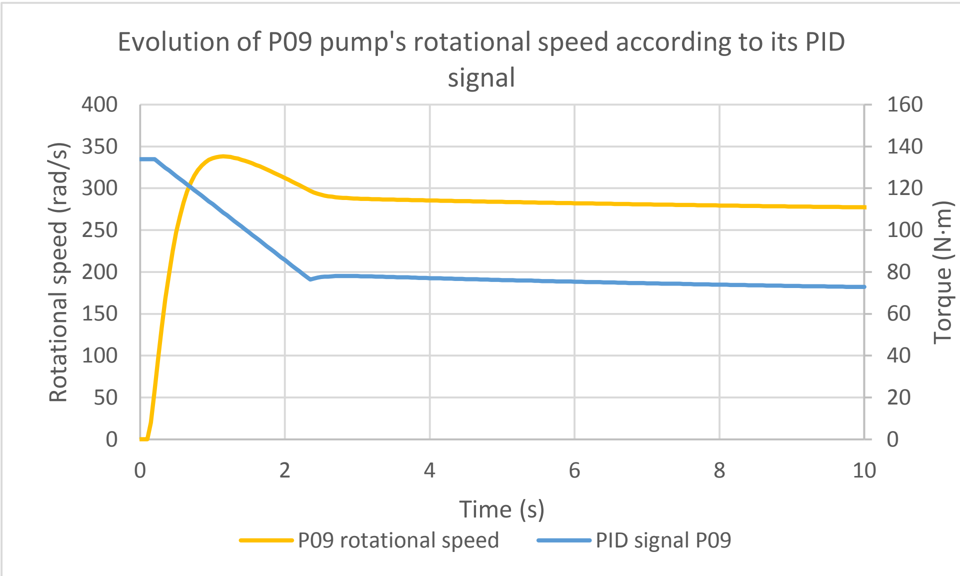


Figure 9.4 Evolution of P09 rotational speed related to its PID signal

The pressure peaks for each pumping system are different due to the different values of maximum torque, pressure set point, pump and motor inertia. The highest pressure peak is experienced in pump P09, with an elevation of the 54% of its set point value, which is $1{,}02 \cdot 10^7$ Pa . The lowest overpressure is produced by pump P11.

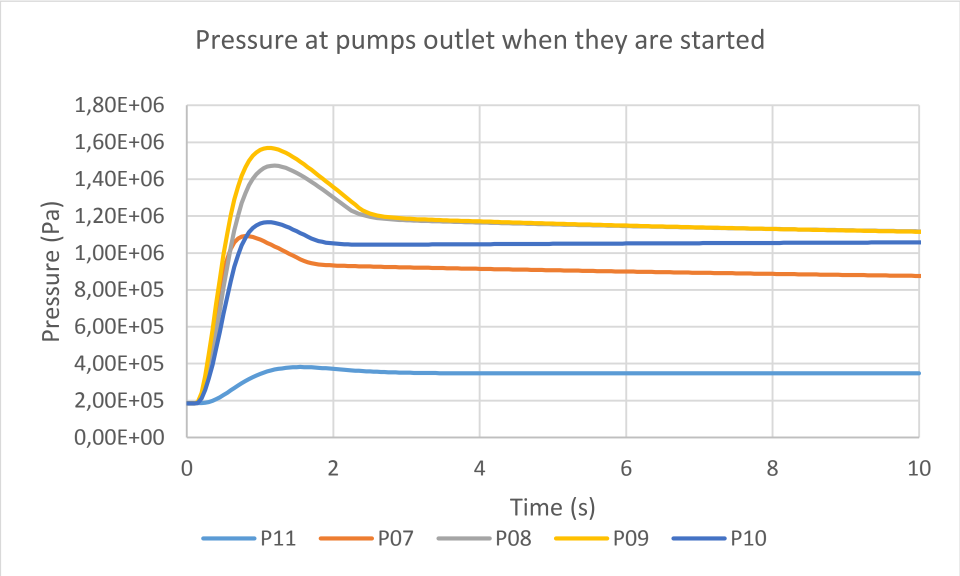


Figure 9.5 Pressure evolution during the start of each pump

The dependency of the pressure peak cannot be assign to just one property but the PID controller output value plays an important role. As it can be inferred from the image below, the slowest stabilization of the PID signal is in the pumping system P09 since the pressure peak is the latest one to be stabilized. On the other side, as PID signal P11 slope is the flattest, the overpressure generated at P11 is lower than in the other pumps.

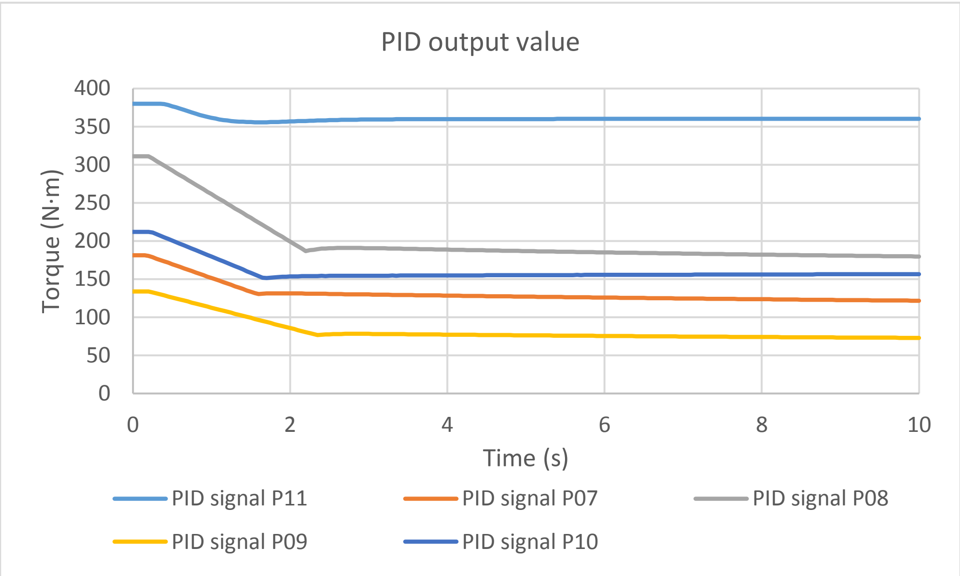


Figure 9.6 Evolution of the PID output value as each pump is started

As the pressure is the input value for the PID controllers, rotational speed vary in direct proportion. Consequently, pump P09 is the most affected and its rotational speed also reaches the highest peak.

P11 pump start-up

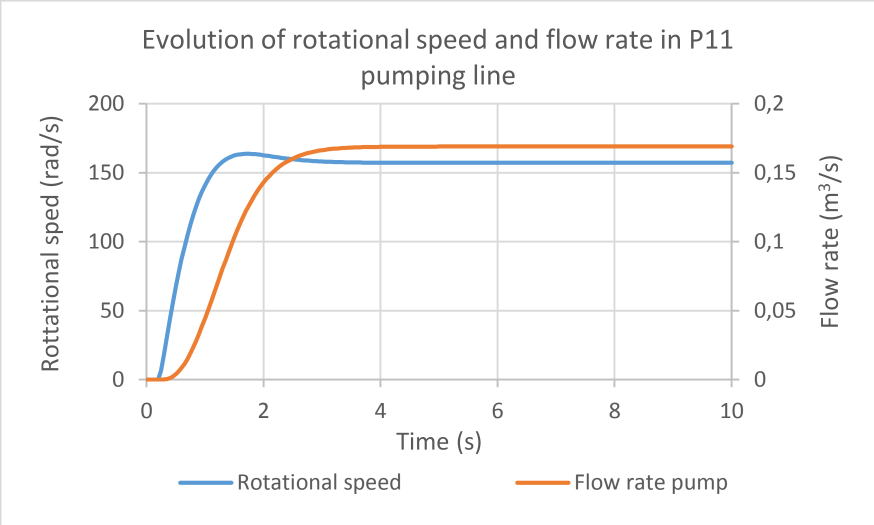


Figure 9.7 Evolution of P11 pump properties

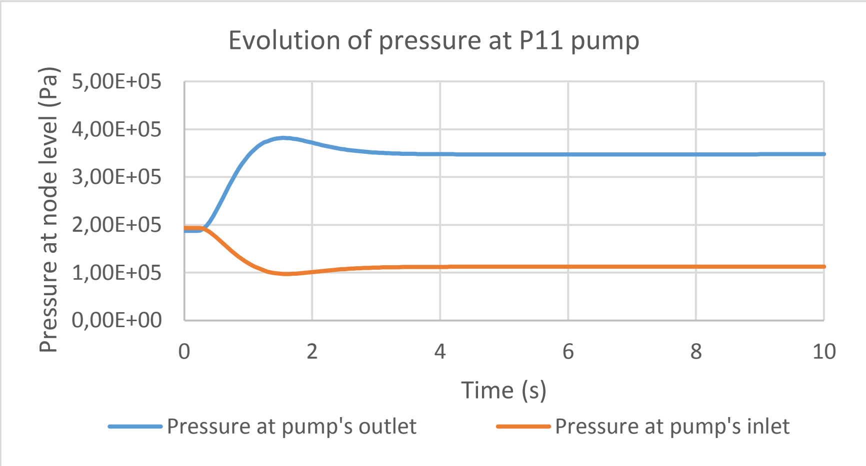


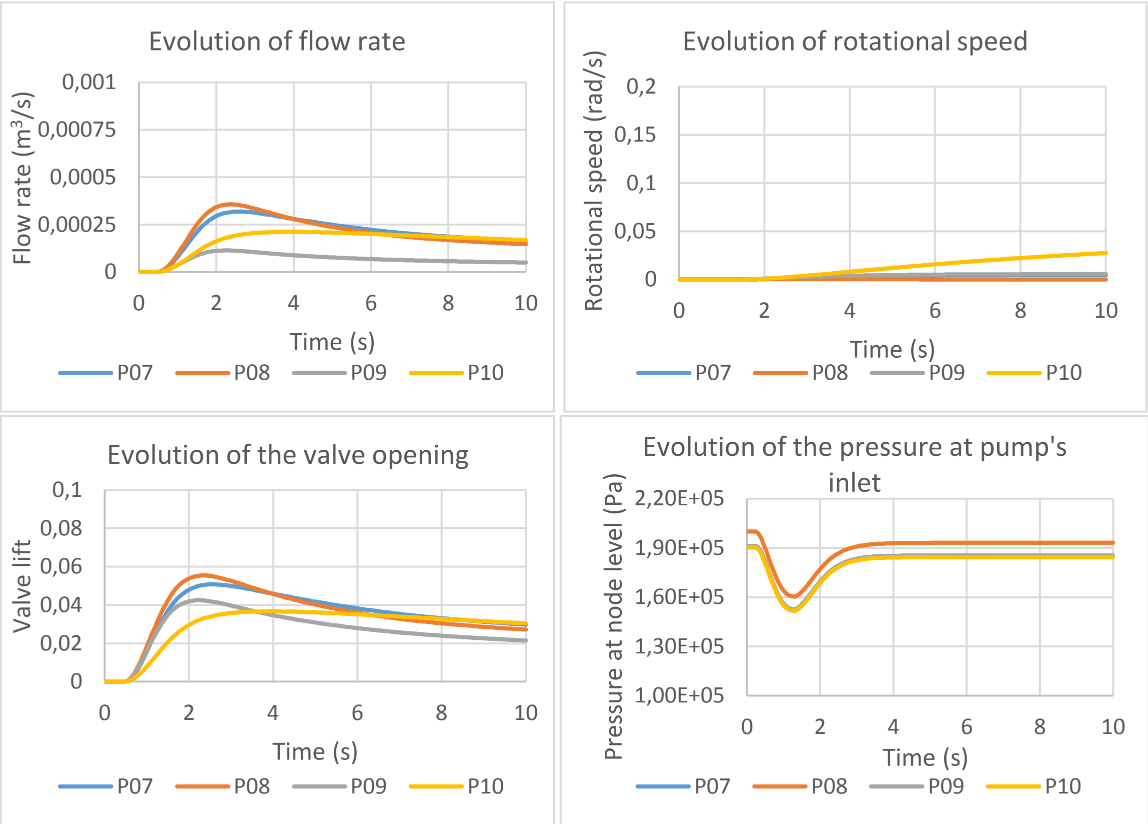
Figure 9.8 Evolution of P11 pump pressure property

Pump P11 is the first pump to be started. Notice that when pressure stabilizes, rotational speed and flow rate do also. If the pump is not activated, both pressures are the same and equal to the pressure that the Pneumatex is providing to the piping system ($2{\cdot}10^5$ Pa) because flow does not move and there are no pressure losses.

When the pump starts, the upstream node pressure increases due to the action of the pump. The downstream node gets its pressure reduced due to all the pressure losses that exist in each component of the piping system when flow starts.

Effect in the other pumping lines

The effect of the pump P11 start is minimal in the other pumping lines. Flow starts moving in all the rings at a very low rate and forces the pump to have a minimal rotation speed. Valves are almost closed and pressure drop caused by components loss are also small.



Figures 9.9 Pumping lines evolution of the flow rate, rotational speed, valve lift and pressure at pump's inlet

P07, P08, P09 and P10 pumps start-up

As for the start of the other pumps, a common behavior can be seen in the response of the system. Firstly, the start of the pumps is not producing a significant perturbation in the other rings. However, as it is a closed piping system, the other rings experience small changes in pressure and flow rate. Also, in the common return line, the changes are more important but far from being too severe to cause any component failure. To see the full results of each of the pumping start and the effect to the other pumping lines, see Annex section H.

The flow distribution during the start up

At 0s, pump P11 is activated and flow stabilizes in few seconds. The flow that is suctioned by the pump comes mainly from the accumulator but also from the three way valves. A small part of the flow moves through the pumping lines.

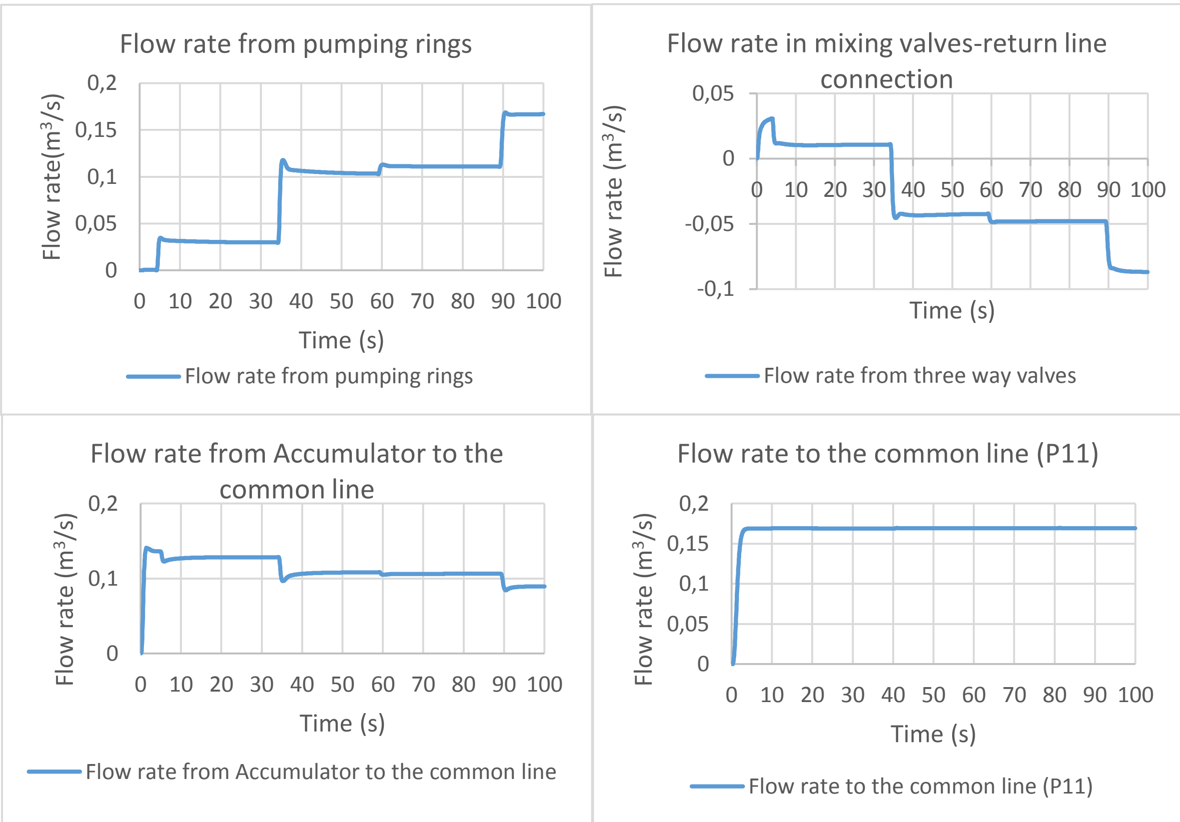
At 4s, pump P07 is activated. The flow rate in the pumping lines increases due to pump P07 activity. Consequently, the pressure reorganization of the system provokes that flow from the three way valves and the accumulator gets reduced.

At 34s, pump P08 is activated. The consequences of its start are a flow rate increase in the pumping lines and a decrease in the flow rate going from the accumulator to the common line. The flow rate that is inside the pipes that connect mixing valves and common return line changes its direction and moves downstream, suctioned by the lines' pumps.

Twenty five and fifty five seconds later, pump P09 and pump P10 are started respectively. The flow rate is regulated and, in stationary state, the direction of flow is the following:

- Pumping lines operate as normal because the pressure is stabilized in the system. These pumps suction flow.
- Flow moving inside the connection mixing valves-common return line is moving downstream, suctioned by the rings' pumps.
- The accumulator provides flow to the common line.

The following figure shows the described evolution of the flow rate in the piping system.



Figures 9.10 Evolution of the flow rate during the start of the cooling system

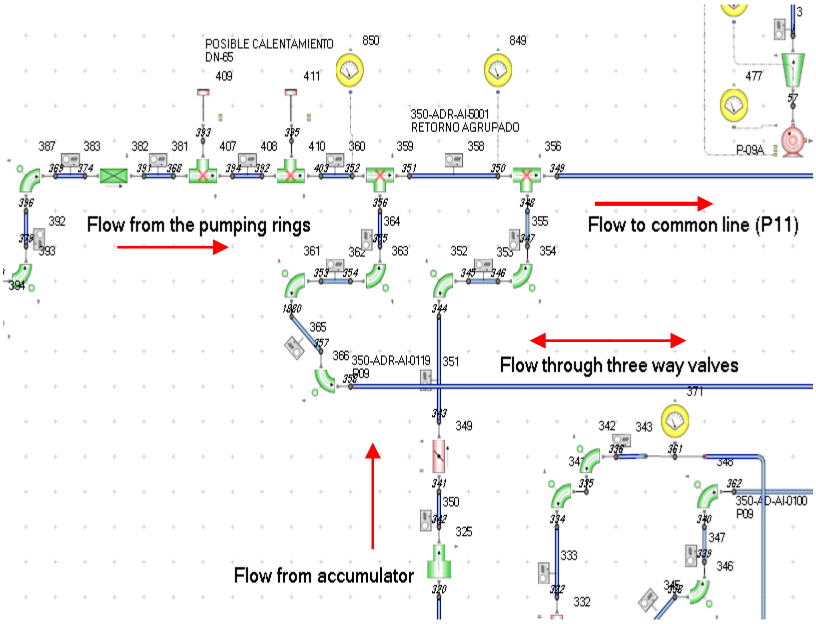


Figure 9.11 Part of the Flowmaster model where some pipe connections are connected

9.1.3. Improvement actions

Firstly, from the response of the system, it has been detected a pressure peak in the start of all the pumps. This pressure peak is produced by the delay time between PID controller and pump. The overpressure may damage and reduce the life of the piping components.

In order to avoid the pressure peaks, it is necessary a modification of the PID controller's characteristic values. However, it is an extensive study of design, validation and PID implementation which is out the scope of this project. The PID characterization study can be the continuity of this project inside CELLS plans of activities' development in the fields of stability and reliability for the cooling system.

An advantage for the continuity of this project is that the adjusted model built for this project is very helpful for the design and PID implementation, in order to simulate the response of the system according to the PID parameters. Finally, the validation should be tested physically in the ALBA's cooling system.

In the following section, alternatives to the actual PID set parameters are proposed in order to verify if there is room for improvement. Properly changing the PID characteristic values, the overpressure generated at the startup of the pumps can be reduced significantly.

9.1.3.1. PID controller tests

In order to detect pressure peak variations and their correlation with the PID, changes are made one by one. The actual PID controller is a proportional-integrative with the following parameters:

- Proportional constant, K_P = 0,75
- Integrative constant, K_i = 0,2
- Derivative constant, K_d = 0

The simulations is made on the P09 pumping ring, as the corresponding pump is generating the highest overpressure signal. For each parameter, the properties evaluated are the following:

Table 9.2 Table of the different values simulated for each PID controller parameter

K_p	0	0,75	1	2	10
K_i	0	0,2	0,5	2	5
K_d	0	0,1	0,2	0,5	2

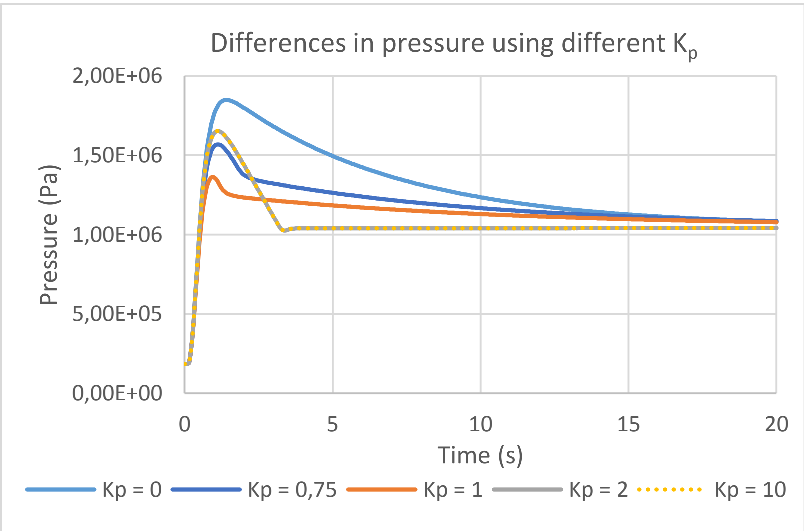


Figure 9.12 Differences in pressure response at pump outlet using each value of K_p

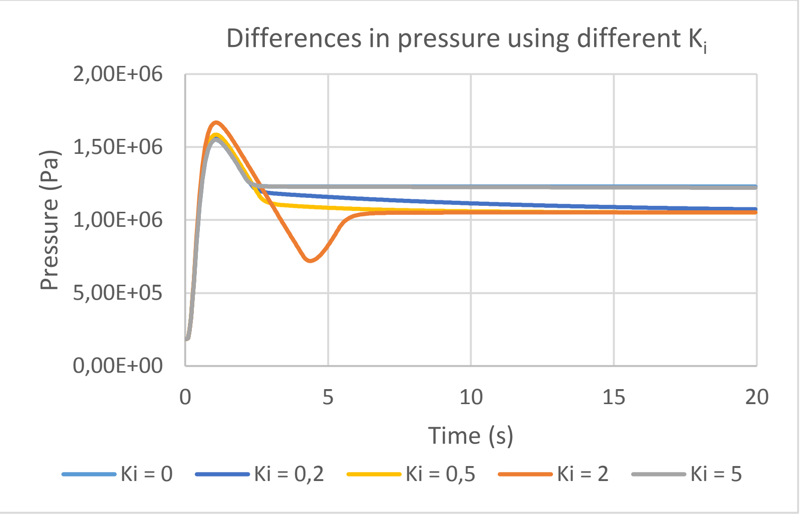


Figure 9.13 Differences in pressure response at pump outlet using each value of K_i

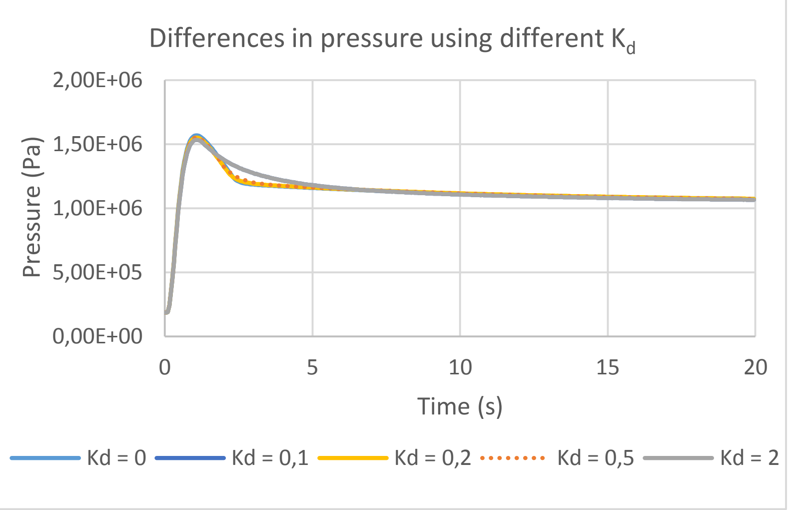


Figure 9.14 Differences in pressure response at pump outlet using each value of K_d

According to the results obtained from testing different parameters, it is verified that PID controller can be improved in order to achieve better response in peak pressure. For the proportional constant, setting $K_p = 1$, the simulation produces a pressure peak of 32% the pressure set point while the pressure peak with the original K_p arrives to the 54%. The simulations testing different values of K_i and K_d did not show any significantly difference in pressure peak but they do in the pressures slope.

As a consequence of the result obtained, it is verified that there is room for improvement in the field of digital control technology by adjusting the PID controlled in our system.

9.2. Unexpected pump shut-down

The shut-down of the cooling system should take place when there is not heat generation, which means that the electromagnets are not activated. However, the system might also experience pumping failures when the synchrotron is in normal working state.

According to ALBA's synchrotron needing, the scope of this simulation is the following:

- Investigation of unexpected pumps' stops. It may happen when synchrotron is in operating state or not. For this reason, two different simulations are made; with no heat transfer and with heat transfer. The pumps' stop analyzed are the followings:
    - Shut-down of P07 pump
    - Shut-down of P09 pump
    - Shut-down of P08 pumps (stop of one pump)
      (both two pumps simultaneously)
    - Shut-down of P10 pumps (stop of one pump)
      (both two pumps simultaneously)
    - Shut-down of P11 pump

- Simulation of the simultaneous pumps' stop. This simulation aims at analyzing the stop of the cooling system when all pumps are stopped simultaneously. This simulation is made without thermic effect as it is supposed that the synchrotron is not operating when this action is taken.

9.2.1. System's response with no heat transfer

In the adjusted model, the scripts that regulate the opening of the three ways valves, in function of the temperature, have been removed and the valves opening has been set at 50%. The power exchanged in heat exchangers has been set at zero and these components only act as a pressure loss.

i. <u>Shut-down of P08A pump (stop of one pump)</u>

Pumps P08 are two pumps (A and C) mounted in parallel. As their components are identical, the simulations show same results for both P08 pumps when they act simultaneously. However, this simulation simulates the failure and shut-down of the P08A pump. As a consequence, a transient state starts because the pressures are not in equilibrium anymore. In P08 pumping ring, the pressure decreases from the pressure set point immediately.

As a response, P08C PID controller, sends the signal to its pump to increase the rotational speed and gain pressure until the pressure set point is reached. The flow rate that was divided into two pumps, now is suctioned only by P08C pump. As P08C is powerful enough, the pressure set point is reached and its flow rate is doubled. Thus, the transient events ends when the pressure set point is reached again in the pumping lines and the system returns to its nominal operating state. The time need to reestablish the stationary state is 50 seconds.

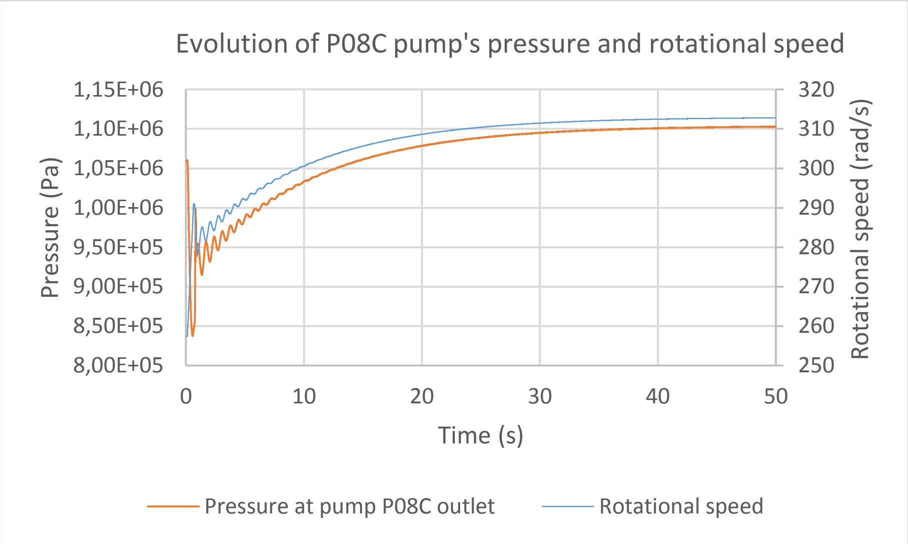


Figure 9.15 Transient event experienced in P08C pump outlet when P08A pump is stopped

The effect of the transient event in P08 pumping ring is showed in the following pictures:

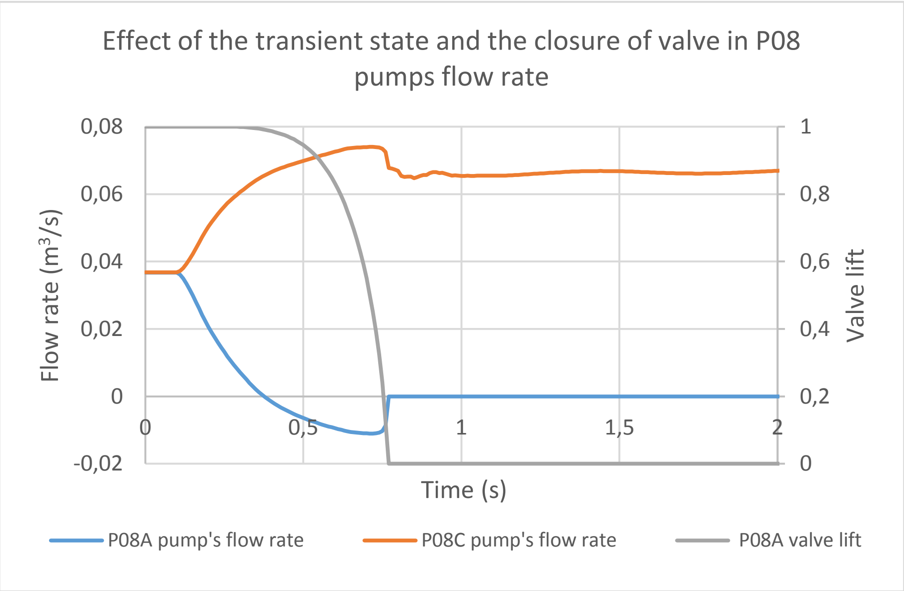


Figure 9.16 Flow rate and valve opening evolution in P08 pumping line

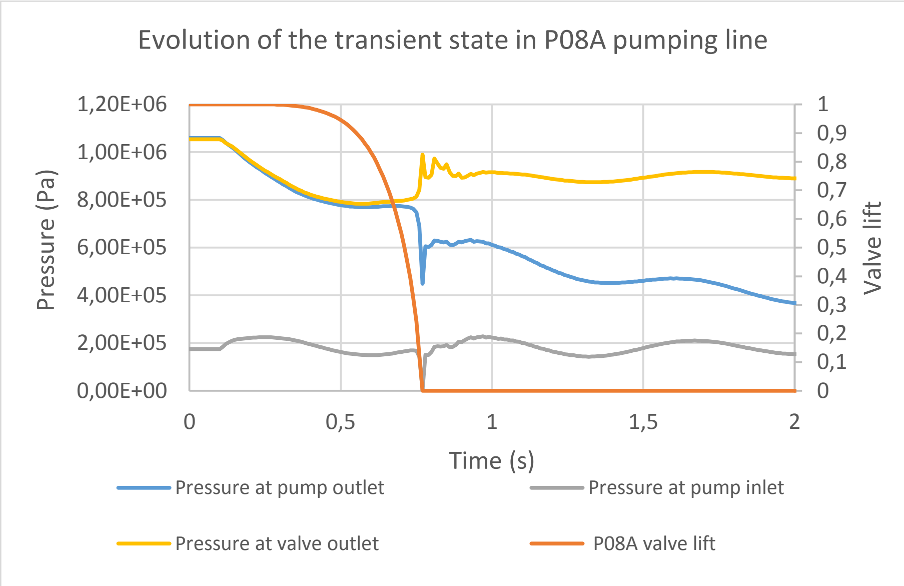


Figure 9.17 Reaction in P08A pumping line to its pump closure

As it can be inferred from the figures above, the closure of the valve happens around 0,8 seconds after the simulation's start and it has an impact in the system. In this situation, the valve does not close fast enough and flow rate moves in reverse direction during 0,3 seconds until the valve closes.

In Figure 9.16, it is seen that the flow in P08A piping line is suctioned by P08C pump. As a consequence, the flow changes its direction and moves downstream until the valve closes. When the P08A valve closes, a disturbance is generated through all the pumping lines. At the outlet of the valve, the phenomena of water hammer is created. The phenomena has a small amplitude and disappears in less than 0,5 second.

At P08A pump, the drop of pressure reaches the vapour pressure and cavitation occurs at 0,8 seconds, even though the pressure recovers immediately. Furthermore, the closure of the valve produces more consequences. Firstly, it generates a negative pressure wave that travels and generate an immediate pressure drop through all the piping system. See in Figure 9.17 the drop in pressure propagated in the other pumping lines.

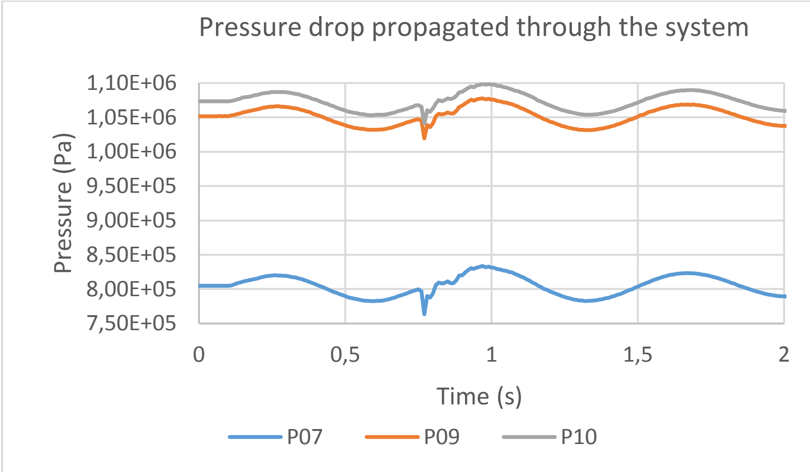
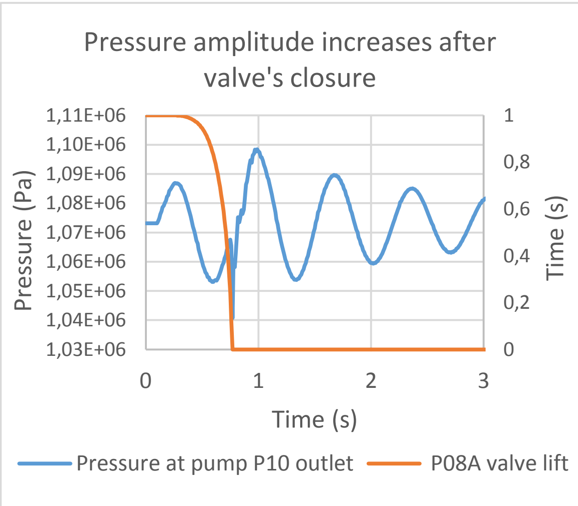


Figure 9.18 Pressure drop detected in the other pumping lines

Secondly, when P08A is stopped, the system pressure start to fluctuate as it is not stable. When the valve closes, the amplitude of the pressure drop is higher than the pressure fluctuation and, as a result, the amplitude of the pressure fluctuation increases. Hence, the system needs more time to reach the stationary state, around 50 seconds to reach the pressure set point again. The pressure fluctuations disappear after 20 seconds.

The fluctuation of pressure leads to the PID controllers to send sinusoidal signals to the pumps, which are converted into a sinusoidal variation in the rotational speed of each pump. These consequences can be noticed in the figures below.



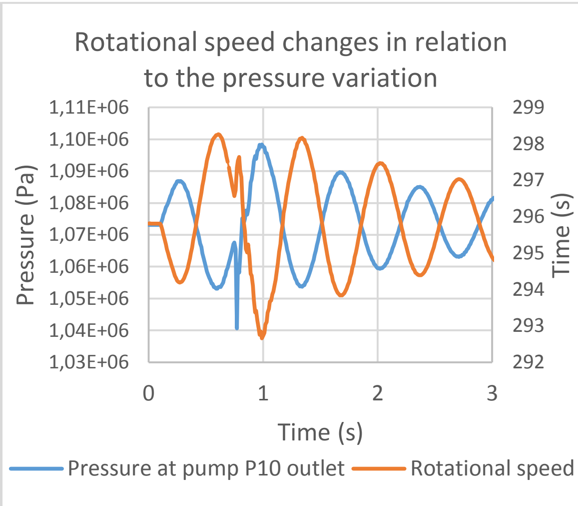


Figure 9.19 Amplitude increases after the valve closure *Figure 9.20 Relation between pressure and rotational speed*

With regard to the other pumping lines, the highest effects of the P08A pump's stop can be seen in the common return line because it is connected directly, as flow travels from the P08 pumping ring to the return line.

See in the figures below, the effect of the transient state in the common return line (P11). As the pressure set point for P11 pump is 3,5·10^5 Pa, when the pressure value surpasses the set point level, the PID controller sends the signal to reduce the rotational speed and, on the other hand, when the pressure lowers the set point value, the pump rotational speed gets increased until its maximum in case the pressure has not arrived yet to the set point value. The maximum pressure oscillations happens after the valve closure and have an amplitude of 0,3·10^5 Pa.

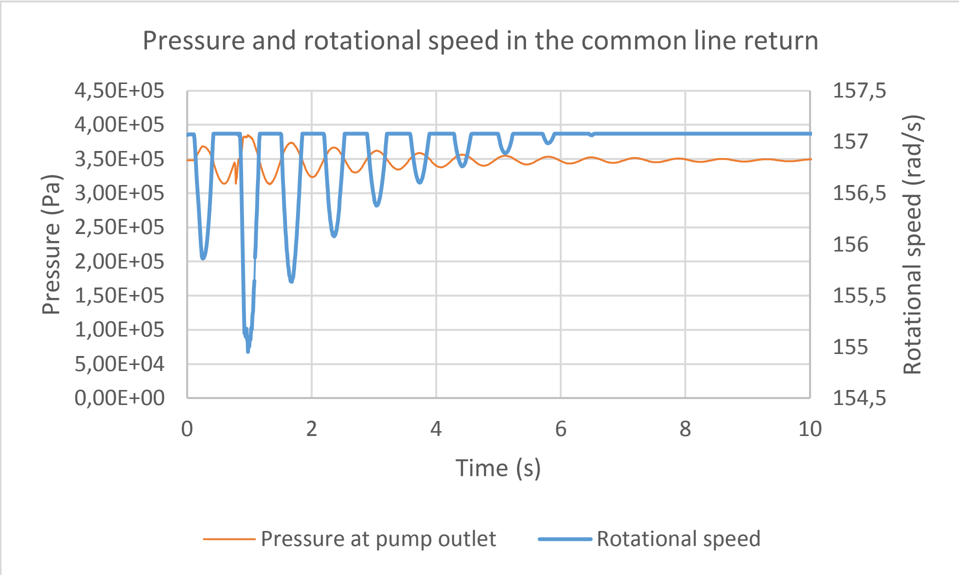


Figure 9.21 P11 pump behavior during P08A stop

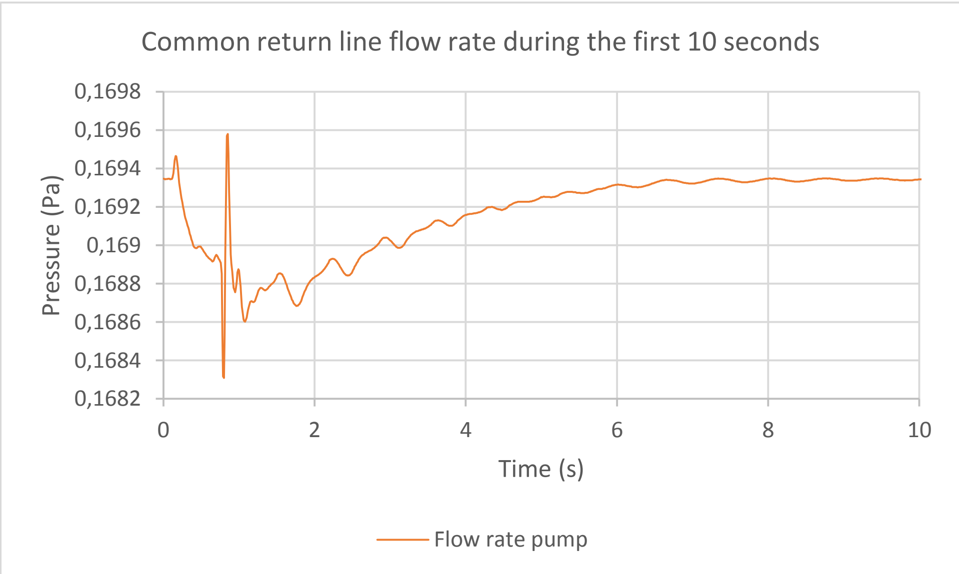


Figure 9.22 Evolution of P11 pumping line flow rate

With regard to the flow distribution, it will be back to the operating state once the system reaches the pressure equilibrium. Then, the flow distribution will be exactly the same as the normal operating system because P08C pump can counteract the pressure loss and maintain the pressure at the set point level.

There is a decrease in the flow suctioned to the pumping lines because the pump's force of suction is reduced as P08A pump is stopped. Then, the flow that moves from the pumping lines to the P11 pump is less than in operational state and, as a results, P11 pump suctions more flow from the accumulator, the difference of flow that is not obtaining from the pumping lines.

The transient evolution of the flow rate is seen in the following figure:

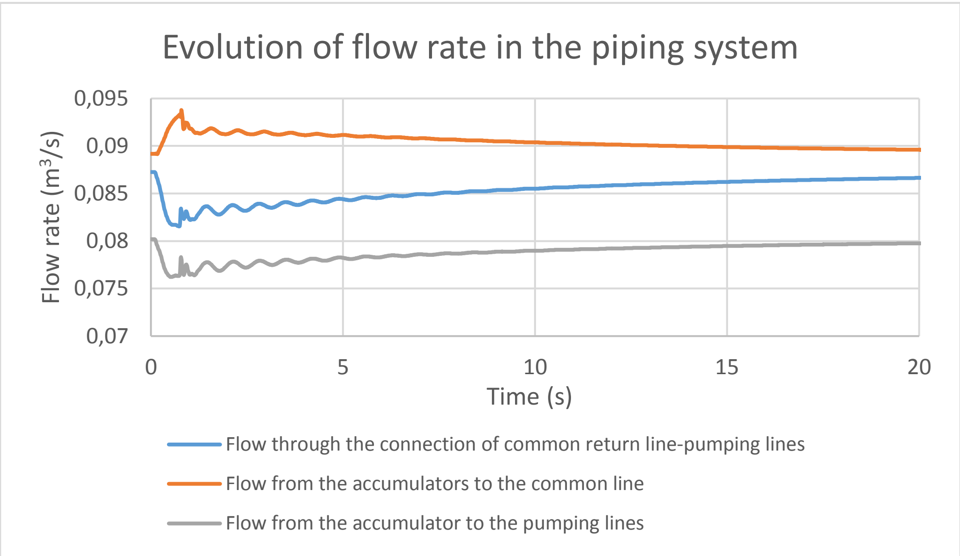


Figure 9.23 Evolution of the flow rate distribution in the system as a consequence of P08A pump stop

ii. **Shut-down of P08 pumps simulation (both two pumps simultaneously)**

In this simulation, it is modelled and simulated the stop of the two P08 pumps. The main interest about this simulation is to see how pressure changes while a whole pumping station turns as inoperative. The fluidic dynamic simulation is also a case of study.

The results of the system's response has showed that stopping a whole ring results in a transient state where pressure, rotational speed and flow oscillate until a new state of pressure equilibrium. The duration of this transient event is about 25 seconds, when the valve closes entirely. However, in this case, the closure does not produce any effect in the system as the pressure slope is nearly flat. Before its closure, the valve oscillates because flow is constantly being reduced as the P08 pumps do not suction anymore.

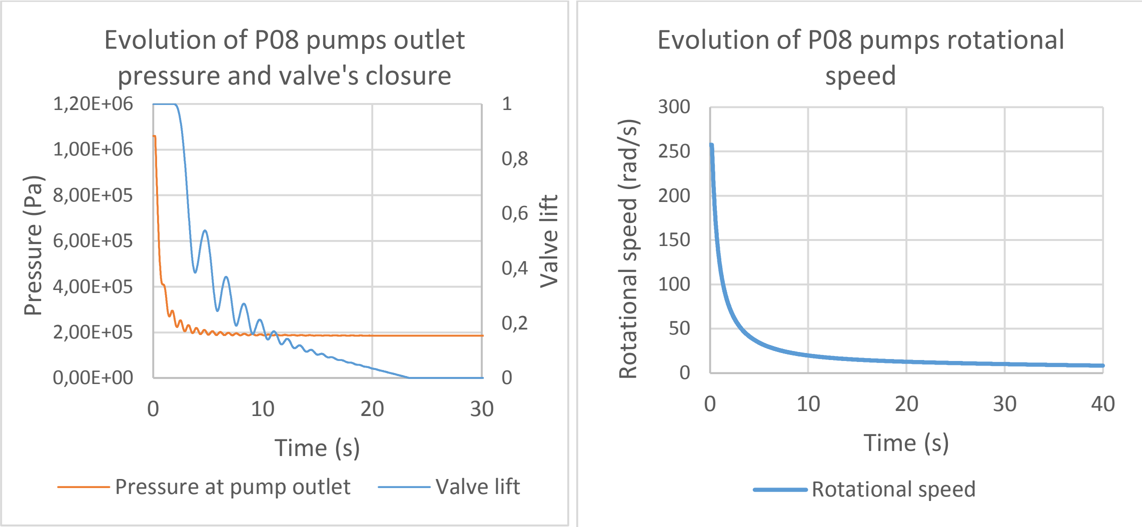
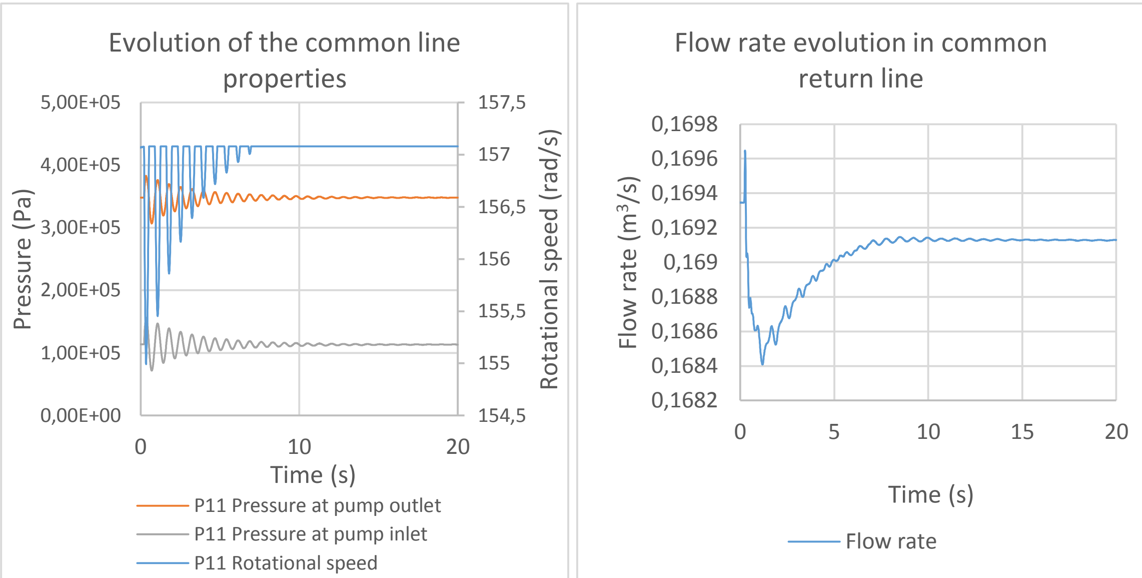


Figure 9.24 Behavior of P08 pumps when they are forced to stop

The effects seen in other pumping lines are higher than in previous simulation. As the most affected pump line is the P11 pump line (common return line), only these results are exposed in this section.



Figures 9.25 Behavior of P11 pumps when P08 pumps are stopped

See Annex section H to see the pressure, rotational speed and flow rate variation in each pumping ring when P08 pumps closes.

With regards to the flow distribution. Due to the stop of P08 pumps, the pumping lines cannot suction as much flow as before. As a consequence, the flow rate that moves from the accumulator and the connection mixing valves to the pumping lines decreases and the accumulator moves more water to the common return line (P11 pump).

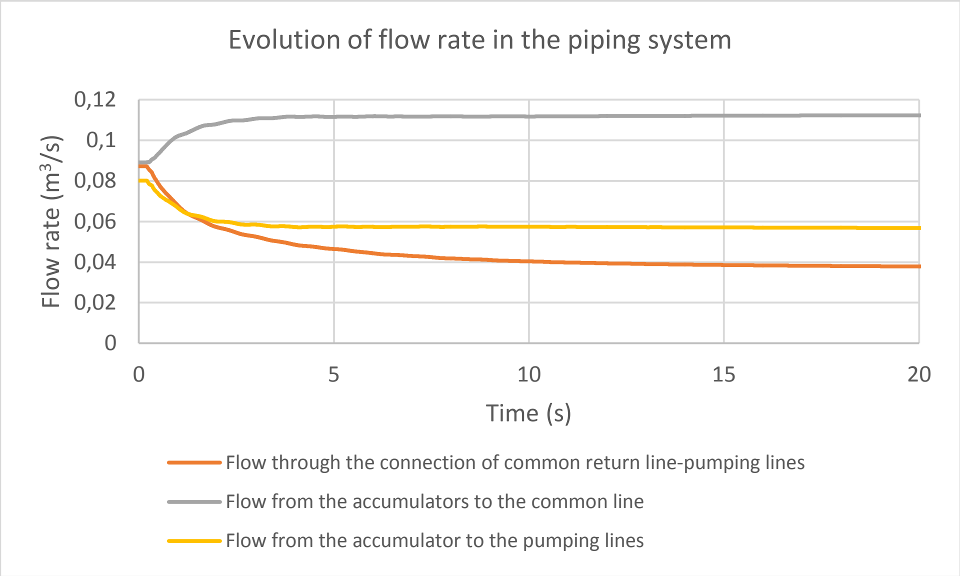


Figure 9.26 Evolution of the flow rate distribution in the system as a consequence of P08 pumps stop

iii. Stop of P10A pump simulation (stop of one pump)

P10 pumps are two pumps (A and C) mounted in parallel. This simulation simulates the failure and stop of the P10A pump. As a consequence, a transient state starts because the pressures are not in equilibrium. This simulation will lead to a different response of the system than the obtained stopping P08A pump as the pumps are different.

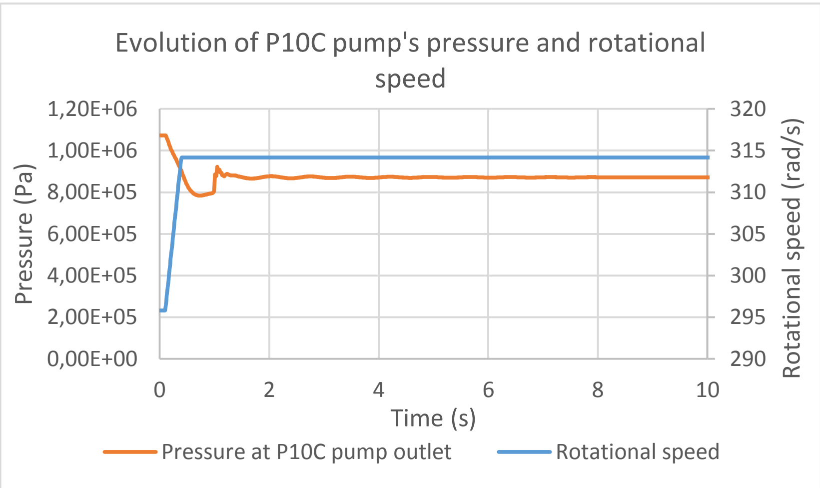
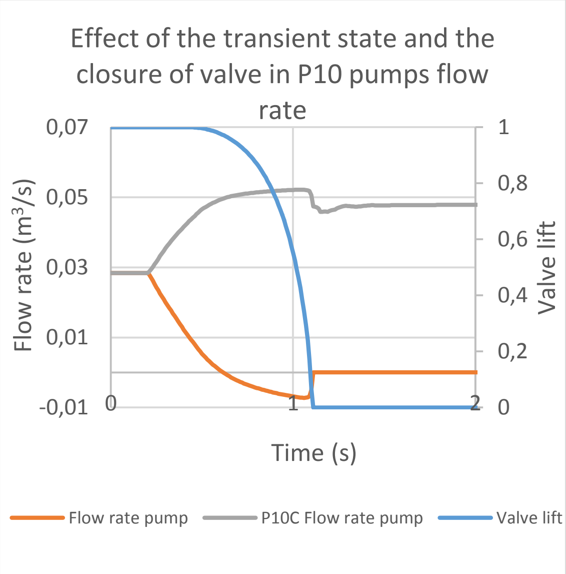


Figure 9.27 Behaviour of P10C pump when P10A pump is forced to stop

In this case, when the P10A pump stops, P10C pump increases its rotational speed in order to maintain the pressure set point. However, P10 pumps have less power than P08 and the pump reaches its maximum rotational speed and can't counteract the pressure's decreases. As a result, pressure and flow travelling by P10 pumping ring are reduced. The closure of the P10A valve generates a brief water hammer at the valve outlet and increases the amplitude of the pressure oscillations.



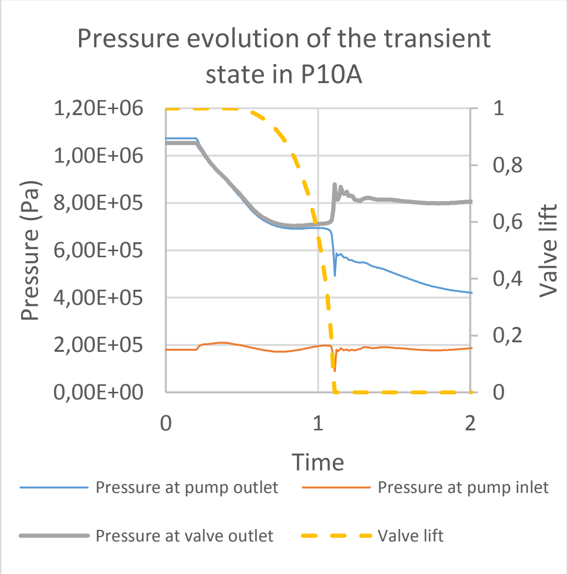


Figure 9.28 Effect of the P10 pump stop in P10 line *Figure 9.29 Behavior of the P10A pump when it is stopped*

The following figure show the distribution of flow rate until the new stationary state is reached.

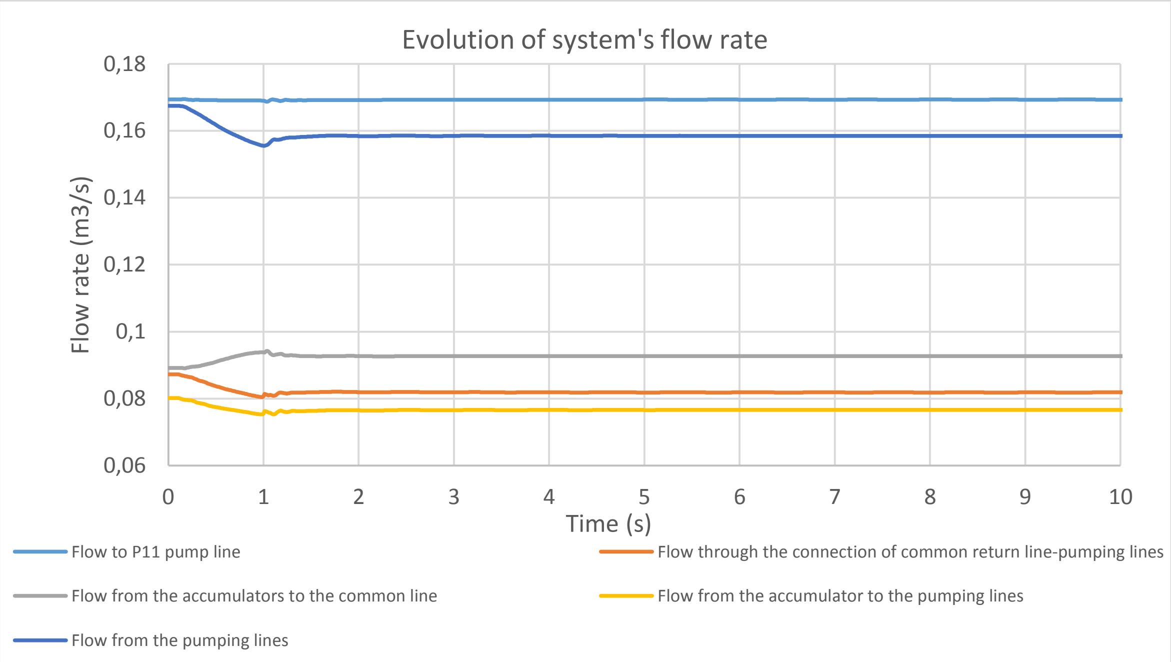


Figure 9.30 Changes in flow system due to the shut-down of P10A pump

iv. Stop of P11 pump

In this simulation, it is modelled and simulated the shut-down of P11 pump.

This line is working at the lowest pressure set point of the pumping lines, $3{,}5 \cdot 10^5$ Pa. When P11 pump is stopped, the valves also closes slowly. As a consequence, the pressure perturbations caused in the system are less important than in P08 or P10 pumps shut-down. Thus, in this simulation it is a case of interest the flow distribution of the system as this pump brings the water to the heat exchangers for cooling the water, which is important when the cooling system is cooling down the ALBA's electromagnets.

With regards to the flow distribution system response, once the P11 pump is stopped, flow to P11 pump line decreases until zero and the pumping are the only ones suctioning the water. As P11 pump does not suction flow anymore, flow from the accumulator to the common return line reverses its direction and travels from the common line to the accumulator. The following figure, shows the evolution of the flow distribution in the system once the P11 pump is stopped.

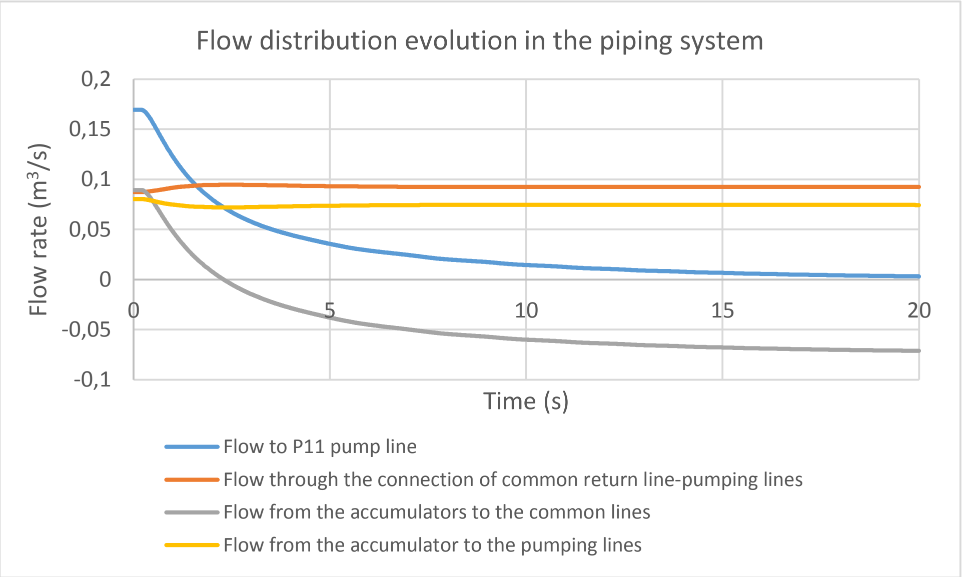


Figure 9.31 Evolution of flow inside the system

v. Stop of the rest of pumps

The following stops can be find in Annex section H:

- Stop of P10 pumps simulation (both two pumps simultaneously): simulation is very similar to the P08 pumps' stop. The fluctuation of the pressure and rotational values are less significant in the other pumping lines as P10 pumps suction less flow than P08 pumps.

- Stop of P07 and P09 pumps: the simulation is similar to stopping the pumps in other pumping stations. As both pumps move less flow than P08 and P10 pumping lines, the effect in the other rings are less significant.

9.2.2. System's response with heat transfer

The study of these simulations aims at finding problems if any of the pumps fail and, as a consequence, stop when the synchrotron is in operating state, which means that heat at the ring is continuously generated. The objective of the study is to determine if there are any pressure and temperature problems as a result of the failure and the effects in the whole system.

From the System's response with no heat transfer simulations, it was verified that the highest pressure oscillations were taking place due to P08A or P10A pump shut-down. With regards to the other simulations, the pressure effects were not as significant as the mentioned previously and the behavior was similar. For this reason, in this section it is only studied the P10A pump shut-down with heat transfer.

The shut-down of the P11 pump is also a case of study because the previous simulation, with no heat transfer, has showed that flow gets suctioned from the pumping lines, and, consequently, it does not reach the heat exchanger. Then, in this simulation, the flow distribution plays a critical role in the thermic response of the system.

i. <u>Shut-down of P10A pump simulation</u>

From the data obtained it is verified that there is not a significant difference in pressure. See it in next figure.

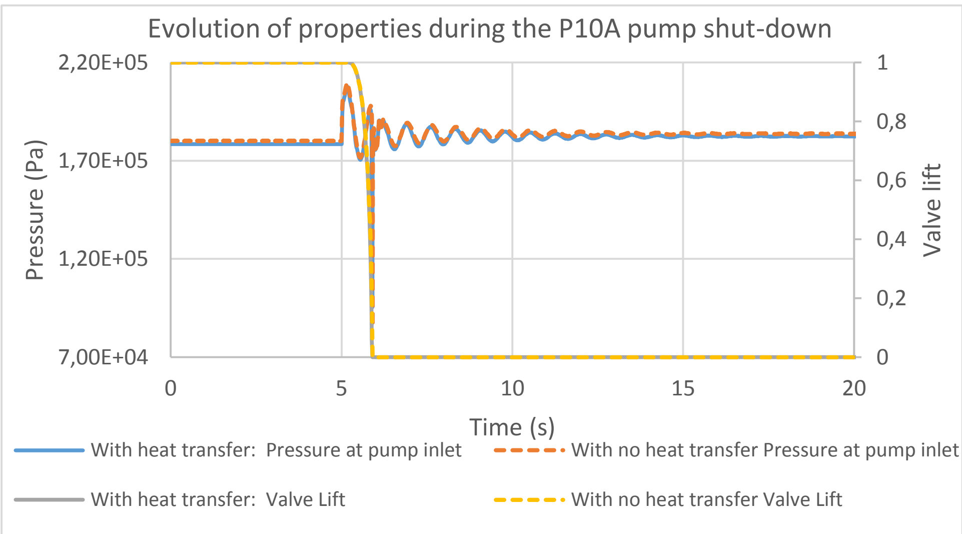


Figure 9.32 Evolution during P10A pump shut-down

Hence, the analysis is focused on detecting changes in system's flow rate and temperature.

As for the flow rate distribution, when the pump is stopped (at 5 seconds), the position of the three way valve changes from 0,75 to 0,765, increasing minimally the flow rate from the common return.

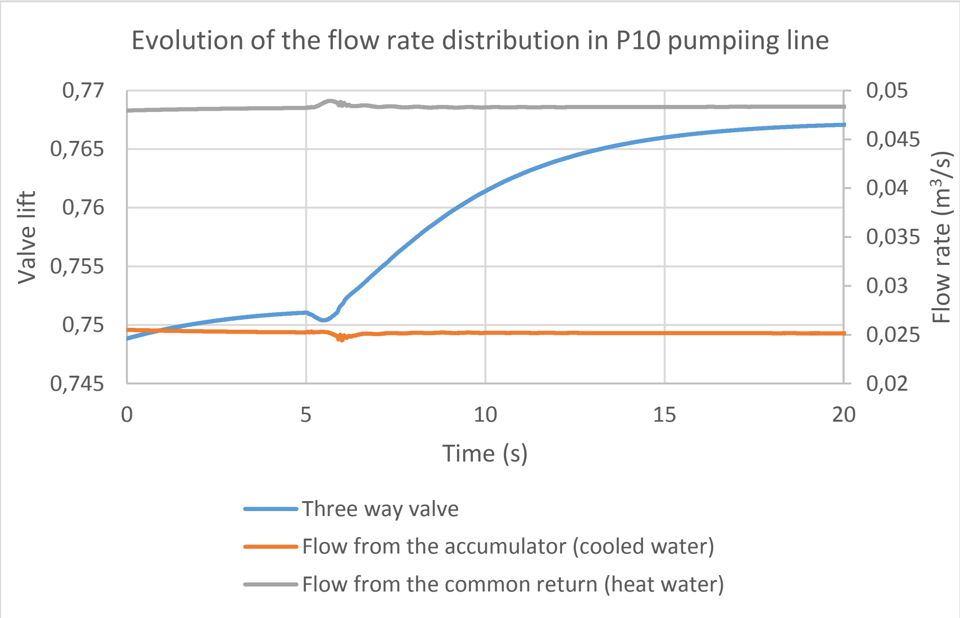


Figure 9.33 Evolution of the flow rate

Once 10A pump is stopped, less flow travels inside the line. As a consequence, the temperature at heat exchanger outlet increases. The increase is small, less than 1°C.

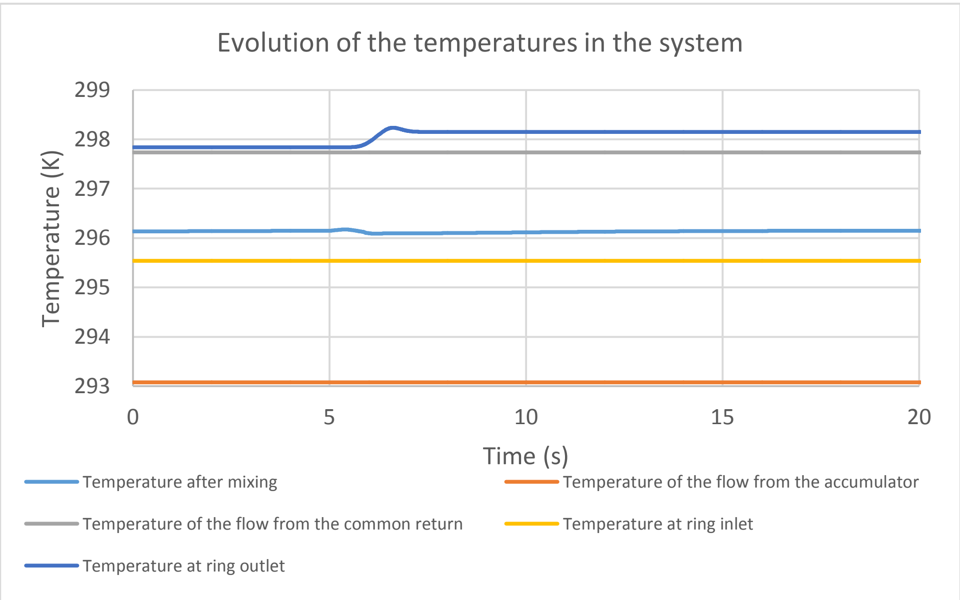


Figure 9.34 Temperature evolution in the system

ii. Shut-down of P11 pump simulation

The previous simulation with no heat transfer was useful to determine the flow distribution. Based from the flow distribution obtained, the thermal behaviour is the case of study in this simulation because when the P11 pump is stopped, the flow doesn't move through the common line return and consequently, the flow is not cooled and it gets hotter as it moves through the consumption rings.

The following images show the system's local response (with a short period of time) after the pump's shut-down.

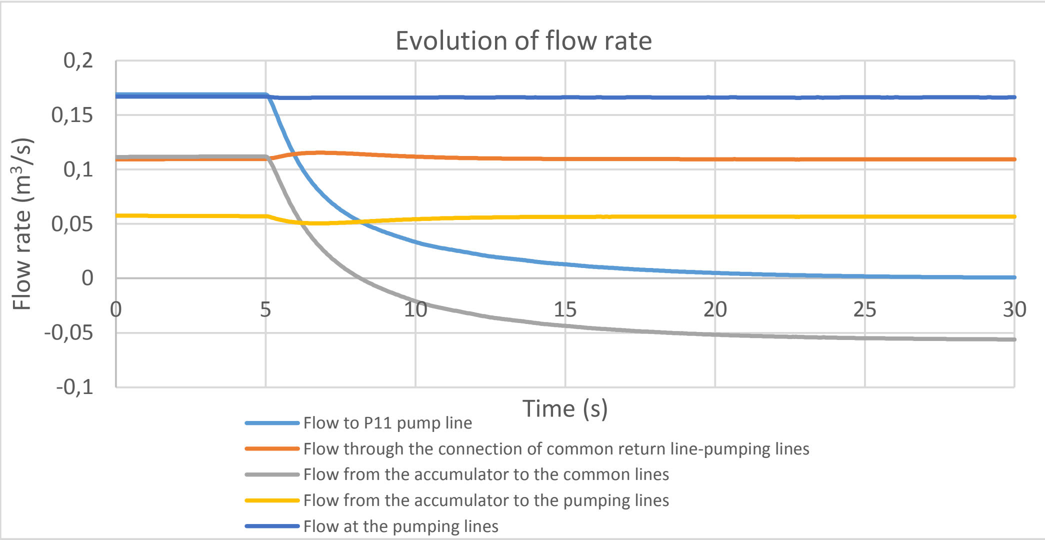


Figure 9.35 Evolution of the flow rate during the first 25 seconds of the transient state

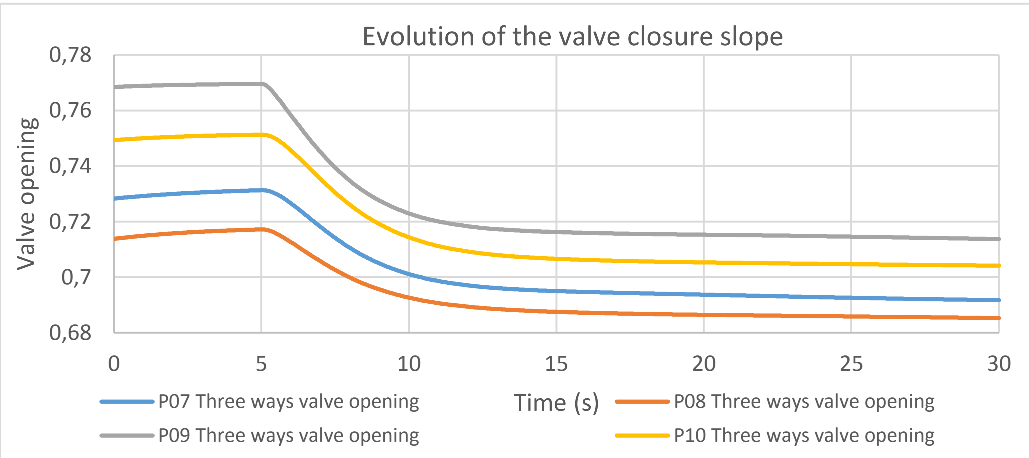


Figure 9.36 Evolution of the valve closure as a consequence of the pump shut-down

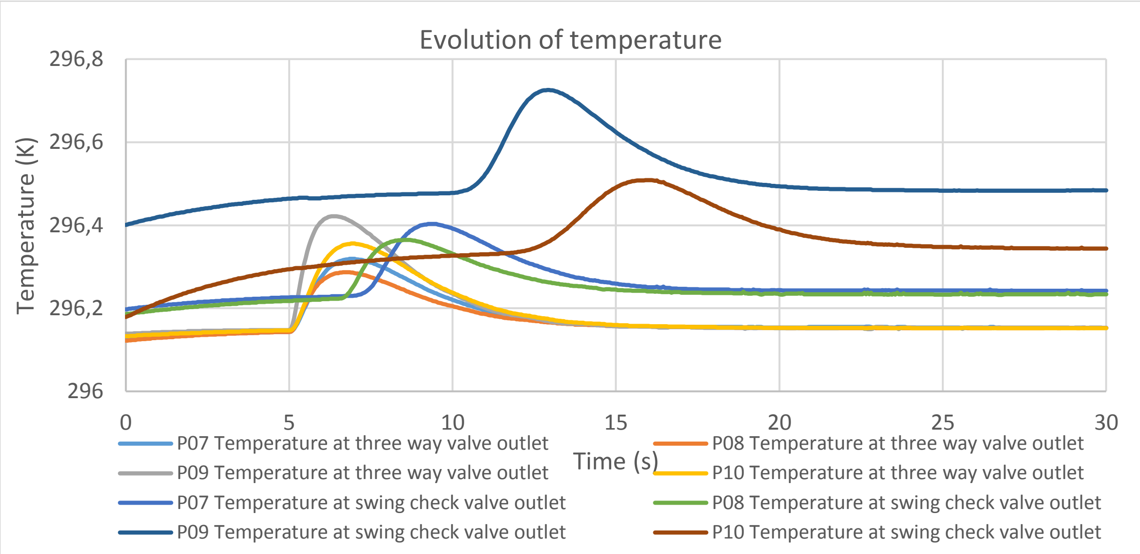


Figure 9.37 Evolution of the temperature in two different points in the pumping lines

In Figure 9.35, it can be validated the assumption that the flow rate suctioned in the P11 pumping line tends to zero when the P11 pump is stopped. In Figure 9.36 and Figure 9.37 it can be seen that the change in the valve's lift produce an immediate change in the temperature at the three ways valves outlets. However, it can also be seen that the flow needs some more time to arrive to the swing-check valve. In consequence, the time for the flow to move through all the system is longer and requires more tie as exposed in the next figures.

<u>Long simulation</u>

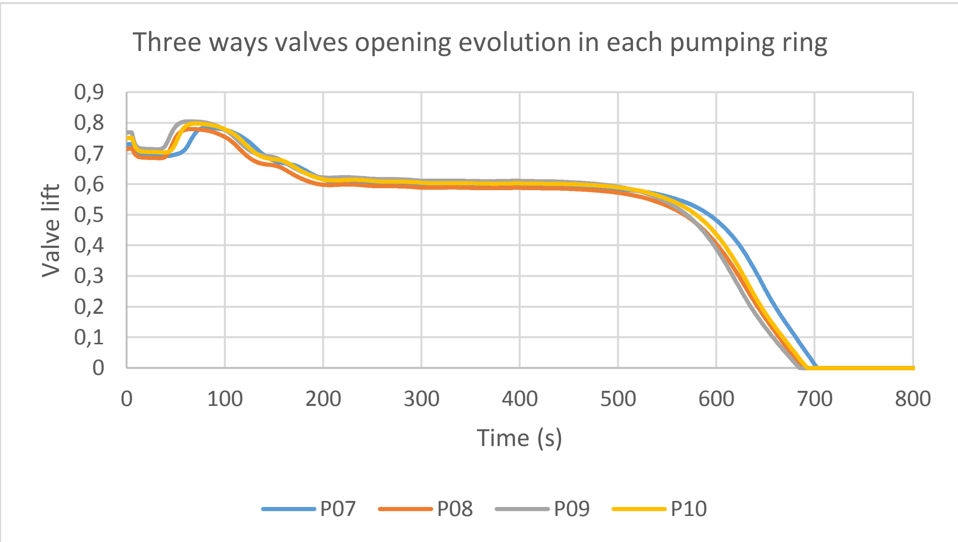


Figure 9.38 Evolution of opening from hot and cold water in each pumping line

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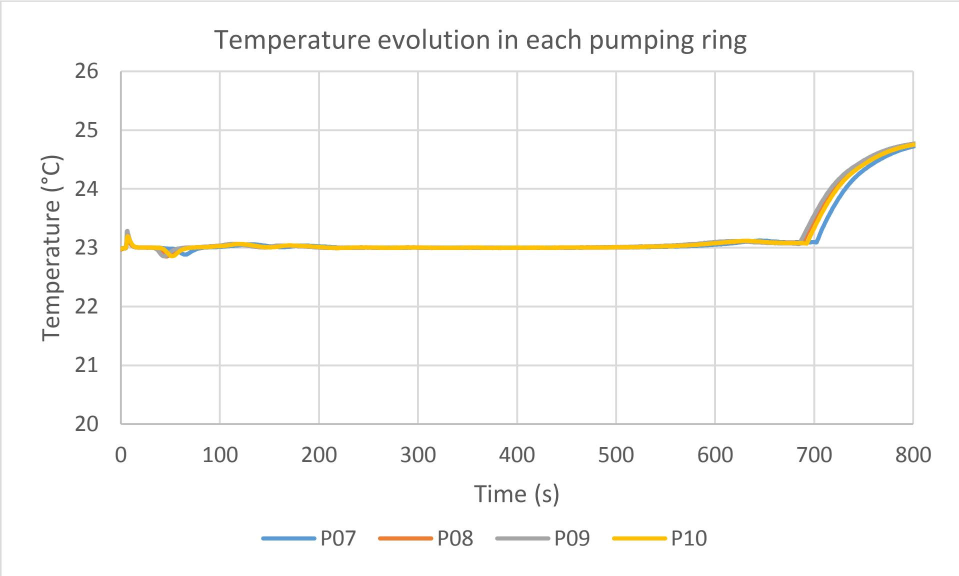


Figure 9.39 Temperature evolution in the system

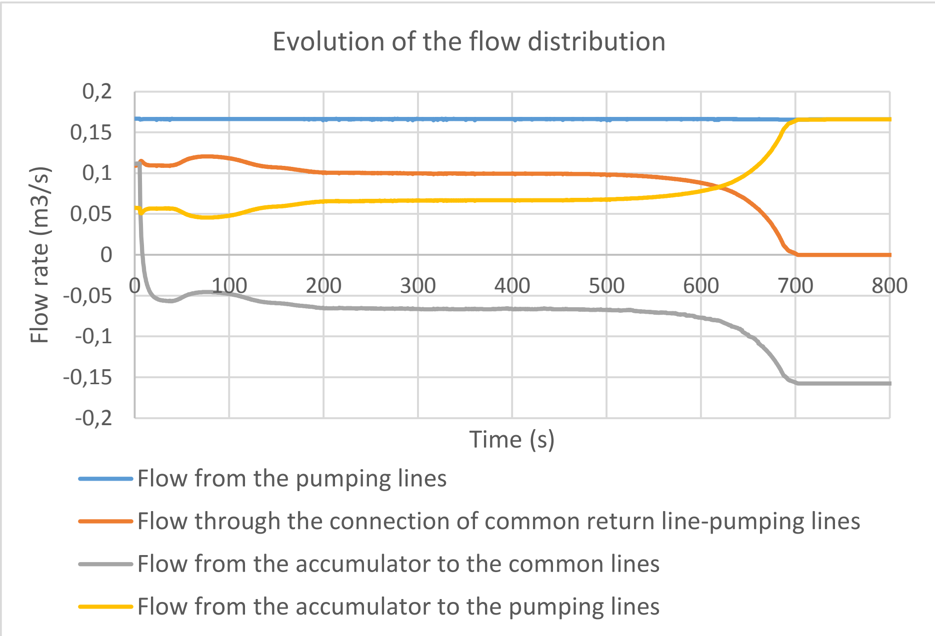


Figure 9.40 Flow distribution in the system

In accordance with the results obtained, the three ways valves regulate their opening in function of the flow temperatures that result from mixing flow from the accumulator (cold water) and flow from the common line (hot water). The temperature at a pumping level does not start growing until ten minutes after the P11 pump stop. Temperature needs that much time to grow because it is being regulated in a complex and giant system, where the flow require some time to complete its whole refrigerating cycle.

9.2.3. System's response to a simultaneous pumping stoppage

The objective of this simulation is to determine if whether the technicians could or should stop all the pumps at the same time or not in a critic case. The actual shut-down steps in the cooling system are the following:

1. Stop of P07 pump
2. Stop of P08 pumps
3. Stop of P09 pump
4. Stop of P10 pumps
5. Stop of P11 pump

Note that all steps are sequential, when one pump stops and the system stabilizes, next pump is stopped.

The following figures are a collection of the data obtained from the simulation, where some relevant information can be inferred.

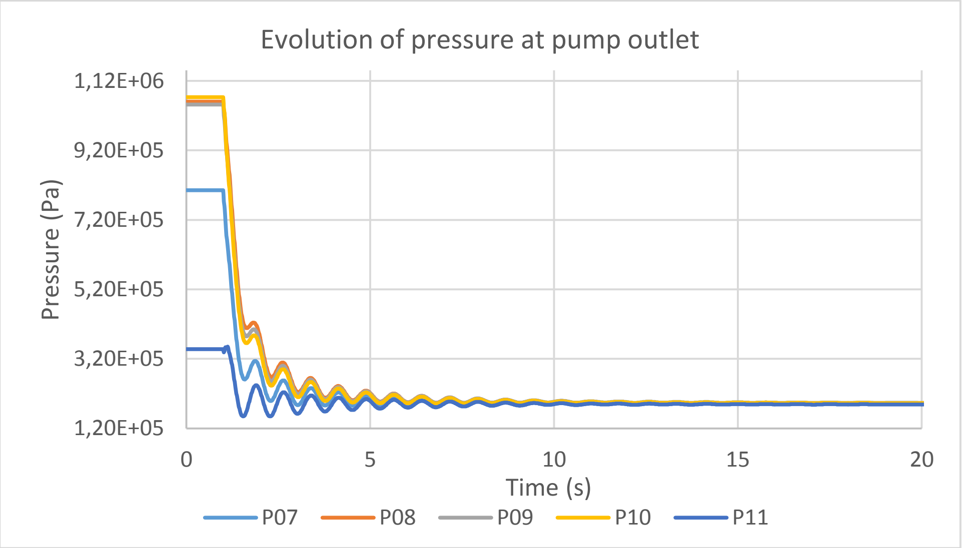


Figure 9.41 Pressure evolution at the pump outlet

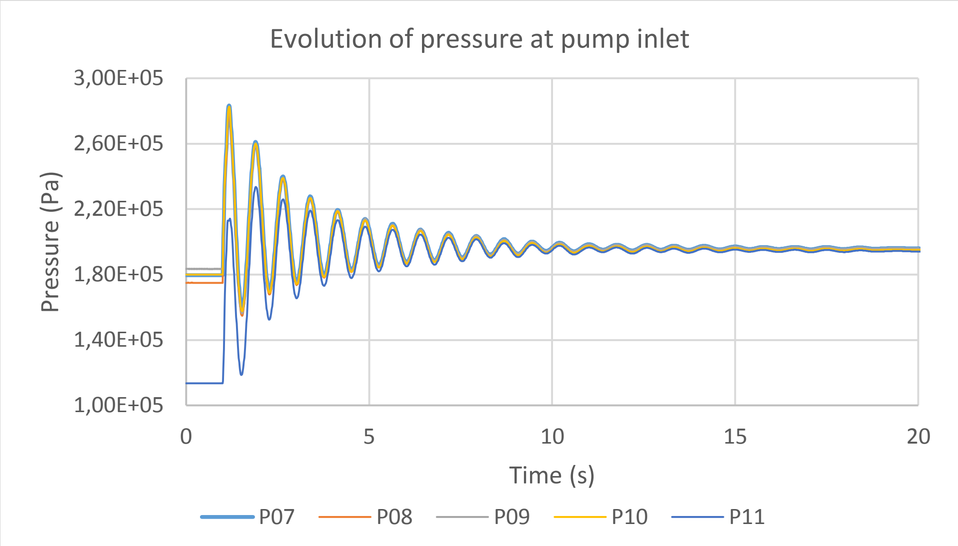


Figure 9.42 Pressure oscillations at pump inlet

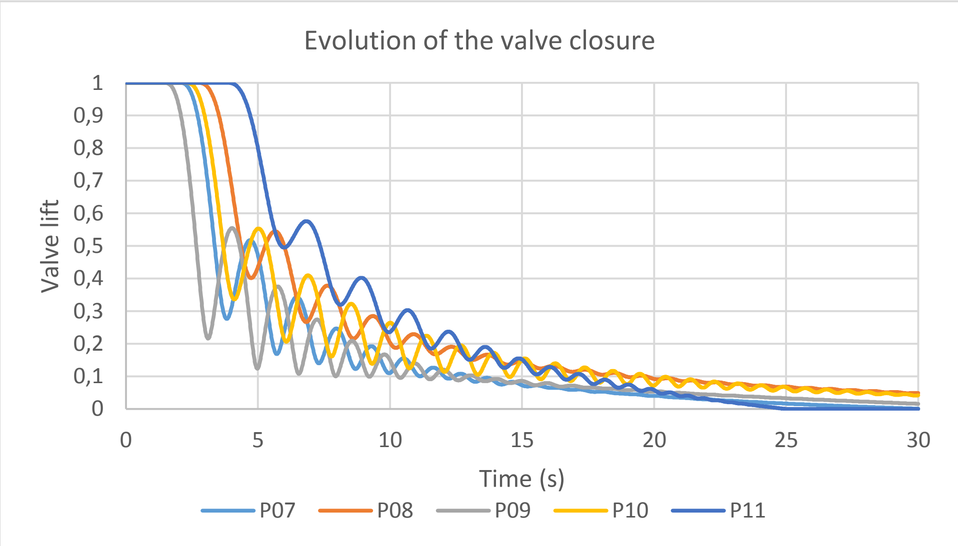


Figure 9.43 Evolution of the valves closures

From the results obtained it can be inferred that the stoppage of all pumps at once is producing more amplitude pressure oscillations than closing sequentially and all the valve closure is delayed. It is a consequence of stopping all the power of suction. In other words, when only one pump line is being shut-down, the power of suction from the other pumps, make the transient state a shorter period in time compared to stopping all the pumps at the same time.

Moreover, as valve closes slowly, the system does not experience water hammer either cavitation phenomena. The closure valves slopes also show relevant information about the closure of the valves. The information is the following:

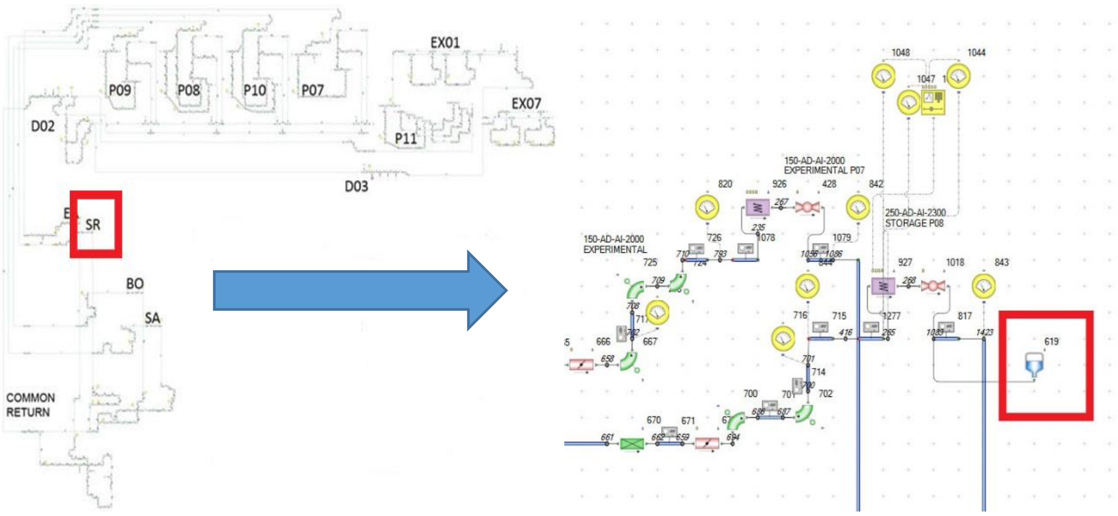
- The higher quantity of flow in the line, the latest the valve starts to close. By this fact, in ascending order (from earlier to later) the closure slopes are: P09 < P07 < P10 < P08 < P11.
- The higher the pressure set point is, the latest the valve finishes its closure. The order of closure from earlier to later is: P11 < P07 < P09 < P10 < P11. Even though P09 pressure set point is slightly higher than P10 pressure set point, as P09 pumping line brings eight times less flow than P10 pumping line, P09 valve closes before.

9.3. System's response to presence of air

In Flowmaster simulations, it is assumed that the pipes only contain liquid inside and no air can be found, only counted in case of cavitation. However, it is known by the R&D department from ALBA's synchrotron that there are air formations near the rings, and they have had problems specifically in the Service ring area.

An accumulator of air vessel can simulate the effect on the pressure response of the system of air in the pipes. Air in pipes minimizes the pressure oscillations as it absorbs them. For this reason, an air vessel accumulator has been placed near the rings area during the shut-down of the pumps.

For this simulation, the test will be focused in the shut-down of P08 pumps (both pumps simultaneously) as the highest pressure perturbations in the system have been noticed in this case. See in the next image, the place where the accumulator is set.



Figures 9.44 Place where the accumulator is set

The simulation is evaluated at the accumulator outlet in order to verify the accumulator effectivity.

The simulation evaluates the effect of different accumulator's height, which is traduced as the quantity of air that the pipes holds inside. The height will comprise the following values:

- No accumulator
- 0,01 ; 0,5 ; 1 ; 2

9.3.1. System's responses to air level inside the accumulator

In the Figure 9.45 it can be seen the different pressure responses according different quantities of air. Hence, it is validated that air minimizes the pressure waves.

It can be observed that with a reduced quantity of air, the signal still shows big pressure amplitudes. When the air volume is increased, the pressure amplitude decreases and also the frequency of the waves. With a high quantity of air, the pressure waves are absorbed.

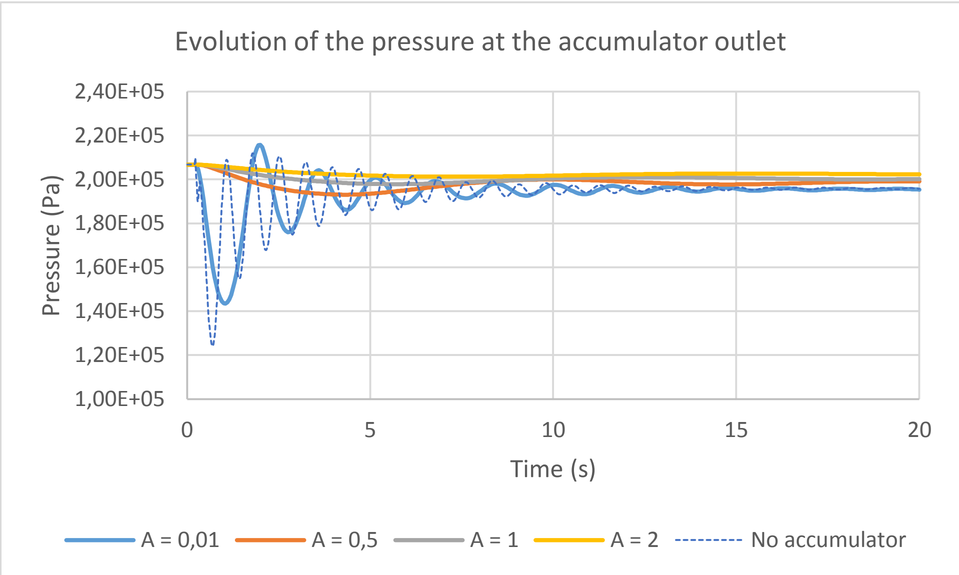


Figure 9.45 Differences by setting different quantities of air

It may be seem that air is a solution in order to minimize pressure oscillation but, in fact, air in pipes can generate a range of problems, such as:

- Air reduces the effective diameter and, as a consequence, it results as a reduction in the pipe's capacity.
- The presence of air may modify the turbulence structure of the fluid and also the wall shear.
- Air can facilitate the corrosion as it provides with more oxygen.

9.4. Summary of results

With regards to the start-up of the system, firstly, it has been necessary to introduce new scripts in order to successfully simulate the transient conditions imitating the real start-up in ALBA's synchrotron. Thereupon, it has been proceeded to the evaluation of the simulation response.

Firstly, it is detected an overpressure in the start of each pump. The overpressure generated due to the pump's acceleration and inertia may reduce the life-time of the piping components. Although it is out of this project's scope, it has been proposed to study and modify the characteristic parameters of the PID controllers (K_p, K_i, K_d) in order to find out the optimum values for the system.

With regards to the design and PID implementation, the adjusted model, designed for this project, can be used in order to find out the optimum values and verify the overpressure generated at the pumps outlet. The tests made in this project has showed up the following improvement. The overpressure's for P09 start-up can be reduced from 54% to 32% if the proportional constant is set at 1, instead of 0,75.

It is also observed that the pump's start-up generates pressure variations in the other pumping lines, yet, the variations are residual and appear not to be very dangerous. The start-up has a duration of 100 seconds.

With regards to the stoppage of the system, the following studies have been focused in unexpected pumps shut-down. The first part has comprised the analysis of the model with no heat transfer and the second part has included the thermal regulation. In general terms, the pressure distribution has been observed to be the same in both cases.

From the simulations with no heat transfer, the behavior of the system has showed some patterns:

1. The pressure oscillations produced by a pump shut-down are more significant if the stopped pump was in a line where more flow moved inside. By this fact, the shut-down of P08 and P10 pumps are the ones that produce higher perturbations in the other pumping lines. However, the perturbations are not too high and they stop in a short range of time.

2. The unexpected shut-down of one of the two pumps mounted in parallel that operate in P08 and P10 pumping lines generates during a short period of time water hammer effects. The reason is that one pump is stopped while the other pump in parallel tries to compensate the flow reduction, and as a result, the flow quickly changes its direction, provoking a very fast closure of the non-return valve's lift. Thus, the phenomena of

water hammer is generated at the valve outlet and it enlarges the pressure oscillations of the system, probably generating cavitation as the pressure reaches the vapor pressure during an instant of time.

3. The shut-down of all the pumps in one line does not produce any dangerous phenomena for the piping system. The process of shut-down is slow and the valve closure variates its opening during the transient event. Finally, when the valve closes totally, the pressure and flow rate in the line has been reduced significantly and, as a consequence, pressure variations are short in time and in amplitude.

4. In all the simulations, the most affected pumping line is the common return line and it is because we are simulating a closed piping system where the flow from the pumping lines converge in the common return line.

5. When the P11 pump is stopped, the flow distribution changes completely. A new flow distribution is achieved comprising only the consumption side. The residual flow now moves to the accumulator, which will be suctioned by the pumping lines. As a result, the flow does move through the coolers.

6. The system response to a simultaneous stoppage of all pumps shown that there are not potential problems in the pumping lines. However, oscillations in pressure may become more significant in this case.

From the simulations with heat transfer, the following simulations were proposed:

- Shut-down of P10A pump: aimed at finding out if with thermal changes, the water hammer was also appearing in the system's response.

- Shut-down of P11 pump: aimed at analyzing the system's thermal response as the flow does not moves through the coolers.

From the results obtained by the previous two tests, it is noticed that, in first place, the temperature of the pumping line variates around ±0,5°C when the pumps stop and the valves close. For this reason, the pressure response seen in the simulation with and with no heat transfer is very similar.

The first simulation, shut-down of P10A pump, has showed that the system is robust against this level of flow variations. The reduction of flow in the P10 pumping line has the consequences to increase 1°C more than the flow temperature at the heater exchange outlet. It is not even noticed in the other lines in the system as it is compensated by the change in the three ways valve opening ratio.

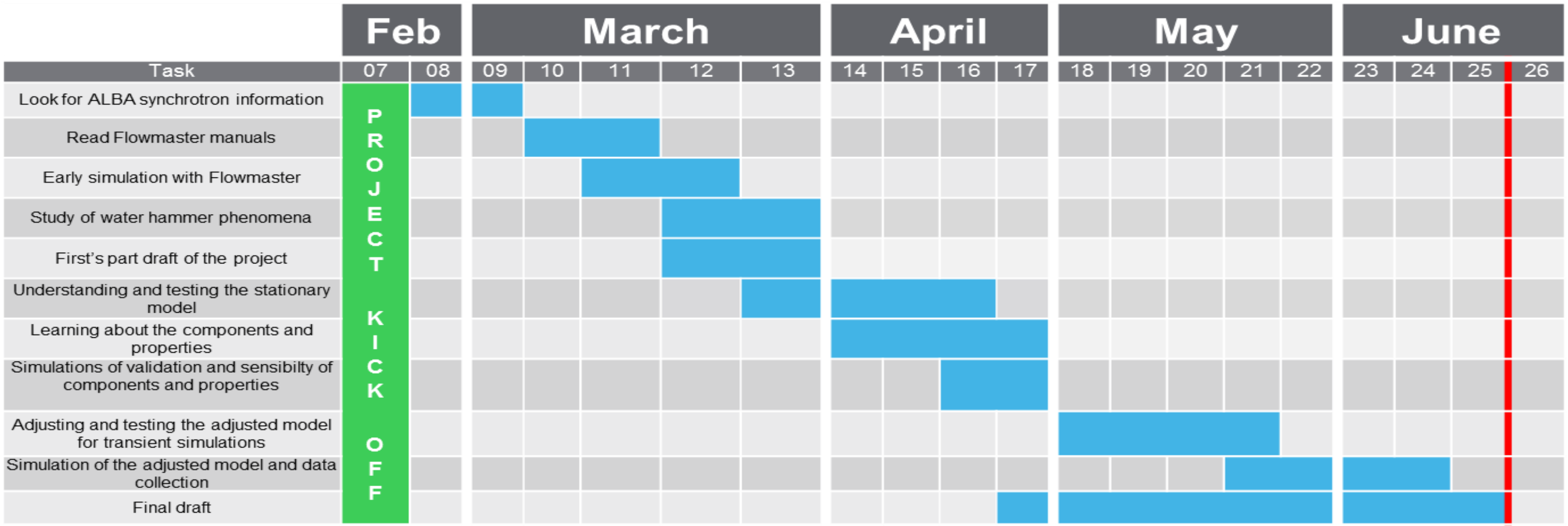
The second simulation, shut-down of P11 pump, has showed that the system's temperature needs around ten minutes to increase and to notice that the P11 pump was stopped. At eleven minutes from the stop of P11 pump, the three ways valves closes totally and only the flow from the accumulator can move through the pumping lines. It is a consequence of the temperature increase in the system and it tries to cold down letting more of the flow from the accumulator. However, the accumulator's flow is not cooled down and the temperature continues rising.

Finally, the last simulation has intended to do a more realistic simulation. In Flowmaster model, the air generation in the pipes cannot be modelled unless the air is created by cavitation. In this simulation, the set of an air vessel accumulator has pretended to simulate an air's bag. The results have shown that the pressure oscillations are more absorbed if there is more air in the system. However, it must be kept in mind that air is a problem for the piping system and not a solution, although it reduces the pressure oscillations.

10. Project scheduling

According to the project's necessities, an adequate action plan was designed in order to meet deadlines and objectives of this study. Its proposal is just indicative and it is a good reference to know how the project's progress is. As it is known, technical projects may experiences difficulties and contingencies and it does not mean that every part must be finished in the predetermined time but the planning helps to achieve your plans in time, with good results and presentation. Project's planning has been designed with a Gantt chart.

10.1. Gantt diagram



11. Environmental impact

The simulations executed and presented in the present document may be beneficial in order to detect instabilities and piping problems related to pressure changes in transient events. Hence, this identification allows to identify possible problems in time, which it leads to economic expense reduction in possible problems that may appear in the system.

Moreover, the operations that are needed in order to repair a component in the piping system must be done without any fluid in the pipes. It means that the system must be drained. The deionized water may be contaminated due to losses and friction in the pipes. Therefore, the refill must be done with new pure deionized water and the contaminated water must be properly recycled. Avoid emptying and refilling the system, it leads to energy and fluid saving. Also, the recycling cost of water is reduced.

Avoiding problems is not only good in environmental field but also means minimizing the time needed in repairing and time is worthy.

Moreover, the determination of the system response using numeric simulations instead of physical experimentation, it is traduced in energy saving. As the physical system is not tested under extreme conditions, it is avoided to wear off the piping components and component life-time is not reduced.

12. Project budget

The project budget has been designed according the structure of the budget of material execution, whose abbreviation is *PEM* in Spanish.

For this design, expenses related to employee and material to perform this project has been taken into account.

The project has been led by a junior engineer dedicated exclusively in this project for a total of 300 hours. The supervision has been taken by a senior engineer with a dedication of 30 hours along the project. See in next table the project budgets for material and employee.

Table 12.1 Expenses of the project

Cost of the employee			
Resources requirements	**Units (h)**	**Unit cost (€/h)**	**Cost (€)**
1 Junior engineer	300	15	4500
Junior engineer social security expenses (7%)			315
1 Senior engineer	30	30	900
Senior engineer social security expenses (33%)			297
TOTAL			6012

Cost of material					
Material needing	**Initial cost (€)**	**Amortization period (years)**	**Annual amortization (€/year)**	**Time (years)**	**Accumulated amortization (€)**
1 Laptop	900	5	180	0,5	90
Flowmaster license	1000	1	1000	0,5	500
Microsoft Office license	100	5	20	0,5	10
Office expenses, rent and maintenance	1000	1	1	5	500
TOTAL					1100

According to the Spanish law, the article 131 of the "*Reglamento General de la Ley de Contratos de las Administraciones Públicas"[9]* approved by the Royal Legislative Decree 1098/2001, at 12th October, stablish that the base budget in construction contract will be obtained incrementing by a 13% the budget of material execution and the 6% as a concept of benefit to the contractor. The value-added tax will be applied to total of the budget of material execution and general expenses of the structure.

According to the actual law, FOM/1824/2013 30th September 2013, it is determined the Contracted Operation Budget indicated in the Table 12.2.

Table 12.2 Contracted Operation Buget

FINAL BUDGET OF THE PROJECT	
Expenses	**Cost (€)**
Employee cost	6012
Material needing	1100
TOTAL	**7112**
General expenses (13%)	924,56
Contractor benefit (6%)	426,72
PEM before IVA tax	**8463,28**
IVA (21%)	1777,29
Contracted operation budget	**10240,57**

The final budget of the project is TEN THOUSAND AND TWO HUNDRED FORTY EUROS WITH FIFTY SEVEN CENTS (**10.240,57 €**), taxes (*IVA*) includes.

Conclusions

It has been confirmed that Flowmaster® software meets with the specifications necessary to successfully model and simulate the different transient situations raised in this project. The preliminary tests realized with simpler models have verified its utility.

The previous model available of the cooling system has been modified and adjusted in order to successfully simulate compressible flow effects during fast transient events. With the readjusted model, the transient simulations have provided reliable results that have led to solid conclusions.

Regarding to the pumping system start-up, it has been discovered that all the rings are experiencing significant pressure rises when their corresponding pumps are activated with maximum values in Booster Ring (P09). The duration of the transient is of about 100 sec. Based on a series of tests, it has been found that the proper modifications of the PID parameters can lead to a reduction of these overpressures.

Regarding the pump shut-downs, the change of conditions in one pumping station has significant effects in the rest of rings and the common return pipe. The highest pressure perturbations are produced in the rest of the pumping lines when pumps P08 and P10 are stopped. On the other hand, P07 and P09 stops generate much lower effects on the rest of the system. This is due to the higher flow rate that is being pumped by P08 and P10 pumping stations. It is also noticed that the common return line experiences pressure oscillations in all the cases due to the closed loop system configuration.

The unexpected shut-down of only one of the two pumps at P08 or P10 pumping stations may bring the system to experience slight water hammer, possible cavitation and higher amplitude in the pressure oscillations due to the fast closure of the non-return valves. In the P08 ring, only one pump is capable of compensating the lack of flow rate due to the other pump stop. However, in the P10 ring when only one pump operates the nominal flow rate cannot be achieved.

The simultaneous shut-down of all pumps has shown to generate higher pressure oscillations along the entire system but no water hammer is experienced. Therefore, it might be safe to shut-down all pumps at the same time in case of emergency.

The shut-down of P11 has a strong effect because it changes completely the flow distribution in the entire system. It is especially important during thermal regulation because the flow stops moving through the coolers and the water temperature cannot be controlled and rises. The thermal transient provoked by the P11 stop reaches the rest of the pumping lines with a delay of around 10 min. At this point the water temperature starts to rise without control because the three way valves cannot cool the common return water. This is because the water temperature in the accumulator is already higher than the set point. As a consequence, it is critical to know the P11 condition to protect the cooling system.

In the case that one of the P08 or P10 pumps fails and stops with the thermal regulation system in operation, the system can still work effectively due to its robustness against small changes in flow rates. In this cases, the three way valves will auto-adjust in order to keep the mixed water temperature at the correct set point.

The presence of air in the pipes has been simulated with accumulators located close to the rings. It has been confirmed that in the case of a significant amount of air the frequency and amplitude of the pressure fluctuations are lowered.

In general, all the simulations analyzed are reliable and, in order to successfully end with the project, the predictions should be validated with experimental measurements at the synchrotron cooling system.

To conclude, pressure, rotational speed and flow rate fluctuations have been predicted with short duration and relatively low amplitudes for most of the transient conditions. The different observed behaviors and the system responses, such as the flow distribution in the pipes, may be used as a reference to find out if there is any problem regarding to the pumping system during normal operation. Consequently, it is proposed to monitor these data continuously for an effective and better system protection.

Acknowledgement

I would like to appreciate the help that the mentor of this project, Xavier Escaler, has provide along the conception and realization of the project.

My thankfulness to his accessibility, dedication to clarify all the concepts and willingness to help, having him as a great Fluid Mechanical professor during my classes of the subject and a great mentor in this Bachelor's Thesis.

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Complementary bibliography

During the trials and learning of Flowmaster program, some documents were helpful. Those documents are the followings:

Flowmaster Easy Start Guide. AppNote MG581320. Modified on: January 21, 2013

Flowmaster Plant & Piping Applications. Mechanical analysis, Flowmaster V7. MGC 06-12

Flowmaster V7 – New User Training. Version 10

Flowmaster Easy Guide – Pumps and Pump Controllers. Application Example

Design for Pressure Surge in Flowmaster. By Doug Kolak, Technical Marketing Engineer, Mentor Graphics