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Final Master Project

STUDY OF COOLING WATER NETWORKS USING ASPEN HYSYS

Master in Environmental Engineering and Sustainable Energy

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NOMENCLATURE

Symbology	Description
Pi	Pressure of component i
Ti	Temperature of component i
RH	Relative humidity
ρi	Density of component i
g	Gravity
h	Suction head
F.P.	Power factor of the load (cosϴ)
V_{L-L}	Voltage line-to-line
η	Efficiency
$I_{AC3Ø}$	Three phase current
ΔT	Thermal gap
ΔP	Pressure drop
k	k-value of coolers/valves in Aspen HYSYS (constant)
Qi	Flowrate of component i
AE	Absolute error
RE	Relative error

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EXECUTIVE SUMMARY

Due to the drought affecting Spain, it is necessary to be aware that consuming less water today will allow more water to be available tomorrow. This project studies one of the current problems suffered by one of the cooling towers of REPSOL S.A. site in Tarragona (Pobla de Malfumet). Due to the lack of cooling water supply in some of the plant's equipment and units, an increase in water consumption is being considered.

This project is focused on Repsol's one cell cooling tower, also named 417-E-203. The temperature gap of the cooling tower is 15ºC by design, however, it currently works with a temperature gap of 6-7ºC. Two ways for improving water savings are studied: (i) implementing an Aspen HYSYS simulation of the overall cooling water circuit to find the equipment units that are bottlenecking the system, and (ii) studying the effect of the increase of concentration cycles so as to safe make-up water in the cooling tower, always maintaining and monitoring via corrosion coupons, the condition of the piping and avoiding unwanted corrosion scenarios.

With the help of the simulation some equipment units that act as bottlenecks and affect the proper performance of the tower have been detected and proposed to the enhancement

1. INTRODUCTION

1.1 Water scarcity

Since the start of the hydrological year in 2022, Spain received 28% less rain than expected (Rodrigo Marinas, 2023). In 2023, Catalonia declared an emergency state to drought in 22 municipalities of Girona and Tarragona, and it does not seem it is going to get any better (Rodrigo Marinas, 2023). The current episode is creating harmful direct impacts in the natural systems and the most vulnerable economic sectors.

The General Secretary of the United Nations, Antonio Guiterres, lamented that climate breakdown has begun, with impacts from climate change and global warming becoming more frequent (Pearce et al., 2023). In this case, Spain suffers one of the most significant climate-related weather events: a drought. Since the end of 2022, Spain has a prolonged meteorological drought, which is considered the ninth most severe climate disaster over the world in 2023 (Pearce et al., 2023). Indeed, the beginning of 2023 has been registered as the driest since records were first kept in the 1960s (Horaci Garcia, 2023).

International research made by the EM-DAT database determines that the total cost due to water shortage is around 2,400 million dollars, which means 50 dollars per capita of loss (Pearce et al., 2023). This economic impact is focused on providing water resources to help farmers.

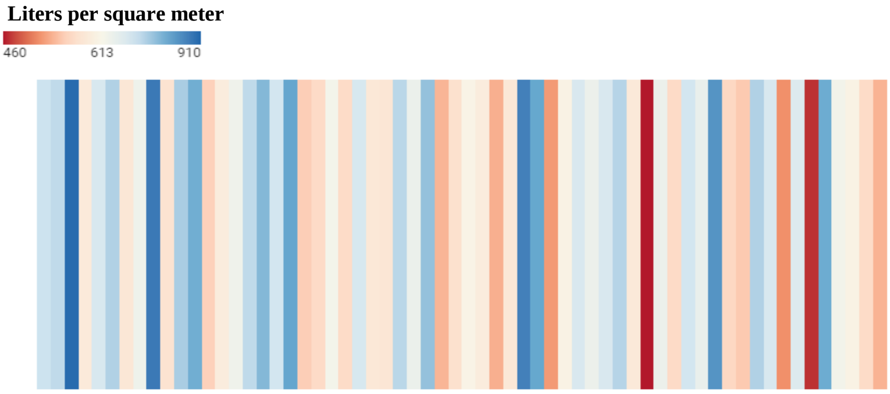


Figure 1. Liters per square meter of rain in Spain from 1961 till 2022 (Romero Fresneda et al., 2020).

The situation does not seem to improve, the general temperature increase shows unfavorable prospects for the future. A World Wildlife Fund (WWF) study described a picture of Europe in 2050, where, at least, 17% of the people is at high risk of scarcity, with Spain being identified as one of the countries that will face the greatest risk of water stress. In addition, the environmental WWF projection shows that around 75% of the people worldwide will have a difficult access to water by 2050 (José A. González, 2023).

In Spain, water consumption is distributed as follows: 67% by agricultural sector, 19% by industrial and energy sector and 14% for urban consumption. Along with agriculture, which is the highest consumer of water, tourism generally harbors every summer season more than 50 million visitors and when rainfall is scarce, this generates additional water stress (P. González, 2018).

Industrialization plays one of the most important roles and is putting water scarcity under huge pressure. It is expected that industry use 4% more water each year, which will increase water consumption from approximately 19% to 38% in 2040 (Aquastat, 2015). This will increase the serious risk of water shortage and environmental problems in the future. In addition, industrial effluents that come from refineries, chemical industry and more, are dumped into oceans and rivers, releasing pollutants to water. As a result, the impact of water quality led to negative long-term effects. Total organic compounds and compounds that contain nutrients can cause eutrophication, and heavy metals have an impact on the environment and human health (Rahman et al., 2021).

Like in many industrialized countries, investments in technology and infrastructure are essential to develop a proper water management model and guarantee the long-term availability of water.

1.2 Project definition

The world is facing a huge risk of water scarcity, thus is important to save water as much as possible. Petrochemical industry is a high-water consumer and use cooling towers as the main equipment to refrigerate water. Cooling towers are designed to be suitable for application to any heat load configuration and design conditions. However, developing practical knowledge for the design and simulation of a cooling towers, considering every perturbation of a real system, is challenging. This project is focused on Repsol's one cell cooling tower, also named 417-E-203. The temperature gap of the cooling tower is 15ºC by design, however, it currently works with a temperature gap of 6-7ºC. The lack of water in some equipment, once served by this tower, has caused them to be removed from its circuit, and they now receive cooling water from other cooling towers. This problem, likely due to an excessive pressure drop in the corresponding lines, has motivated the need to identify the facilities that need to be cleaned or replaced. By design, specific units, as for example, “benzene” and “WAO” (treatment of spent soda via Wet Air Oxidation) also belong to the network of the cooling tower 417-E-203, although they are currently aligned to another cooling tower due to lack of flow availability in the circuit.

The network supplied by 417-E-203 serves and refrigerates the area of “ethylene” and other units such as “energies”, “hydrotreatment” and “distillation” units, where historically there have been incidents due to a low cooling water flow. For this, among other reasons, it is indicated that there is not enough water availability to supply all the cooling water required in the system. The current recirculation flow rate is 3000 m^3/h with two pumps running, which matches the design flow rate of the corresponding cell of the cooling tower. The cell capacity can be easily increased by increasing the diameter of the distribution nozzles.

One possibility to manage the lack of water in some units is the increase of the recirculation flow rate above the design flow rate. This would lead to an increase in fresh water consumption and, consequently, higher energy consumption by the pumps. To avoid this, it is proposed to simulate the circuit using Aspen HYSYS. The project will be focused on water conservation, aiming to identify the most effective ways to enhance water distribution in certain equipment that could adversely impact the proper performance of the cooling water network.

There are several variables that can improve water conservation in a cooling system. In this project, two of these variables will be studied: (i) the flow distribution resulting from given pressure drops and (ii) the number of concentration cycles. In terms of water flow distribution, a simulation with Aspen HYSYS will take place and will help to analyse the amount of water that can be saved once the equipment that generates an additional load loss (due to fouling or lack of flow) has been identified. Once the equipment causing the water shortage has been detected, increasing the design flow rate of the circuit can be avoided. On the other hand, the number of concentration cycles is related to the make-up water that must be supplied to the system due to losses. An increment in the number of cycles will result in a lower fresh water consumption. The limitation, however, is water quality, which will be deteriorated as the number of cycles is increased due to the rise in salt and impurities concentration. In this case, cooling water has to comply with the limits allowed by the tower design.

1.3 Location

Industrial processes generate the largest amount of waste heat energy that needs to be removed. Cooling towers are essential for maintaining the optimal operating temperatures and preventing processes from overheating. The natural process of evaporation makes them very effective heat transfer media to reduce equipment damage and even safety hazards.

Repsol’s industrial plant has a number of cooling towers that supply cooling water for all facilities where it is required.

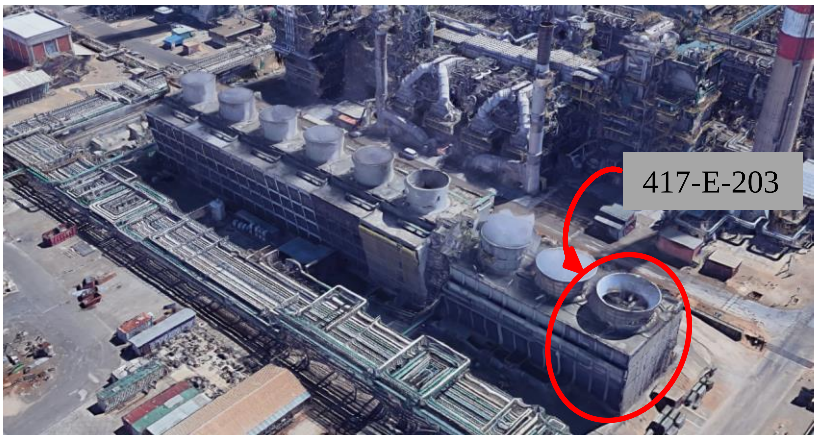


Figure 2.Unit 417, cooling towers.

In this project, the cooling tower studied is located the first starting from the right. It is designed with one cell only, called 417-E-203. There are also four other cooling towers, three of which are composed by one cell, while another one consists of six cells. A cell is defined as the smallest subdivision of a tower and operates as a single equipment in terms of air and water flow. The mission of the cooling circuit is to supply the cooling water necessary for all processes in the “Distillation”, “Hydrotreatment”, and “Ethylene” and “Energy” areas. The circuit consists of the following elements:

- Cooling Tower: 417-E-203.

- Pumping System: Pumps 417-G-1-A/B driven by motors GM-1-A/B and pumps 417-G-1-C driven by turbine GT-1-C.

- Distribution Network: Distributes cooling water to equipment in different units.

2. OBJECTIVE AND SCOPE

The aim of the project is to save water supplied to the cooling tower circuit 417-E-203. To achieve this objective, two targets are defined: (i) identify those streams with excessive pressure drop, in order to propose possible solutions that ensure an adequate water flow for all the required units, without the need to increase the recirculation flow; and (ii) study the number of concentrations cycles that can be increased while fulfilling with the tower's design limits. In order to address each of the targets, specific objectives are set for each case.

To reach target (i) a simulation model of the cooling water network is developed using Aspen HYSYS™. This simulation includes 232 facilities that require cooling water (CW) supply from 417-E-203, and also will allow Repsol to make decisions on how to enhance water distribution in the circuit, reducing make-up water and also, would contribute to help improving water shortage. This can be done by manipulating the pressure drop in the simulation until it matches with the real plant conditions, and find out which units need to be repaired instead of increasing the recirculation water flow.

The simulation details have been thoroughly included to achieve maximum accuracy, e.g., including all piping isometrics, equipment design pressure drops, temperature, pressure design flowrate and composition.

The existing difference between the current and the design temperature gap of the 417-E-203 cell (6-7ºC versus 15ºC, respectively) calls for the exploration of alternative configurations that can save cooling water and enhance the cooling water system. This involves calibrating the simulation with actual plant data on the current stream flowrate in each unit and, as a result, obtaining the actual current pressure drop of each equipment, which may differ from the design one. Then, once the desired and the actual performance are known (through dynamic simulation), the results can be compared in order to identify the equipment units that should be studied in more detail in the future to improve the performance of the cooling water network. For this reason, the main objectives of providing the simulation are:

- Create a digital twin simulation which includes all design parameters of the plant at steady-state mode.
- Modify the initial digital twin to dynamics mode, this tool will help to ascertain whether the system will be capable to deliver the expected flow.
- Modify the second digital twin in order to reflect the actual situation of the plant by dynamics mode. It is required to calibrate the simulation including additional pressure drop thought digital valves. It is required to use the dynamic mode to calculate the flow distribution according to the pressure drop of each stream.
- Implement the cooling tower simulation into the general simulation.
- Implement pumps into the general simulation in order to know the actual operation conditions. Include the characteristic pump curves and power supplied.
- Analyse the results to find the bottlenecks in the cooling water network and explore possible solutions to solve debottlenecking.
- Assess which amount of water is expected to be saved due to the identification of the network troubleshooting.
- To adjust the pumps power according to water consumption in order to save water and electrical energy consumption.

For target (ii), it would be necessary to evaluate another variable, the number of concentration cycles of the cooling tower, in order to assess the amount of water evaporated and drained during the different seasons of the year. Various water quality improvement alternatives must be studied to increase the number of cycles and reduce make-up water consumption. For this reason, the specific objectives are:

- Study the variability of different temperature and relative humidity scenarios to analyse the effects of ambient air changes.
- Analyse how water quality evolves regarding the increase of concentration cycles and how it affects the cooling tower’s performance. Evaluate the maximum number of cycles that the tower is able to operate within the design limits. The number of concentration cycles is related to the make-up water consumption.
- Analyse how the cycles of concentration would change if make-up water resources came from a Wastewater Treatment Plant (WWTP) scenario.

The structure of this project is based on explaining how the simulation has been developed in Aspen HYSYS, how a cooling tower works, which units are included in the water cooling network and how water can be saved from enhancing flow distribution and cycles of concentration.

3. COOLING WATER SYSTEM

3.1 Cooling tower performance

The cooling tower studied is composed by a unique cell and a fan, and supplies CW to all the equipment that require refrigeration in four different areas which are “Ethylene”, “Energies”, “Distillation” and “Hydrotreatment”.

The return cooling water enters at the top of the cooling tower through the distribution system. Water falls downward due to gravity, and gets colder by contact with air. Meanwhile, the air moves vertically upward through the filling in counterflow. Along the tower, the hottest water (entrance) is in contact with the wettest air at the top. At the bottom of the tower, the coldest water which have reached the maximum temperature exchange is in contact with the driest air entering to the tower. Thus, the efficiency of the cooling tower is raised regarding crossflow cooling towers. It is worth to mention that, after the distribution system, there is a film fill for improving the thermal exchange in the tower performance. It is used to increase the surface area and allow for a greater evaporation rate. (Hensley, 1998)

Indeed, water losses are generated by the evaporation cooling principle. These losses are reduced by a drift eliminator located at the top of the water distributed system, which captures large water droplets trapped in the air stream. Thus, the system is specifically designed to secure a constant recirculation flowrate through the addition of make-up water.

The vertical air movement within the cell is generated by a fan located at the top of the tower. In this type of induced draft tower, the air velocity at the outlet is 3 or 4 times higher than at the inlet (Hensley, 1998). The tower outside surface has a corrugated casing panel, which encloses most of the tower parts, including the drift eliminators or the tower basin.

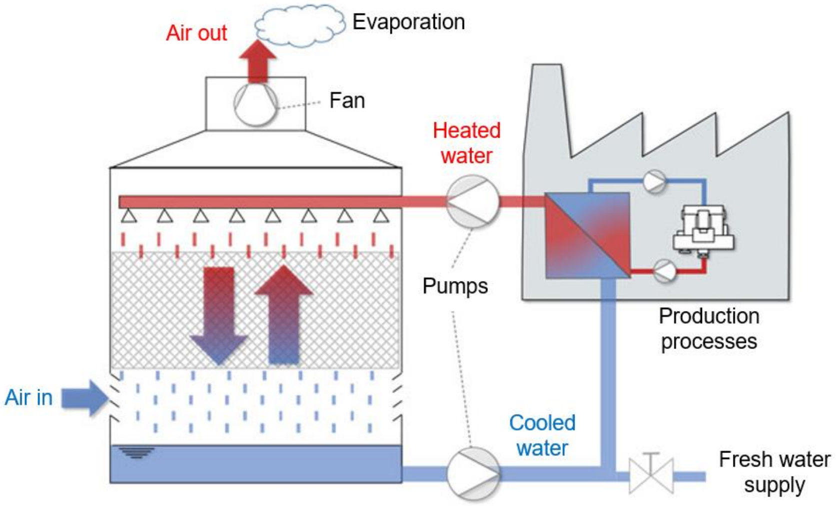


Figure 3. Induced draft counterflow tower (Schulze et al., 2018).

Despite being designed to achieve 15ºC of thermal gap, the tower works now on a thermal gap of 7-8ºC. In regular conditions, the water temperature at the outlet should be below 30ºC. At higher temperatures, the metals used in the tower such as piping are susceptible to corrosion and require regular monitoring to fight against material deterioration. The typical design flowrate is 3000 m^3/h.

3.2 Cooling water network

The cell that makes up the tower is built in a single structure on a concrete basin for the collection of cold water and its subsequent channelling to the pumping sump.

The actual cooling water supply is drawn from a 650 m^3 basin, connected to a pumping system that sucks water at a certain pressure. Suction pressure is given by basin depth h, which is about 0.6 meters. The higher level of the basin must remain between the 85-90% to enhance the pressure conditions in the suction line.

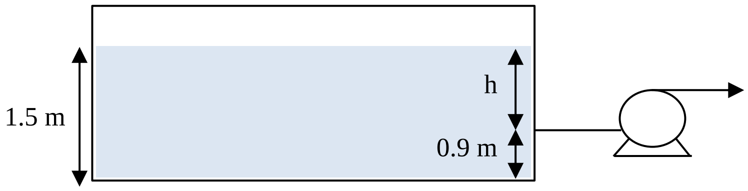


Figure 4. Scheme of the basin.

In order to estimate the suction pressure of the water system, the next equation is followed:

$$P_{gauge} = \rho_{water} \cdot g \cdot h \qquad (3.1)$$

In this case, since h is equal to 0.6 meters, the pressure suction results in 0.6 kg/cm^2g.

Under normal working conditions, two centrifugal pumps, driven by electric motors, are able to supply the cooling water at required pressure. Each pump line can supply up to 1500 m^3/h, producing a total flow of 3000 m^3/h altogether. In case all consumers are working, the delivery pressure in the general manifold would be around 5 to 5.6 kg/cm^2. If this pressure falls below 4 kg/cm^2, a third stock centrifugal pump, driven by a turbine, will start operating.

The main distribution manifold is about 24” and is divided in two pipelines. One of them supplies cooling water to the boil-off spheres and ethylene plant. On the other hand, the second manifold supplies water to the “Energy”, “Distillation” and “Hydrotreatment” areas. Those areas are composed by different units: U-411, U-412, U-413, U-414, U-617, U-618, U-613/615, U-672/653, U-676, U-425, U-454, U-645, U-654, U-657, U-652/651, U-642/641 and U-631/632/634 which are defined in Annex A.1.2. The process diagram of the cooling water network can be seen in

Figure 5, where blue streams refer to cooling water supply and red streams refers to cooling water return.

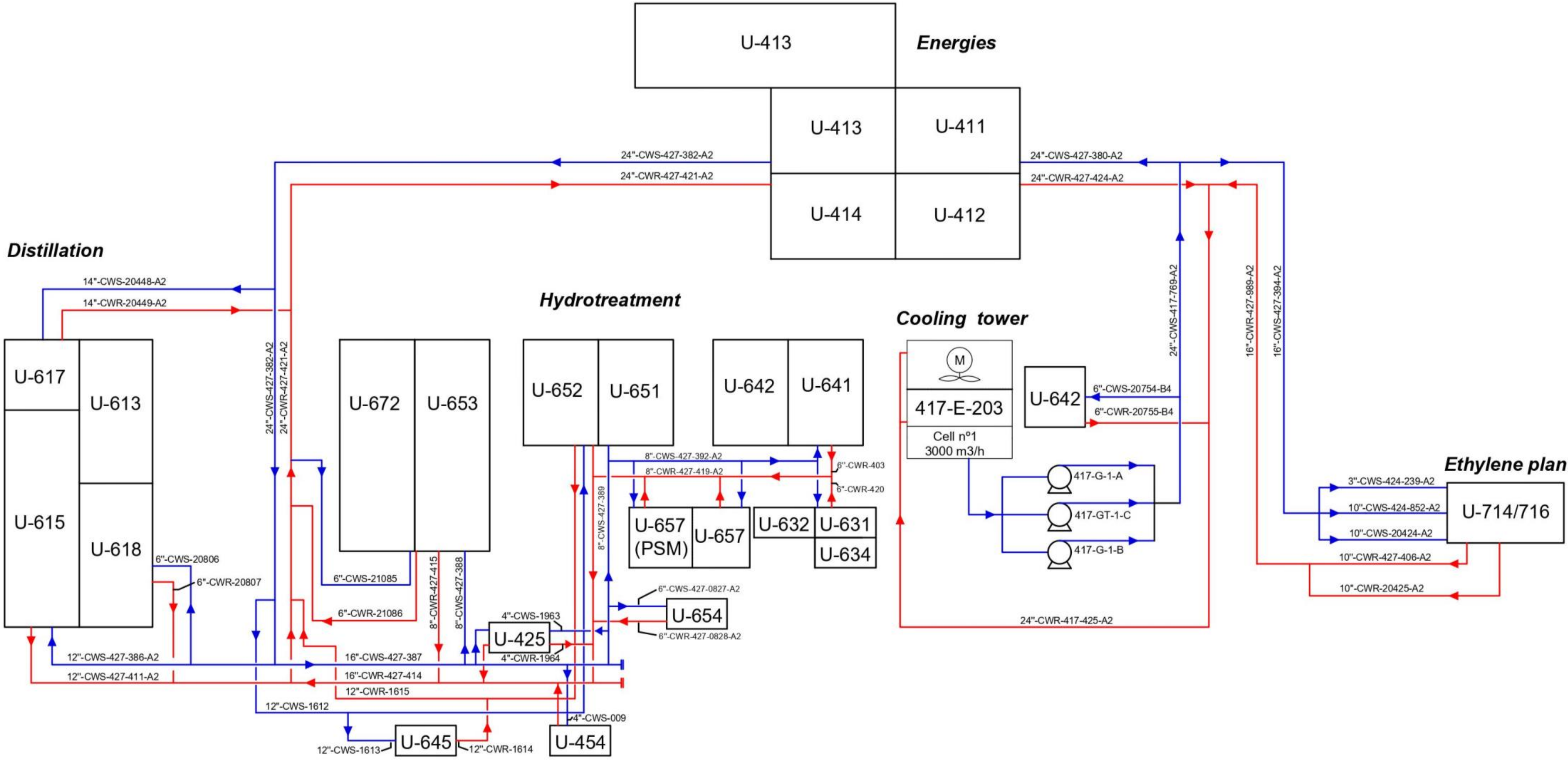


Figure 5. Process diagram of the cooling water network.

3.3 Equipment list

Cooling water is supplies through a wide and large pipeline network consisting of 25 units, each with their respective equipment, such as heat exchangers, or refrigeration system for pumps and compressors. The equipment list of each unit can be found in Annex A.1.2. If all the equipment worked ideally, the network design conditions would match current operation. However, there are differences affecting the actual performance. To begin with, certain units or equipment are currently out of service and, consequently, have been excluded from the simulation. On the other hand, fouling causes to work under ideally conditions and some of the equipment performance will be affected.

3.3.1 Heat exchangers

Heat exchangers work as coolers, which are used to refrigerate fluids that are within a certain rage of conditions and temperatures. Those fluids correspond to the process side and have to be suitable for cooling water quality.

3.3.2 Pump reservoirs

The cooling water network sometimes cools the mechanical seal buffer fluid of pumps, this fluid can be methanol or glycols, usually. The most common sealing plans consist of API 52, 53/53A, 54, E and 62. They use a sealant vessel or reservoir, continuously opened in order to provide circulation and cooling to the contacting wet outboard safety backup seal by thermosiphon effect.

In addition, cooling water can be used to refrigerate the oil of pump engines to extract temperature heat from friction, and to cool the parts of pump turbines more exposed to thermal stress.

3.3.3 Compressors cooling

Compressors also require cooling water to refrigerate air and remove waste heat. Those can be such as lube oil coolers, intercoolers and aftercoolers. Lube oil coolers are responsible for refrigerating compressor engines, while intercoolers cool the air between two stages (more than one are possible). Additionally, aftercoolers refrigerate the air leaving the final stage of the compression unit.

3.3.4 Sample cooler

Hot fluids such as boiler water, thermal oil or other hot products have to be sampled and analysed regularly. Thus, a cooling system is required in order to cool down samples without changing their composition, preventing the evaporation of volatile components along the way. The sampling system works as a closed circuit to ensure a representative and accurate sample.

This facility requires cooling water supply only during specific moments, and is not considered one of the main water consumers and consequently, not included in the simulation.

4. ACTUAL PERFORMANCE

4.1 Cooling tower thermal gap

The thermal gap of the cooling tower can vary due to certain factors such as ambient temperature, air and water quality, network performance, heat load or airflow.

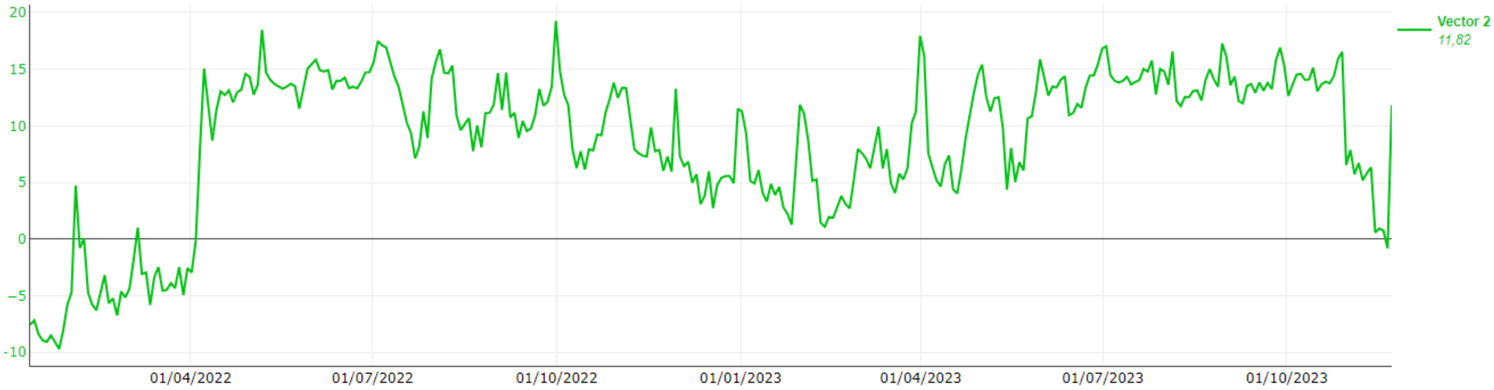


Figure 6. Cooling tower thermal gap tendency of the two last years.

As can be seen in the figure above, the thermal gap decreases during winter season, with the average temperature gap of the last two years being 9.1ºC, far below the 15ºC defined by design.

4.2 Design and actual flowrates

The cooling network is composed of 26 units with 235 equipment units. The number of equipment units in each unit is shown in Table A.6 in Annex A.1.3.

The first step is to gather all data of the design flowrate of the system and the real one flowing through every unit. The design flowrate (Q_{design}) is known by the documented design spreadsheets found in the archives of Repsol. The sum of all units by is 3768 m3/h, considering that all equipment is in service and working at design conditions. On the other hand, actual flowrate of the plant (Q_{plant}) is measured manually, unit by unit, resulting 2899 m^3/h. The tool used to measure is an ultrasonic handheld flowmeter which can quickly detect and determine the flowrate in a pipeline. However, it is worth to mention that some units had implemented a flowmeter indicator (FI), but as some of them were not feasible and accurate due to significant discrepancies between manually measured flowrates, for this reason, only the manual measure was considered in this study.

In order to prevent any confusion, it is crucial to differentiate between the different data obtained and understanding the corresponding meaning. As it is mentioned in section 3.2, the main manifold recirculates a total flow of 3000 m^3/h, this value is referred to the theorical flow rate of the cell which must be circulating in the current situation. The actual plant flow is close to the theoretical one. On the other hand, the design flow rate is referred to the sum of all equipment working at optimal conditions, without considering any change in the circuit conditions, as if everything works exactly since the day it was designed, and for this reason the capacity is higher than the theoretical.

In the next figure, it can be seen the difference between Q_{design} and Q_{plant} in each unit.

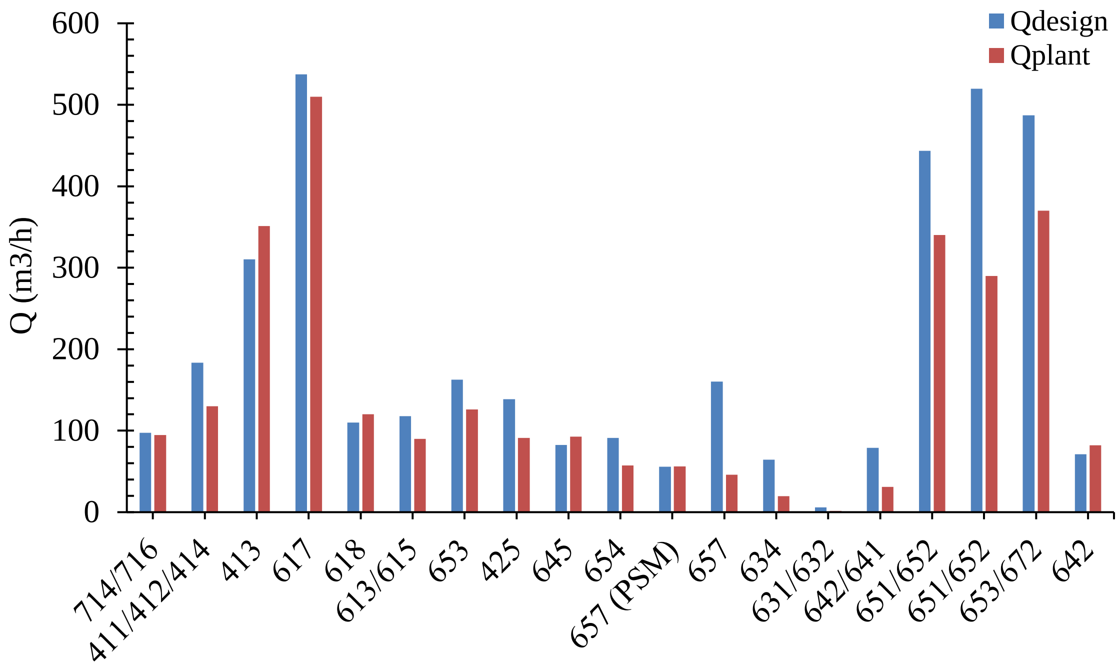


Figure 7. Design flowrate versus measured flowrate in the actual circuit.

Most of units are currently working at lower flow rate than the design, except for units 413, 618, 645 and 642. It is quite regular that the current performance of the network does not follow the same operating conditions as the design. During the years, some modifications have been made and some equipment is out of service or holdup mode. The biggest range difference is found in units such as 657, 651/652 and 653/672. Those units that are included together such as 714/716, 613/615, 642/641, etc., share the same branch manifold to equipment.

These results will help to develop the cooling water network simulation in Aspen HYSYS. Design data will be used to build a steady-state model of the simulation and determine the basic equipment requirements, and then, plant data will help to analyse the results and decisions to be made.

5. ASPEN HYSYS MODEL OF THE COOLING NETWORK

5.1 Introduction to HYSYS

Aspen HYSYS is a chemical process simulator that uses chemical equations and models to replicate their behavior. It simulates everything from simple unit operations to complete chemical plants and complex refineries. In this case, it is going to be used to accurately simulate the pipeline hydraulics in a cooling network. Establishing a strong link between the pipeline and the midstream and upstream processing facilities is essential to ensure an optimized flow throughout the plant lifecycle, ensuring the safe operation of the entire network (Aspen Technology, 2015).

In the operation of the cooling water network, the more units added to the plant over time, the more equipment units that will require cooling water. Additionally, after an extended period of operation, the pipes suffer a pressure drop in the network and become rougher. Bottlenecking can affect the entire production process and hence overall profitability. When the simulation analysis is performed, the bottlenecks of the system will be identified and also, the most critical points could be addressed.

After identifying the bottlenecks, the next step is to analyse the causes of those limitations and to quantify their impact on water consumption. Enhancing the system’s efficiency would reduce the energy consumption, which in turn reduces the associated greenhouse gas emissions.

5.2 Fluid Package

All unit operation models need to perform properly to obtain maximum feasibility and accuracy in the generated results. Since the network system is working with water only, any of the thermodynamic property methods included in Aspen HYSYS for only-water systems would be suitable. These are: NBS Steam Table and IAPWS-IF97. The former method is used for calculating enthalpy of water to high accuracy, and is the most common method for water-only systems (Aspen Technology Inc., 2001). However, IAPWS-IF97 is the state-of-the-art model for the thermodynamics properties of water and steam for industrial applications. It is usually used to simulate steam power cycles, utility systems and optimization-based design; nevertheless, its use has been limited because of its complexity (Bongartz et al., 2020).

In this case, the NBS Steam Table model has been selected since it can be adapted properly to the cooling water network simulation without loss of generality.

With the property package at hand, the next step is to start building the simulation flowsheet.

5.3 Cooling tower modelling

There is no standard model for cooling towers in Aspen HYSYS. Hence, in the baseline simulation, the cooling tower is modelled by combination of a splitter, an air cooler, and a tee.

The amount of dry air at the tower's entrance is 2080 tonnes/h, but these carry additional 37.35 tonnes/h of vapour due to air humidity. The vapour flowrate at the outlet will be larger because of the evaporation effect of the cooling tower (simulated through the "LOSS", see Figure 8). This cools down the hot water, but increases the relative humidity of the air up to 100% (i.e., saturated conditions).

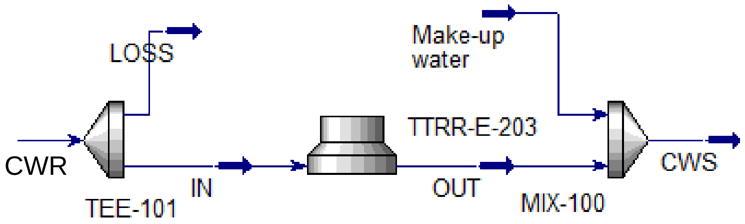


Figure 8. Cooling tower simulation in Aspen HYSYS.

In the simulation, the air temperature obtained at the entrance of the cooling tower is around 35ºC, and at the outlet is 27ºC, the temperature difference is around 8ºC which is quite close to the current performance of the actual tower. Note that, the design wet bulb temperature of the air is 25ºC, meaning that it is the lowest temperature to which air can be cooled by evaporation of water into the air (A.M.Y. Razak, 2007). Water enters the diffusors at the top of the tower at 0.1 kg/cm^{2}g, approximately.

5.4 Pump system simulation

In normal conditions, the water of the basin is suctioned by two pumps. The design pressure delivered to the water along the network is about 5.6 kg/cm^{2}g, as given by the pump curves.

To solve the pump system and replicate real plant conditions, four ADJUST operations are required in Aspen HYSYS. ADJ-1 and ADJ-2 will adjust the flowrate of the inlet stream to the pump until the desired outlet pressure is achieved. ADJ-3 is added to adjust the pressure of stream 379 so that it enters MIX-417 at the same pressure as line 431-2 (otherwise, reverse flows could occur). Finally, ADJ-4 is added to adjust the outlet pressure of pump 417-G-1B and also, ensure a pressure of 5.4 kg/cm^2 in stream 769, so as to match the value of the pressure indicator (PI) in the plant.

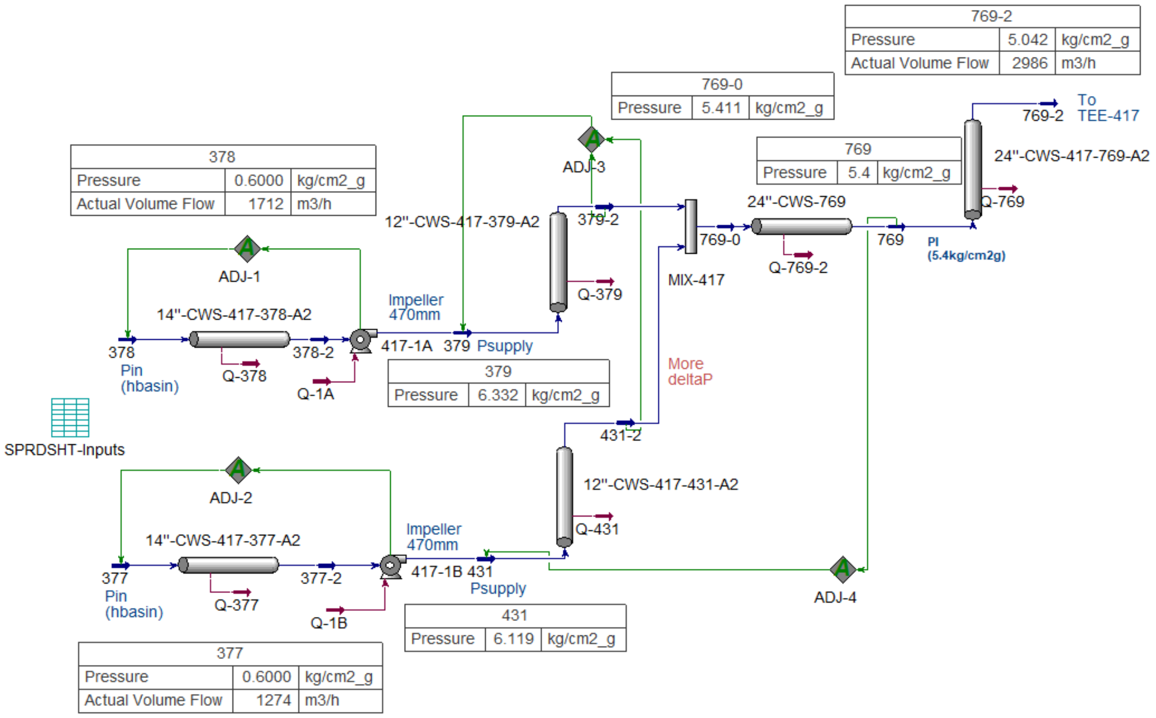


Figure 9. Pump system simulation.

The Aspen HYSYS pump model offers the possibility to enter data on power and suction pressure according to the manufacturer's specifications and connected to the corresponding pipe segments. This allows a more accurate estimation of the flow rate driven by the pump, which belongs to be recirculated within the cooling network. The data of the three-phase induction motor that is indicated by the corresponding manufacturers have been used in equation 5.1.

- Impeller: 470 mm (417-G-1A/B)
- Power factor of the load (F.P): 0.88
- Voltage line to line (V_{L-L}): 6000V
- Adiabatic efficiency (η): 70%
- Three phase current/amps ($I_{AC3Ø}$): Pump 417-G-1A = 42 A; and Pump 417-G-2B = 30 A.

Following the next equation, the power supplied ($P_{3Ø}$) in kW can be obtained (Fleckenstein, 2020):

$$P_{3Ø} = \frac{\sqrt{3} \cdot V_{L-L} \cdot I_{AC3Ø} \cdot F.P}{1000} \tag{5.1}$$

In equation 5.1, the power that the motor must supply for the pump to deliver the pressure obtained with the help of the 4 adjusts has been calculated, the power supplied by pump A is 384.1 kW and 274.4kW by pump B. The stream variables converged at values of 1712 m^3/h in pump A and 1274 m^3/h in pump B. The total flowrate supplied by the pumps according to the simulation is 2986 m^3/h which is close to the actual flowrate (2899 m3/h), less than 3% of relative error. In addition, the pressure inlet at the cooling water network calculates is 5.04 kg/cm^2g, 0.56 kg/cm^2 less than design.

5.5 Cooling water network simulation

This section includes the process followed to obtain the simulation and its results.

5.5.1 Simulation approach

The global steps followed during the simulation are:

A) Create the steady-state simulation using design conditions (ΔT, flowrate, pipe segment, etc.) to model the overall circuit simulated. The flow results obtained will be expressed as $Q_{HYSYS, A}$.

B) Modify the initial simulation to dynamic modelling. Obtain the optimised flow distribution according to the actual data. Those units or equipment that are out of service forever has been deleted. The flow results obtained will be expressed as $Q_{HYSYS, B}$.

C) Include valves in those units or equipment that have a less water flowrate in real data compared to the results from point B. This step is addressed with the help of an algorithm and the aim is to obtain the most accurate simulation (i.e., close to reality), so as to reflect how the plant is currently working. The flow results obtained will be expressed as $Q_{HYSYS, C}$.

5.5.2 Assumptions

Some assumptions have been made in the simulation to deal with insufficient information for specific equipment units or plant pipelines, as described below.

a) All the pipelines with a diameter below or equal to ¾” have been excluded from the simulation. Consequently, unit 676 has been neglected due to small pipes and flow.

b) Some pipe dimensions have been assumed, as they were not documented. In some cases, they have been measured manually, but this may lead to some measurement errors. Plant drawings are not very accurate either.

c) Design water consumption, temperature and pressure drop of equipment units have been specified based on design data. However, if some individual details were not found, a pressure drop of 0.05 kg/cm^2 has been assumed for pumps and compressors, and 0.5 kg/cm^2 for heat exchangers.

d) Due to the absence of data regarding the design flowrate in certain equipment units, it has been estimated by multiplying the pipe area times a flow velocity of 1.4 m/s.

e) In case there were no data on temperature gaps in a heat exchanger, a ΔT of 6ºC has been assumed. For compressors and pump vessels, the ΔT has been neglected.

f) The flowrate consumption of sample coolers has been considered zero.

Note that these assumptions are expected to have a negligible impact on simulation results.

5.5.3 Steady-state mode

The first step to model the cooling water network effectively involves representing the system within the simulator. The definition of the overall complex layout has been introduced within equipment and pipe segments, including all connections, dimensions, pressure drop, temperature gap, supply and return streams, and all-important points that could have an impact on the process behavior.

In this phase of the project, the TEE operation is used when one stream is divided into different streams, i.e., usually to ensure cooling water is supplied to all equipment units. Meanwhile, several MIXER objects are added to join the streams coming from all equipment units to the main manifold. This is usually employed for cooling water return. All equipment units used in the simulation.

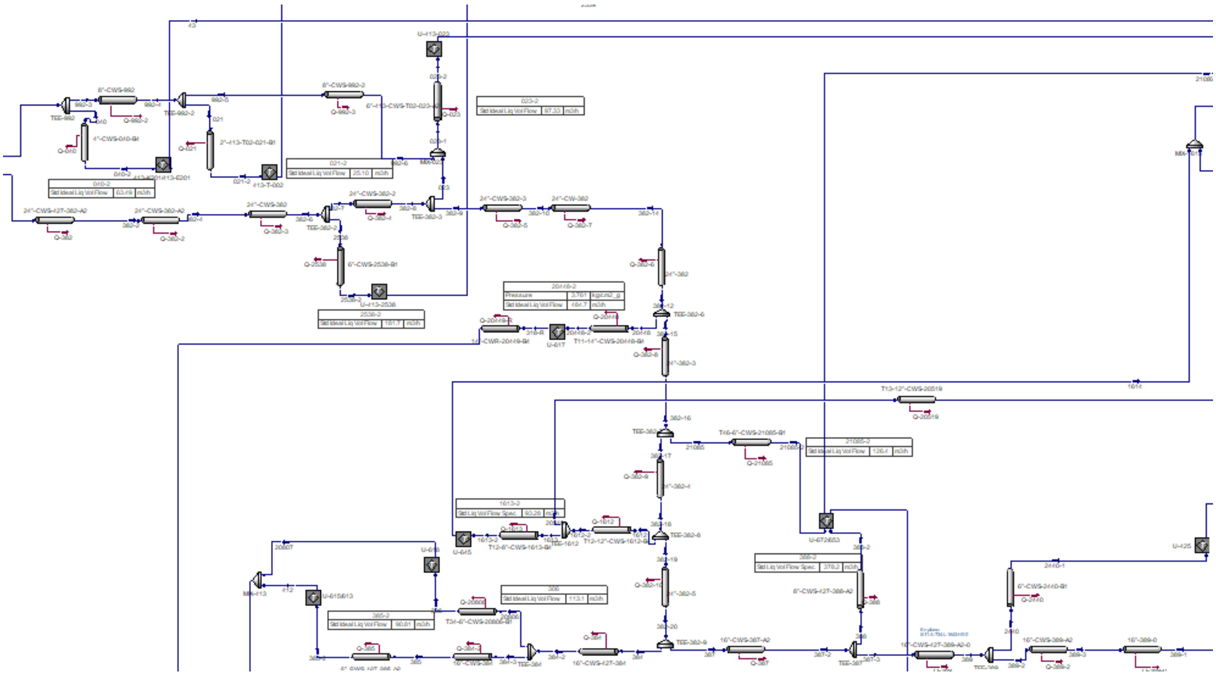
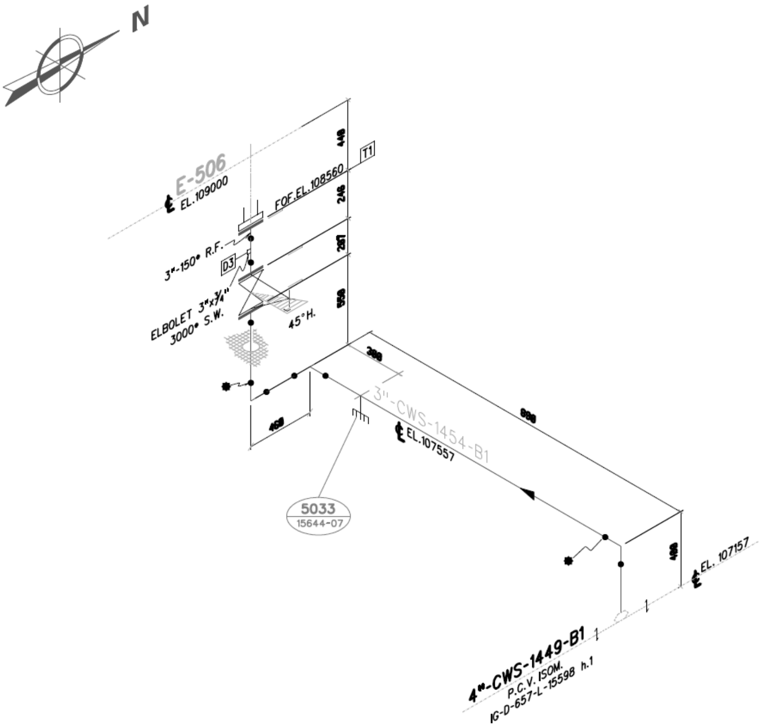


Figure 10. Extract of one part of the cooling water network simulation.

On the other hand, the subflowsheet operation is used to enhance the distribution and organization of collectors and units. This tool facilitates the creation of new working tabs, which can be connected to the main flowsheet. Given the complexity of the network, a subflowsheet is assigned to each unit in the plant. This way, there is a general flowsheet containing the cooling tower, the pumping system, and the overall network connecting all units, while the distribution networks within the units are “hidden” behind subflowsheets.

Finally, the Pipe Segment object in Aspen HYSYS is used to simulate several piping situations, specifying the required information such as pipe dimensions, length, heat transferred, elevation changes, accessories, valves and tees. As can be seen in Figure 11 and Figure 12, the methodology followed consists of introducing segment by segment all length-elevation profiles and accessories of the different streams, according to the information in isometrics and plant drawings, where available. In other cases, direct measurements have been obtained from the plant to fill data gaps. Note that the Pipe Segment object also requires a full definition of the pipe size (e.g., elbows, gate valves, etc.) and heat transfer losses. Heat losses have been considered zero, i.e., the temperature along the pipeline remains constant, even if the pipes are not heat-insulated, heat losses are negligible in the circuit as temperature inside the pipe is close to the ambient. Additionally, at least one stream temperature and one pressure must be introduced to the pipe worksheet.

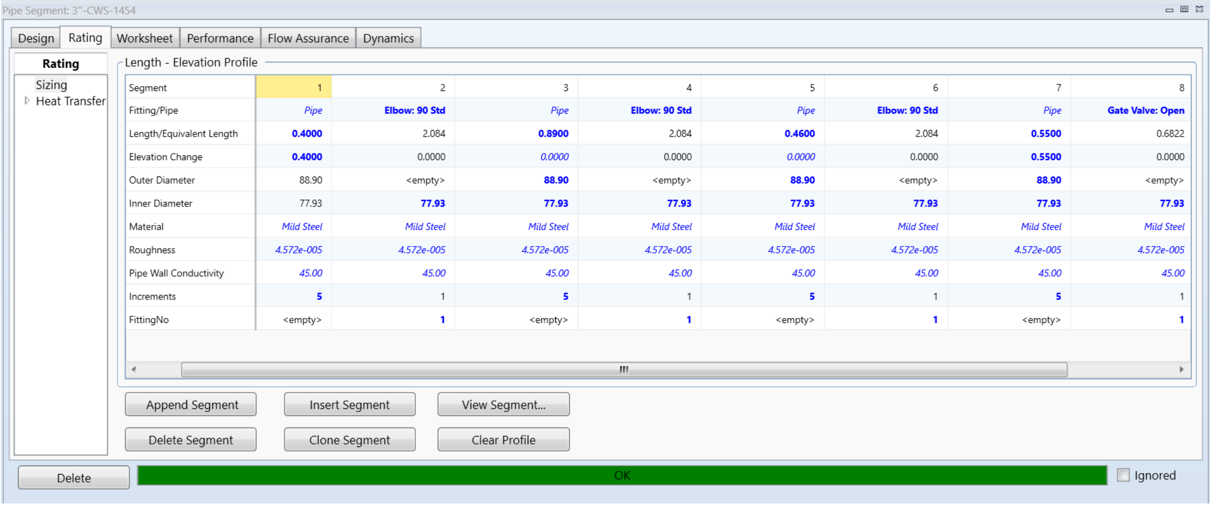


Parameter	Number
Pipe	5
Elbow 90º	3
Gate Valve	1

Figure 11. Isometric view of the pipeline.

As can be seen in the table next to Figure 11, as an example of an isometric, the first step is to include the pipeline and the elevation change which is 0.4m in the sizing page. Then, another segment must be inserted (Appended Segment), but this time the option of "Elbow: 90 Std" has to be selected. The same method is used for the following elements shown in Figure 11. Diameter, length and elevation change of each pipeline segment have been specified according to the data provided by the Engineering Department of Repsol. The result segment can be seen in Figure 12.

In case of not having isometrics available in some units, pipeline plans have been used, so not all valves and elbows could have been detected. However, as the pressure drop of those accessories are not significant due to the magnitude of the circuit, the error is going to be neglected.



Segment	1	2	3	4	5	6	7	8
Fitting/Pipe	Pipe	Elbow: 90 Std	Pipe	Elbow: 90 Std	Pipe	Elbow: 90 Std	Pipe	Gate Valve: Open
Length/Equivalent Length	0.4000	2.084	0.8900	2.084	0.4600	2.084	0.5500	0.6822
Elevation Change	0.4000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5500	0.0000
Outer Diameter	88.90	<empty>	88.90	<empty>	88.90	<empty>	88.90	<empty>
Inner Diameter	77.93	77.93	77.93	77.93	77.93	77.93	77.93	77.93
Material	Mild Steel	Mild Steel	Mild Steel	Mild Steel	Mild Steel	Mild Steel	Mild Steel	Mild Steel
Roughness	4.572e-005	4.572e-005	4.572e-005	4.572e-005	4.572e-005	4.572e-005	4.572e-005	4.572e-005
Pipe Wall Conductivity	45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Increments	5	1	5	1	5	1	5	1
FittingNo	<empty>	1	<empty>	1	<empty>	1	<empty>	1

Figure 12. Pipe sizing segments in the Pipe Segment operation.

Once the total flowrate is included in the simulation, it is possible to plot the holdup profile (pressure loss) through the pipeline. The simulation includes a total number of 994 Pipe Segment operations, 233 TEEs, 227 MIXERs and 1915 streams.

5.5.4 Equipment units

In addition to all the operations mentioned in section 5.5.3, the critical component in the simulation is the equipment comprising the refrigeration circuit. In this case, coolers are introduced to simulate heat exchangers. Only the cooling water specifications must be included, such as temperature difference between the outlet and the inlet, the pressure drop, and the operating flowrate. Regardless of whether temperature difference or operating flowrate is missing, the duty/heat transfer can be introduced.

In addition, valves are used as a replacement for compressor cooling systems and pump reservoirs. The refrigeration system of the compressors and pump reservoirs generate a low temperature difference. Hence, for simplicity, instead of including a cooler, it has been included a valve with the corresponding pressure drop, without ΔT. The valves have certain features available such as flowrate control valve, which is going to be used in the future steps of the project.

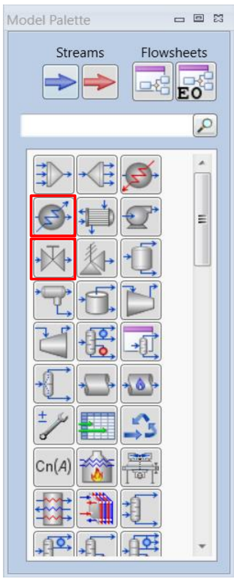


Figure 13. Model Palette

The next figure illustrates all streams and equipment units that are part of the water cooling network of unit 642/641. This one contains 6 heat exchangers, and 10 valves which represent the pump reservoirs. Additionally, it has 68 Pipe Segment operations, 13 TEEs and 12 MIXERs.

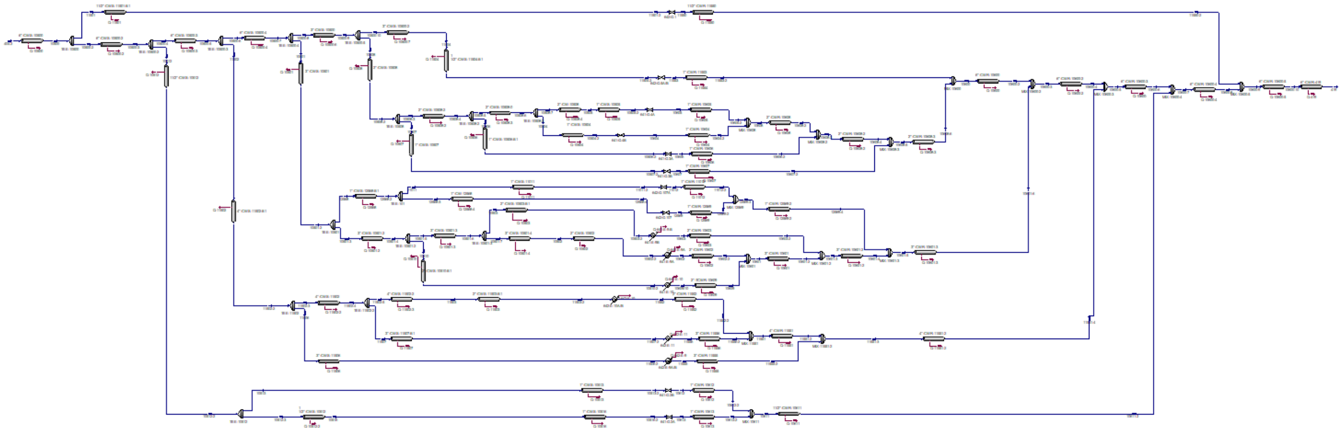


Figure 14. Simulation of Unit 642/641.

5.6 <u>Calibration of the simulation</u>

Calibrating the simulation involves mimicking the operation of the current cooling circuit. The aim is to replicate real conditions, which leads to include modifications to some units. This implies to reproduce the same values as those measured on the plant and identify those points where there is a deviation of results between the theorical and actual distribution of flow.

In general, steady-state simulation involves analyzing the system assuming that variables work at a constant operating point. Conversely, a dynamic model takes into account the rates of mass and energy accumulation, allowing to determine the time required by the system to reach a stable condition.

In Aspen HYSYS, however, the dynamic mode can also be used to automatically calculate the flow distribution through a pipeline network, based on the pressure drop of each of the lines; a question out of reach of the steady-state simulation. Take the MIXER operation as an example. In steady state, the user would specify the flowrate of (n-1) of the (n) streams connected to the MIXER, and the pressure of the inlet streams. If two or more of the inlet streams have different pressures, the simulation will set the pressure of the output stream according to the lowest pressure among the inlet streams. This situation must be avoided in the simulation since, in reality, reverse flows would occur under such conditions. In real life, the pressure of all the inlet streams would be the same in the mixing point, as the flows would be distributed according to pressure losses, i.e., the larger the flowrate of a line, the higher the pressure drop through the pipeline. This calculation is automatically done in Aspen HYSYS's dynamics mode, which distributes (i.e., estimates) the flowrates of a network so that the pressure of adjacent streams entering a MIXER (or exiting a TEE) become equal. Note that, while this calculation is still not perfect since it neglects static head contributions of the process (Sarah-Jane Brenner, 2001), it still reflects results closer to reality compared with the steady-state simulation.

5.6.1 Dynamic mode

Once the whole water circuit is introduced in steady-state mode, based on design conditions, it is time to convert the simulation into a more accurate model (i.e., closer to reality). This is done by resorting to a dynamic simulation, which is the expectation to enhance the reliability of the results.

Firstly, there are two different ways of modelling piping hydraulics in Aspen HYSYS, both of which have similar capabilities and support rigorous calculations for piping networks through dynamic modelling. One is Aspen Hydraulics, which consists of a subflowsheet that can be added to the main flowsheet and connected to other equipment. However, this tool does not include any type of equipment unit (e.g., heat exchanger) in the same subflowsheet the user is working on, so it is not a suitable option for this project. The other dynamic simulation option is the Aspen Pipe Segment Model, which is designed for basic pipeline design. This tool can be used in the main flowsheet or even in subflowsheets connected to different equipment units. It is available in the regular palette, and can be activated in the Dynamic Mode tab. (Jones, 2013)

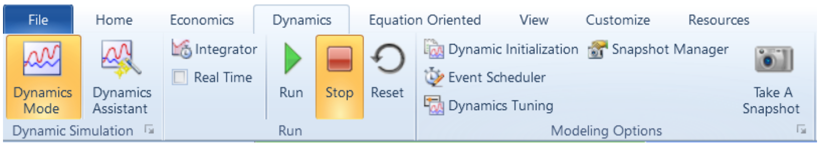
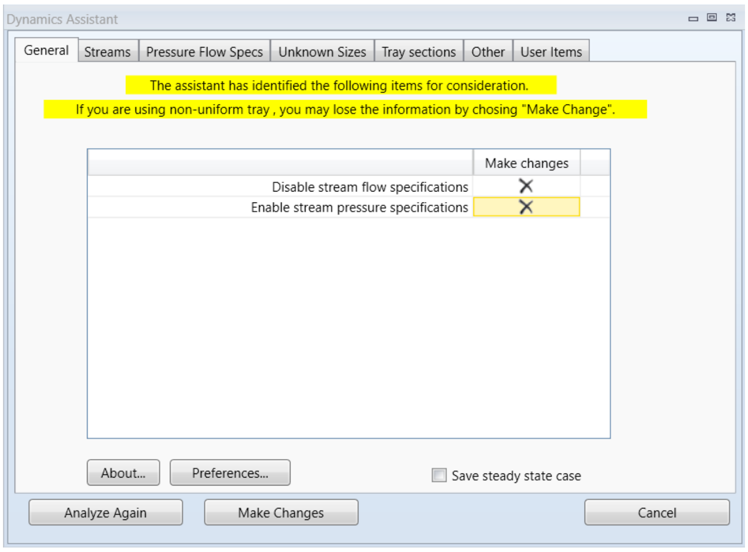


Figure 15. Dynamics tab.

In Dynamics Mode, it is fundamental to specify the pressure and/or flow of a material stream in a flowsheet. To satisfy the degrees of freedom of the pressure-flow matrix, a certain number of pressure-flow specifications need to be introduced by the user. In this case, as there are two material streams, i.e., the cooling water supply (CWS) and the cooling water return (CWR), two pressure-flow specifications have to be included. Any of the following combinations are allowed for these specifications: inlet pressure-outlet pressure, inlet pressure-(any) flow, or (any) flow-outlet pressure. After some tests, it was decided that the best option was to specify the inlet pressure and one flow because both values are known and can be measured in the plant.



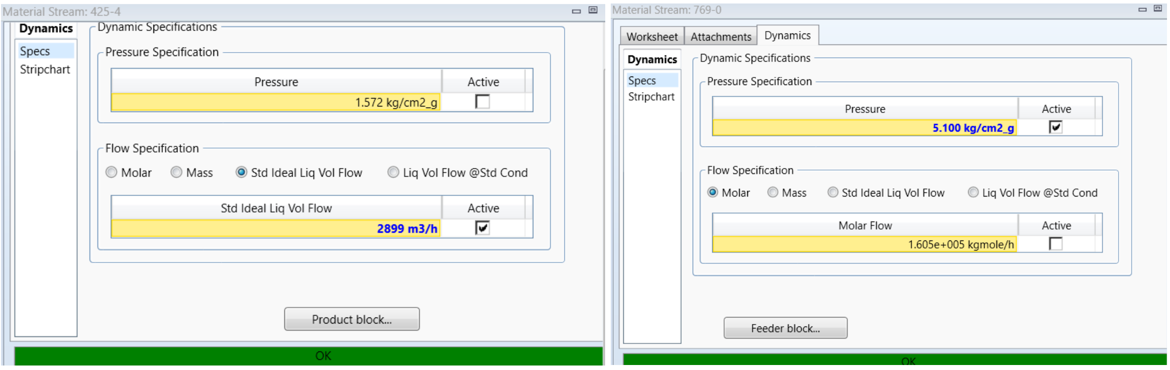
The assistant has identified the following items for consideration.

If you are using non-uniform tray , you may lose the information by chosing "Make Change".

	Make changes
Disable stream flow specifications	☒
Enable stream pressure specifications	☒

☐ Save steady state case

Figure 16. HYSYS Dynamics Assistant.



Material Stream: 425-4 — Dynamic Specifications

Pressure Specification

Pressure	Active
1.572 kg/cm2_g	☐

Flow Specification: ○ Molar ○ Mass ● Std Ideal Liq Vol Flow ○ Liq Vol Flow @Std Cond

Std Ideal Liq Vol Flow	Active
2899 m3/h	☑

Material Stream: 769-0 — Dynamic Specifications

Pressure Specification

Pressure	Active
5.100 kg/cm2_g	☑

Flow Specification: ● Molar ○ Mass ○ Std Ideal Liq Vol Flow ○ Liq Vol Flow @Std Cond

Molar Flow	Active
1.605e+005 kgmole/h	☐

Figure 17. Dynamic specifications.

As can be seen in Figure 17, a flow of 2899 m$_3$/h is specified in the outlet stream and the pressure inlet specification is 5.1 kg/cm^{2}g.

When steady-state mode is converted to dynamic mode, all the water flow distribution of the network starts to converge, equalizing pressure of inlet streams to the mixers. As the flow distribution is changing, the pressure drop of the equipment units will also change. In Cooler and Valve objects, the pressure drop is determined by a k-value, which had been specified in steady-state mode together with the design data. The relation between the flowrate and the pressure drop and the k-value [kg/hr/sqrt(bar-kg/m^3)] is given by equation 5.2, as defined in (Sarah-Jane Brenner, 2001):

$$flowrate = \sqrt{density} \cdot k \cdot \sqrt{P_1 - P_2} \tag{5.2}$$

5.6.2 Flow distribution results

Once the Dynamic Mode has been activated and the system has converged, the next step is to analyse the flowrate and pressure profiles obtained, and compare it with design and plant values, so as to identify those facilities or points of the real plant that deviate from the expected operational performance (i.e., that resulting from the dynamic simulation). This will allow to ascertain the location of equipment units and lines that act as bottlenecks, finding out what are the consequences of this malfunctioning in terms of pressure drop and temperature change, according to the dynamic simulation.

Some of these problems can be found in:

- Heat exchangers with lower-than-expected water flowrate
- Heat exchangers with an excessive consumption of cooling water
- Pipelines with a significant pressure drop (more than 2 kg/cm^2, according to the unit design manual provided by REPSOL)

In Figure 18 can be seen the flow distribution obtained in the simulation. Major water consumer is unit 617 followed by units 413, 651/652 and 653/672.

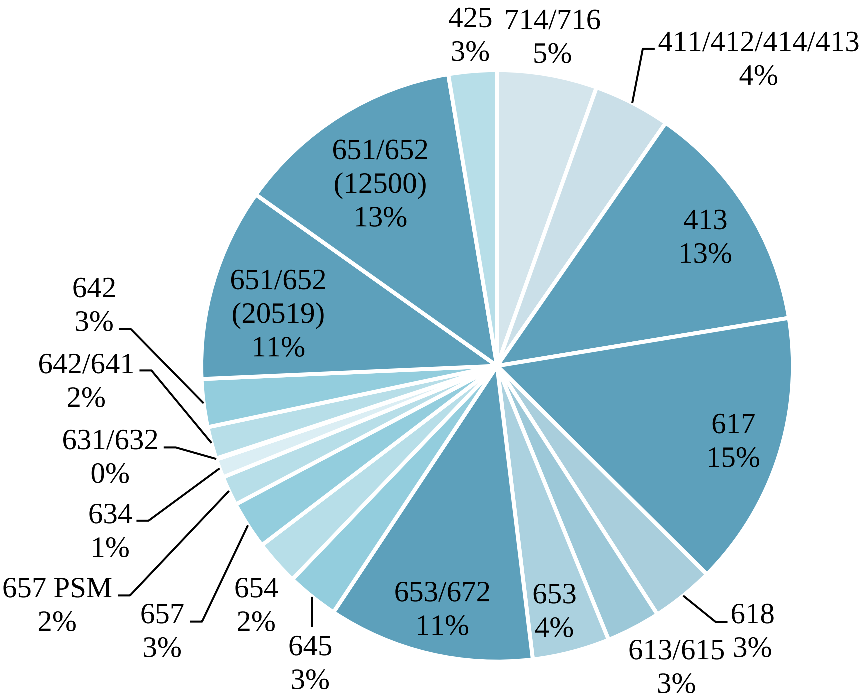


Figure 18. Flow distribution (%) of cooling water according to Aspen HYSYS' simulation.

The results for the inlet water flow to each unit are illustrated in *Table 1*. Streams with red numbers (AE >0) receive less water in reality (i.e., in the plant) than in HYSYS's simulation ($Q_{HYSYS,B}$). This suggests that those units where more water is distributed than in Q_{plant} have to be manipulated to increase the head loss in that unit and, consequently, the system starts distributing the water flowrate in order to be adapted to reality.

$$AE = Q_{HYSYS,B} - Q_{plant} \tag{5.3}$$

Table 1. HYSYS flow distribution vs design and plant flow.

Units	$Q_{HYSYS,B}$ (m^3/h)	Q_{plant} (m^3/h)	Q_{design} (m^3/h)	AE*(m^3/h)
417 (total)	2899	2899	3718.25	0
642	75.82	82.00	71.25	-6.18
714/716	158.3	94.50	97.545	63.80
411/412/414/413	121.54	130.00	183.55	-8.46
413	369.75	351.28	310.4	18.47
617	436.1	510.00	537.20	-73.90
618	99.5	120.00	109.97	-20.50
613/615	85.9	90.00	118	-4.10
653	122.5	126.00	162.5	-3.50
653/672 (388)	326.4	370.00	487.13	-43.60
645	82.27	92.70	82.59	-10.43
654	71.53	57.20	91.181	14.33
657	75.65	46.00	160.40	29.65
657 PSM (1449)	46.81	56.00	55.72	-9.19
634	29.5	19.50	64.45	10.00
631/632	1.603	1.50	5.88	0.10
642/641	50.6	31.00	79.14	19.60
651/652 (20519)	305.5	340.00	443.29	-34.50
651/652 (12500)	363.3	290.00	519.72	73.30
425	76.48	91.00	138.664	-14.52

*AE is the absolute error between HYSYS flow distribution and actual plant flowrate.

In units 617/618/653/651 an excess of water is observed because they are the units closest to the beginning of the network, therefore, if there is conflicting equipment (due to dirt or other cooling problems due to closed valves) they take more water than required to compensate for the head loss and causing that the units at the end of the manifold do not receive the required water as indicated in the simulation results.

In order to decide which are the steps to modify the circuit, or how to know up to which point is necessary to include pressure losses an iteration algorithm has been developed in the next section.

5.6.3 Iteration algorithm

For the purpose of ensuring a simulation reflecting exactly what is happening in the real plant, pressure drops (valves) will be included to pipelines with a higher flowrate in the simulation than measured in the plant. By doing this, the simulation will recalculate the flow distribution, reducing the flowrate assigned to those streams. This additional pressure drop, artificially introduced into the simulation, mimics the effect of fouling or other event that can increase the head loss in a pipeline.

Of course, introducing a new pressure drop in a given line would result in all flowrates to change, potentially unveiling new problems in other points (i.e., lines) of the simulation. Hence, the process of introducing new pressure drops (i.e., valves) in the simulation has been based on the algorithm shown in Figure 19.

The simulation starts with the introduction of the pressure and the flowrate of the inlet stream of the network. Once the dynamic mode starts, the water flowrates of all lines will change based on the corresponding piping hydraulics. The focus is set on the inlet flows to each unit, whose flowrate, as given by the simulation, is stored ($Q^{unit}_{in,\ hysys}$). The next step consists of calculating the absolute and relative error between $Q^{unit}_{in,\ hysys}$ and the real flowrate to each unit, as measured in the plant ($Q^{unit}_{in,\ plant}$). The main requirements are that the absolute error (AE^{unit}) is not higher than 5 m^3/h, or that the relative error is lower than 10%. If one these conditions are not satisfied by all inlet flows into units, an additional pressure drop is introduced in the unit showing the largest absolute error, i.e., the unit that consumes a higher amount of water in the simulation compared with the real water consumption. Note that only units for which AE^{unit} is positive are considered as candidates for the new valve, as adding more pressure drop to units with an already smaller flowrate would be counterproductive.

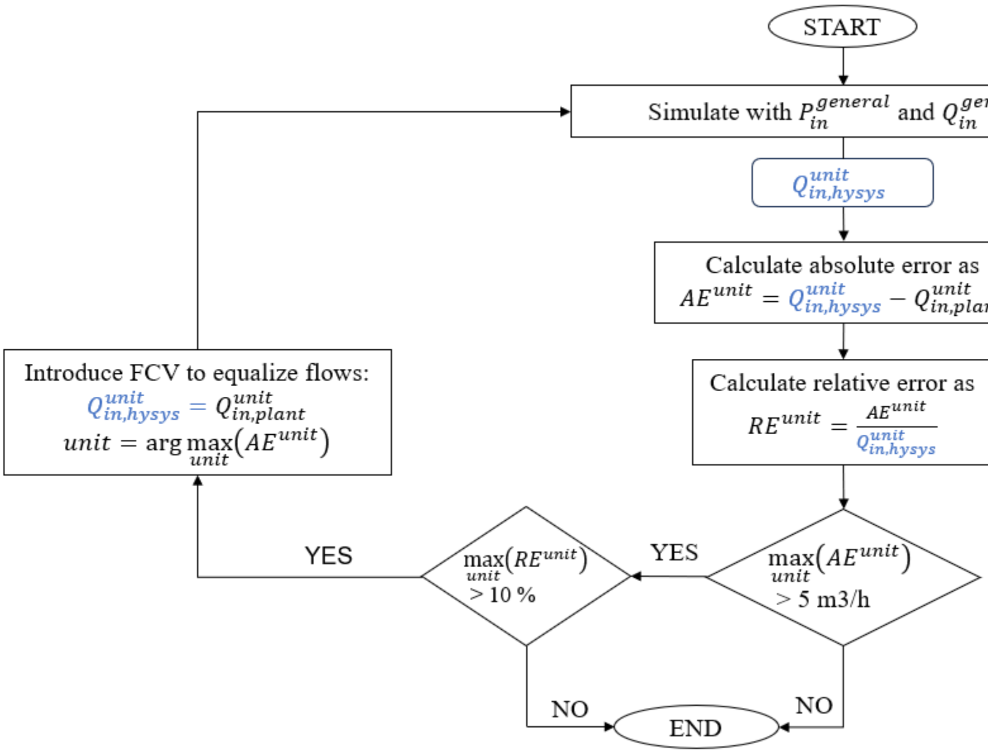


Figure 19. Iteration algorithm flowchart.

As long as all any unit is above the threshold imposed for the absolute or the relative errors, a flow control valve (FCV) will be included in those units in order to apply an extra pressure drop and regulate the water flow.

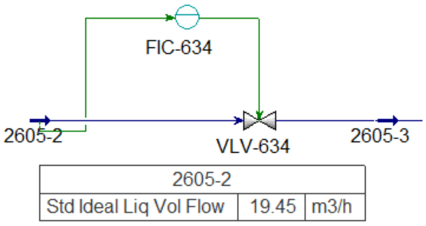
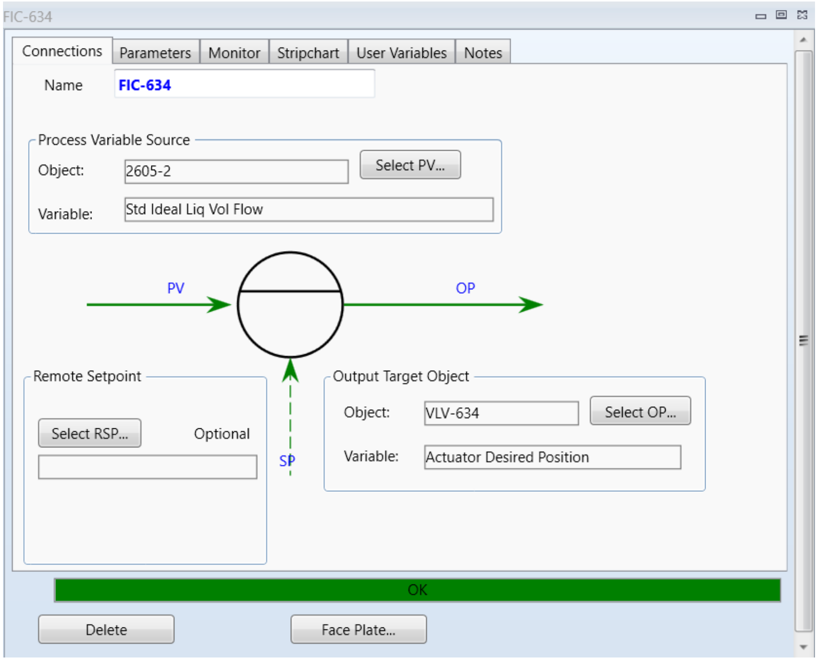


Figure 20. HYSYS control valve set-point.

As can be seen in Figure 21, the flow controller (FIC) sends a signal output between 0-100% of the "Actuator Desired Position" to the FCV, the valve will start to throttle the water flow. In this case, the desired set-point volume flowrate is introduced in the flow controller.



Name: FIC-634

Process Variable Source
Object: 2605-2
Variable: Std Ideal Liq Vol Flow

Remote Setpoint

Output Target Object
Object: VLV-634
Variable: Actuator Desired Position

Figure 21. HYSYS flow controller.

Note that not all iterations consist of including a control valve at the entrance of a unit. The procedure consists of introducing a FCV at those points where there is an excess of water with respect to reality. For this reason, each equipment unit has been evaluated individually within each unit, checking the flowrate of all facilities one by one. If there is an excess of water in a unit in general, a FCV is introduced at the inlet of the unit. On the other hand, if a unit is working properly, but only one equipment (i.e., heat exchanger, compressor, etc.) has problems, then that control valve will be only added in that facility, as it affects the overall unit flowrate containing a higher flow rate than it actually does.

The algorithm took 11 iterations to produce acceptable results in the simulation. The actions taken by adding valve and FIC during these iterations are shown next:

1. Reduction from 29.5 to 19.5 m^3/h in unit 634
2. Reduction from 158.3 to 94.5 m^3/h in unit 714/716
3. Reduction from 23.8 to 11.5 m^3/h in heat exchanger 657-E-7
4. Reduction from 30.2 to 25 m^3/h in heat exchanger 657-E-4
5. Reduction from 120.1 to 87 m^3/h in compressor 413-K-205
6. Reduction from 33.9 to 20.1 m^3/h in heat exchanger 413-E-210
7. Reduction from 363.3 to 290 m^3/h in unit 651/652
8. Reduction from 50.6 to 31 m^3/h in unit 642/641
9. Reduction from 71.53 to 58.1 m^3/h in unit 654
10. Reduction from 17.21 to 8 m^3/h in heat exchanger 657-E-8
11. Reduction from 75.65 to 46 m^3/h in unit 657

A total amount of 11 control valves were included (one per iteration). These are the streams that have more actual pressure drop than in design. Consequently, they are responsible for the fact that some units and equipment do not receive enough cooling water.

In Table 2 can be seen some of the evolution of the absolute error results throughout some of the iterations. In iteration 11, which is the last one, the error values are within the acceptable range for absolute (<5 m^3/h) or relative errors (< 10%) across all units. Finally, the flowrate results of the last iteration ($Q_{HYSYS,C}$) are shown in the next section.

Table 2. Evolution of the AE^{unit} over the iterations.

Iteration	Base	2	6	10	11	11
Units	sim-plant	sim-plant	sim-plant	sim-plant	sim-plant	RE_{unit} (%)
642	-10.79	-9.22	-8.11	-7.39	-2.35	-2.87
714/716	64	0.07	-0.15	-0.05	-0.19	-0.20
411/412/414/413	-8.27	-5.3	-1.87	0.36	0.73	0.56
413	19.06	28.06	9.4	14.98	15.79	4.49
617	-73.2	-62.3	-42.8	-28.4	-25.40	-4.98
618	-20.33	-17.8	-12.2	-7.8	-6.80	-5.67
613/615	-3.96	-1.74	3.09	6.84	0.11	0.12
653	-3.3	-0.2	6.5	-0.1	-0.20	-0.16
653/672 (388)	-43.1	-34.8	-12.6	4.6	8.30	2.24
645	-10.12	-8.26	-3.72	-0.2	0.58	0.63
654	14.45	16.57	25.24	-0.02	0.25	0.44
657	29.77	33.29	20.14	6.37	-0.04	-0.09
657 PSM (1449)	-9.11	-7.45	-0.69	5.03	-0.01	-0.02
634	10.05	0.04	-0.01	-0.09	-0.02	-0.10
631/632	0.106	0.18	0.46	0.75	0.80	53.53
642/641	19.68	22.15	30.9	0.03	-0.07	-0.23
651/652 (20519)	-34	-26.1	-9.3	3.8	6.70	1.97
651/652 (12500)	73.9	84.8	0.1	0	-0.80	-0.28
425	-14.4	-12.31	-4.68	1.09	2.28	2.51

5.7 Results analysis

The pressure and temperature conditions of the main manifold (i.e, CW supply and CW return) are shown in Table 3. As can be seen in the table below, pressure drops and temperature differences are consistent to design parameters.

Table 3. Supply and retorn conditions in simulation B and C (see section 5.5.1).

Parameter	**HYSYS,B**		**HYSYS,C**	
	Supply	Return	Supply	Return
Pressure (kg/cm^{2}g)	5.1	1.0	5.1	0.7
Temperature (ºC)	27.7	37.9	26.0	35.3

The final results (i.e., inlet flowrates to each unit), before and after applying the algorithm necessary to adapt the network to the actual plant data are given in Table 4. The maximum absolute error in simulation B was 73.2 m^3/h, which was reduced to 25.4 m^3/h, giving a relative error of 5.0%.

As can be seen, $Q_{HYSYS,B}$ refers to the flow distribution obtained by HYSYS without any extra pressure drop (as given by the dynamic simulation based on design data) and $Q_{HYSYS,C}$ is the flow distribution that has been adapted with control valves in order to match Q_{plant}.

Table 4. Results and errors obtained.

Units	**$Q_{HYSYS,B}$ (m^3/h)**	**$Q_{HYSYS,C}$ (m^3/h)**	**Q_{plant} (m^3/h)**
417	**2899**	**2898.44**	**2898.68**
642	158.5	74.8	82.00
714/716	121.73	94.48	94.50
411/412/414/413	370.34	130.96	130.00
413	436.8	367.69	351.28
617	99.67	485.5	510.00
618	86.04	113.4	120.00
613/615	122.7	90.27	90.00
653	326.9	126	126.00
653/672 (388)	82.58	379	370.00
645	71.65	93.44	92.70
654	75.77	57.55	57.20
657	46.89	46.04	46.00
657 PSM	29.55	56.08	56.00
634	1.606	19.51	19.50
631/632	50.68	2.3	1.50
642/641	71.21	30.98	31.00
651/652 (20519/1602)	306	347.3	340.00
651/652 (391/12500)	363.9	289.7	290.00
425	76.6	93.44	91.00

Finally, $Q_{HYSYS,C}$ and Q_{plant} results obtained are quite close to each other, and reflect the actual network performance. After these results were obtained, every critical heat exchanger has been analysed and discussed.

6. DISCUSSION

In this section some equipment have been proposed to enhance its performance.

***All information pertaining to this section is strictly confidential and intended solely for the designated recipients.**

7. WATER ECONOMY

As mentioned in section 7.1 below, using recirculated cooling water systems to remove process waste heat requires maintenance considerations through control of make-up water. This process, also called evaporative cooling, is important to minimize the generation of wastewater and fresh water consumption.

7.1 Make-up water

Because of the air is forced against water in the cooling tower a small portion of water flow is vaporized during heat transfer. This cooling method based on evaporation was conceived as a water-conservation device for recirculating cooling water systems, achieving a promising performance. However, this system sacrifices between 3-5% of total water flow owing to evaporation. This can be explained by the combination of two common thermodynamic concepts: latent and sensible heat. Latent heat is generated when a fraction of water is evaporated. In this case, the highest amount of energy is transmitted from the water to the air. In other words, when there is a phase change (evaporation), the range of temperature remains constant, and the energy absorbed by the air is very high. The equilibrium is maintained as long as the heat gained by the air equals the heat lost by the water. On the other hand, sensible heat is generated due to the air-water contact, as long as there is a temperature difference between the air and the cooling water. However, this type of heat capacity does not require a lot of energy to transfer.

Recirculating cooling water requires additives to prevent corrosion, fouling and biologic agents such as bacteria, algae or other types of microorganisms. To secure an appropriate concentration of these additives, it is necessary to implement a drain system. In this system, the amount of water blowdown from tower depends on the number of the so-called concentration cycles, e.g., the ratio of the chloride content of the circulating water to the make-up water (Green DW, 2019).

Therefore, make-up fresh water is added in order to compensate for the amount of water lost due to drift, evaporation, and blowdown. The next figure illustrates how circuit works.

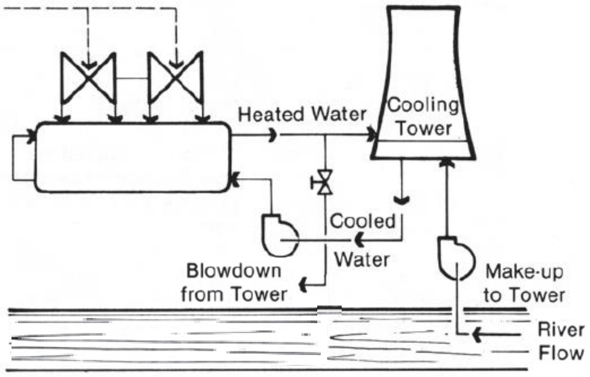


Figure 22.Closed circuit system of the cooling tower. (Hensley, 1998)

Performing the mass balance on the system depicted in Figure 23, it is possible to calculate the amount of make-up water needed to compensate water lost due to evaporation, drift, and blowdown.

$$Q_m = Q_e + Q_b + Q_d \tag{8.1}$$

Here, Q_e is the amount of water evaporated (m^3/h), Q_d are the drift losses (m^3/h), Q_b is the blowdown (m^3/h), and Q_m is total amount of make-up water (m^3/h).

Drift and evaporation losses can be estimated with the following equations (Green DW 2019),

$$Q_d = 0.0002 \cdot Q_r \tag{8.2}$$

$$Q_e = \frac{Q_r \cdot \Delta T}{500} \tag{8.3}$$

where Q_r is the amount of water recirculated within the network (m^3/h), and ΔT is the temperature difference between T_{CWR} and T_{CWS}.

The cycles of concentration are defined in the next equation.

$$cycles = \frac{C_{Process}}{C_{Make-up}} \tag{8.4}$$

Here, C_{Ebro} and C_{proces} are the concentration of the different indicators of water quality (i.e., conductivity, sulphates, calcium hardness, etc) in the make-up and process water, respectively.

Next, the make-up water flowrate at river water concentration has to be equal to the blowdown flowrate at process water concentration, as can be seen in equation 8.5.

$$Q_m \cdot C_{Make-up} = Q_b \cdot C_{Process} \tag{8.5}$$

Note that this is the mass balance of solute in water, ensuring that there is no accumulation or loss of solute in the system.

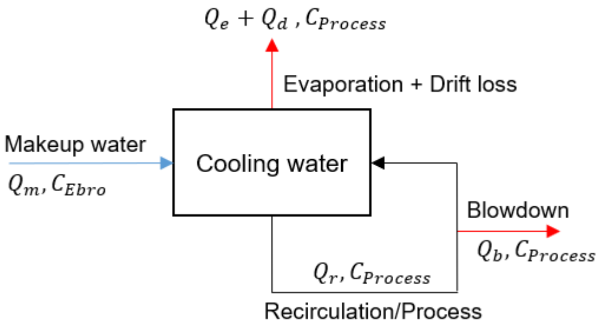


Figure 23. Mass balance scheme.

Water quality and blowdown flowrate are constantly changing during time and season, and for this reason, it is not possible to provide an exact and unique number for the flowrate of the water make-up. Hence, a study can be carried out to analyse how the amount of make-up water needed fluctuates with concentration cycles, for different values of relative humidity, and air temperature.

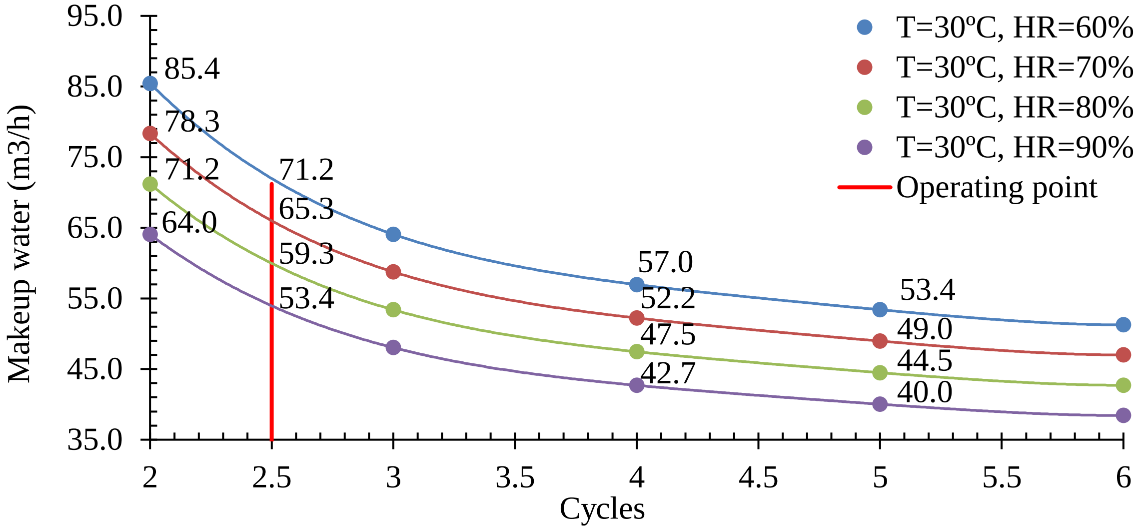


Figure 24. Make-up water at different relative humidity values and cycles of concentration at 30ºC of air temperature.

Temperature approach is the difference between the temperature of the water exiting the cooling tower and the wet bulb temperature of the inlet air and represents the cooling tower capability.

$$Approach = T_{CWS} - T_{wetbulb} \tag{8.6}$$

Figure 24 is obtained assuming that some of the ambient conditions are known, such as the air inlet temperature (30ºC) and the temperature approach (6.1ºC). The dry bulb temperature is basically the air ambient temperature, which is 30ºC, as mentioned above. On the other hand, the wet bulb temperature is the measurement of the air temperature combined with humidity and is always lower than the dry bulb temperature (Wolf & Blecich, 2018).

Typically, in instances where the tower is large, the temperature approach is small because it varies inversely with airflow, as more airflow, the cold water temperature will be closer to wet bulb temperature and consequently, approach would decrease. The calculations containing all the equations of the make-up water consumption is developed in Annex A.1.4.

As can be seen in Figure 24, the amount of water consumed is higher at lower relative humidity. As relative humidity increases, the moisture content in the air rises, resulting in a lower capacity to retain more water. Consequently, less amount of water is evaporated, and less amount of make-up is needed for compensation. Once the air outlet approaches 100% of saturation, it reaches the maximum holding capacity of water vapor.

While relative humidity does not affect the overall evaporative performance of a cooling tower, it does affect the rate of evaporation, as indicated above. This relationship is inversely proportional (Cooling Technologies, 2018). This occurs because enthalpy stays close to constant during relative humidity changes, as can be seen in the psychrometric chart that represents the physical and thermal properties of moist air (see Annex A.1.5).

In case the temperature of air decreases, this means that air is drier and can hold more water vapor, i.e., the amount of water evaporated is higher (Delta, 2021). Consequently, make-up water is going to increase.

As Eq. (8.3) is used to calculate evaporated flowrate in an approximate weather condition, the reality is that this value could change during time. Figure 24 helped to determine that the conditions used to homogenise results in the section below are: air temperature inlet of 30.0ºC, wet bulb temperature of 24.3ºC and a relative humidity of 62.0%.

7.2 Cycles of concentration

*** All information pertaining to this section is strictly confidential and intended solely for the designated recipients.**

8. WATER AND ENERGY CONSUMPTION AVOIDANCE

In order to determine the amount of water and energy that would be avoided, the pumps are first introduced into the final simulation and their respective characteristic curves are added (Figure 27). Subsequently, the suction pressure of 0.6 kg/cm^2 and the desired recirculation flow rate are then entered. Taking into account that the pressure at point 769-3 must be kept constant, the flow rate and power are increased to maintain the same pressure value. The flow rate is increased until all units receive enough quantity of water according to the water distribution without modification.

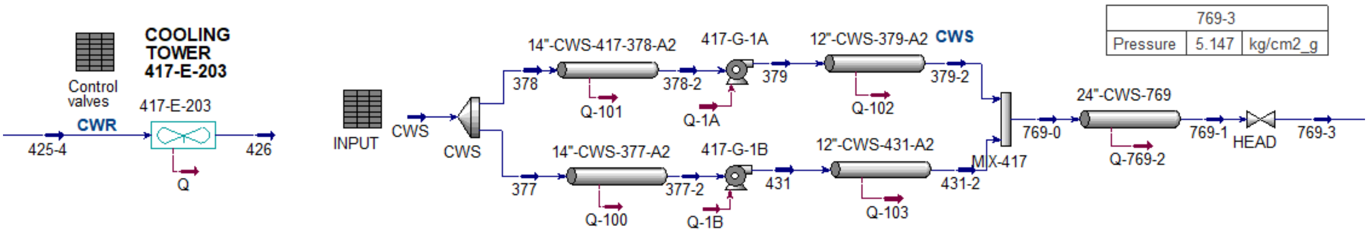
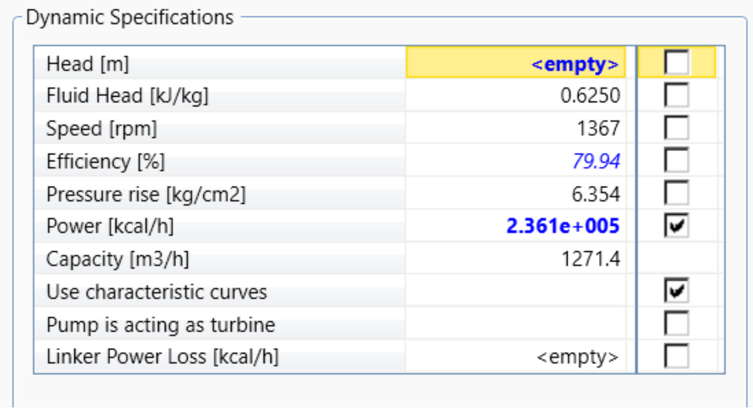


Figure 25. Pump system into simulation.

Once the power is introduced into the pumps, it is necessary to add the characteristic curves of the pump into Rating tab. The use of the characteristic curves in dynamic mode would calculate the capacity (i.e, volume flow) supplied by each pump into the network.


Dynamic Specifications

Head [m]	<empty>	☐
Fluid Head [kJ/kg]	0.6250	☐
Speed [rpm]	1367	☐
Efficiency [%]	79.94	☐
Pressure rise [kg/cm2]	6.354	☐
Power [kcal/h]	2.361e+005	☑
Capacity [m3/h]	1271.4	
Use characteristic curves		☑
Pump is acting as turbine		☐
Linker Power Loss [kcal/h]	<empty>	☐

Figure 26. Dynamic specifications of the pump 417-G-1-B.

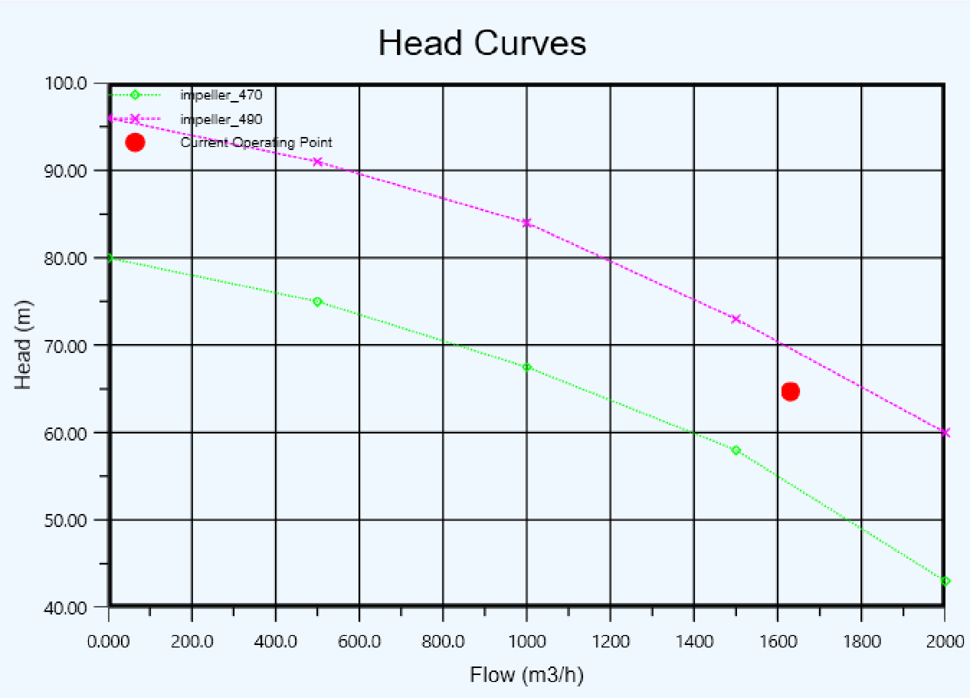


Figure 27. Characteristic curves of pump 417-G-1-B.

***All the results pertaining to this section are strictly confidential and intended solely for the designated parties.**

9. CONCLUSIONS

After analysing all aspects of the work carried out, including the water consumption of the cooling tower, the results obtained are evaluated.

Firstly, the dynamic model of the simulation in Aspen HYSYS allows us to know the main parameters of the cooling water distribution in the network. Results have been obtained both under design conditions, conditions of how the circuit should ideally work and under current operating conditions. Although some equipment with pipes smaller than ¾" were underestimated or certain dimensions in pipes or equipment were undocumented, the flow distribution along the cooling circuit has helped to contemplate and identify those equipment and units that showed a clear example of bottlenecks in the system. The main points found are:

- The simulation helps to improve and optimise the distribution of water to guarantee enough water to the different plant units and to detect possible fouling or cooling improvement scenarios
- There is evidence of those equipment units identified as bottlenecks
- It has been possible to detect the points that can be enhanced, and consequently, the possibility to avoid an increase in recirculation flowrate

However, if it is decided to clean an equipment unit without solving the problems detected in the dynamic simulation, and this facility starts consuming more water, another equipment will start to have less water. For this reason, if the measures suggested in the discussion section the whole system should be reviewed unit by unit after implementing each of the different actions proposed. In addition, a more thorough study should be carried out if any measures want to be implemented.

Secondly, it has been observed how the need for make-up water increases when the relative humidity in the environment is lower, due to the increase in the flow of evaporated water. On the other hand, the need for increased purge is also evaluated when the water quality reaches a set limit.

- The study has analysed and proposed an increase in the cycles of concentration to reduce the fresh water supply to the tower, always working within the concentration limits and monitoring via corrosion coupons, the state of the piping and avoiding undesired corrosion scenarios.

Though the actual data is varying constantly along time, evidence of possible enhancements of the cooling system of tower 417-E-203 has been detected. It has also been possible to successfully develop a tool for predicting results in Aspen HYSYS, even though it will need to be modified and adapted to the real values and conditions at the time when results want to be analysed.

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A.1. ANNEXES

A.1.1. Bernoulli's Principle

The main working principle defining the behaviour of the water network system is the Bernoulli's principle. It explains how fluid moves through a pipeline, why there is more or less pressure drop between two points, or even if the system has the capacity to properly achieve the operating conditions of all facilities.

Certain variables are involved in the Bernoulli's equation for steady incompressible fluid in pipe flows, including pressure change, elevation change, exit jet kinetic energy, and friction losses. The Bernoulli's equation is presented next (White FM, 2021).

$$\left(\frac{p_{in}}{\rho}+\frac{V_{in}^2}{2}+g\cdot z_{in}\right)+h_{pump}=\left(\frac{p_{out}}{\rho}+\frac{V_{out}^2}{2}+g\cdot z_{out}\right)+h_{friction}+h_{turbine} \qquad (A.1)$$

Here, $p_{in/out}$ is the pressure at the inlet and outlet of the pipe (Pa), $V_{in/out}$ is the velocity of the fluid (m/s), g is gravity (m/s^2), z is the head elevation (m), h_{pump} is the pump head from the flowrate and pump power (m), $h_{friction}$ is the head loss (m), and $h_{turbine}$ is the turbine head (m).

A single pipe system may have many minor losses (local) and major losses (friction). The next expression shows how friction losses can be calculated, including major and minor losses due to the addition of devices such as valves, elbows, tees, fittings and so on.

$$h_f=\frac{V^2}{2\cdot g}\cdot\left(\overbrace{\frac{f\cdot L}{d}}^{\text{major loss}}+\overbrace{\sum K}^{\text{minor loss}}\right) \qquad (A.2)$$

$$V=\frac{Q}{A} \qquad (A.3)$$

Here, f is the friction factor, L is the total length of the pipe axis (m), d is the pipe diameter (m), K is the resistance coefficient of the accessories (i.e., valves, elbows, etc.), A is the pipe transversal area (m^2) and Q is the volumetric flowrate (m^3/s). As illustrated in Eq. (A.3), if pipe size changes, the velocity changes consequently. This means that, at larger pipe size, the flow velocity is going to decrease, together with friction losses. In addition, when the flowrate is higher, velocity increases, and thus more friction losses (h_f). This determines how the water flow is distributed as long as the pressure in the nozzles is the same when all the branches join into the same manifold.

Furthermore, it is important to ensure enough *Net Positive-Suction Head* (NPSH) in the pumps. The NPSH provides the head (i.e., pressure) required at the pump inlet to prevent from cavitating flow.

$$NPSH=\frac{p_a}{\rho\cdot g}-h-h_f-\frac{p_v}{\rho\cdot g} \qquad (A.4)$$

Here, p_a is the pressure at suction (Pa), h is the head suction (m), h_f is the loss head suction (m), and p_v is the vapour pressure of the fluid, in this case water (Pa).

A.1.2. List of Units

As can be seen in the next table, all units are defined separately, however, in the main text most of them are written together because they share the same manifold.

Table A.5. List of all units.

Unit	Description
411	Water treatment
412	Boiler steam generation
413	Air instrumentation system
414	Boiler-fuel oil system
417	Water cooling towers
425	Flare gas recovery
613	Crude oil unit
615	Gas concentration unit
617	Isobutane unit
618	Isomerization unit
631	L.P.G Merox Unit
632	Merox Gasoline Unit
634	Kerosene sweetening/hydrotreating
641	Desulfurization unit of medium distillation N-1
642	Desulfurization unit of heavy distillation
645	Desulfurization unit of medium distillation N-2
651	Desulfurization unit of naphtha
652	Platforming unit
653	ISOMAX unit
654	M.T.B.E Unit-1
657	M.T.B.E Unit-2
672	Hydrogen unit
676	Blending
714	LPG storage
715	Cryogenic ethylene storage plant
716	Propylene storage

A.1.3. Equipment units inventory

Table A.6. Number of equipment units in each unit.

Units	Equipment	Heat exchanger	Compressor cooler	Pump reservoir	Pump
411	14	1	13	0	0
412	6	2	4	0	0
413	21	11	10	0	0
414	8	0	0	8	0
417	3	0	0	0	3
425	2	2	0	0	0
613	9	0	0	9	0
615	17	6	0	11	0
617	5	5	0	0	0
618	6	3	0	3	0
631	2	1	0	1	0
632	2	0	1	1	0
634	1	1	0	0	0
641	9	3	0	6	0
642	10	6	0	4	0
645	13	4	3	6	0
651	14	6	3	5	0
652	17	12	0	5	0
653	28	16	5	7	0
654	13	8	0	5	0
657	14	9	0	5	0
672	3	3	0	0	0
676	1	0	0	1	0
714	7	1	0	6	0
715	10	10	0	0	0
716	0	0	0	0	0
Total	**235**	110	39	83	3
Percentage		**46.8%**	**16.6%**	**35.3%**	**1.3%**

*Some equipment may cannot be included in the simulation because it can be out of service.

A.1.4. Relative Humidity and water content

As mentioned in the main text (section 7.1), the wet bulb temperature is the lowest temperature to which air can be cooled by means of the evaporation effect of water at constant pressure.

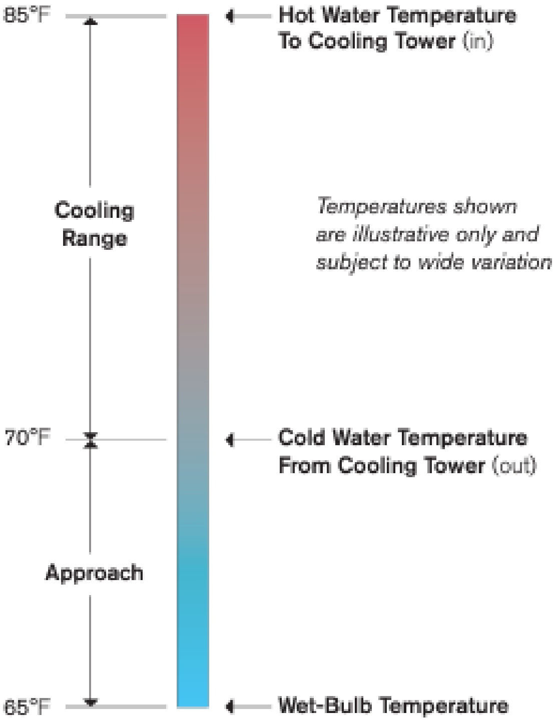

Figure 28. Relationship between range and approach in cooling water operation. (SPX Cooling Technologies, 2016)

This effect can vary according to air humidity and ambient temperature, influencing the amount of make-up water needed and the working conditions required for each season or location. For this reason, the following equations have been used to calculate the amount of make-up water needed in the cooling tower, for given values of relative humidity, air temperature, and concentration cycles (Goodfellow & Curd, 2020).

$$p = p_w - 0.00066 \cdot P \cdot (T_a - T_w) \cdot (1 + 0.00115 \cdot T_w) \qquad (A.5)$$

$$p_w = 6.112 \cdot e^{\frac{17.67 \cdot T_w}{T_w + 243.5}} \qquad (A.6)$$

Here, p is the calculated vapour pressure of water (mbar), p_w is the saturated vapour pressure of water at wet bulb temperature (mbar), T_a is the air temperature (or dry bulb temperature) (ºC), T_w is the wet bulb temperature (ºC), and P is the atmospheric pressure (1013.25 mbar).

On the other hand, the saturated vapour pressure of water vapour at dry bulb temperature (ps, in mbar), can be obtained from Eq. (A.7).

$$p_s = 6.112 \cdot e^{\frac{17.67 \cdot T_a}{T_a + 243.5}} \qquad (A.7)$$

Once the vapour pressure of water has been obtained, the relative humidity of the air stream entering the cooling tower is evaluated through the following formula (Goodfellow & Curd, 2020).

$$RH = \frac{p}{p_s} \cdot 100 \qquad (A.8)$$

From the relative humidity (RH), water content in humid air can be obtained with the following equations:

$$ph'(T) = P \cdot \exp\left(11.78 \cdot \frac{T_a - 372.79}{T_a - 43.15}\right) \qquad (A.9)$$

$$p_h = RH \cdot ph'(T) \qquad (A.10)$$

$$x = 0.622 \cdot \frac{p_h}{p - p_h} \qquad (A.11)$$

where ph’ is the pressure of saturated water at dry temperature (Pa), ph is the partial pressure of water vapour in air (P), and x is the mass water content in humid air. T_a and P are expressed in K and Pa, respectively.

The identical formulae have been used to determine the water content of the exiting air, where the relative humidity is 100% since the exiting air is set to saturated conditions to achieve optimal water consumption. Once water content is known at the entrance and exit of the cooling tower, it is possible to determine the amount of water evaporated by a simple balance.

$$\Delta x = x_{out} - x_{in} \qquad (A.12)$$

$$Q_e = \Delta x \cdot Q_{air} \cdot \eta \qquad (A.13)$$

Here, Q_{air} is the air flowrate (kg/h), which is 2080 tons/h according to the design conditions of the cooling tower. In addition, the efficiency of the cooling tower fan (η) is equal to 62%, according to Repsol.

The following equation illustrates how the flowrate of the blowdown water varies with the number of cycles and the flowrate of evaporated water (Green DW, 2019). Q_d is calculated using Eq (8.2) in the main text.

$$Q_b = \frac{Q_e - (cycles - 1) \cdot Q_d}{cycles - 1} \qquad (A.14)$$

With the values of Q_b. Q_e and Q_d at hand, one can estimate the flowrate of make-up water needed (Q_m), using Eq (8.1) in the main text. These calculations have been repeated for concentration cycles between 2 and 6, and for air relative humidities between 60-90% in order to elaborate Figure 24.

In addition, cooling tower thermal gap is calculated as (Green DW, 2019):

$$\Delta T = (T_{CWR} - T_{CWS}) = \frac{Q_e}{0.00085 \cdot Q_r} \qquad (A.14)$$

This equation can be used to calculate the cooling range of water, and could be useful to make the mass balance in section 7.1.

A.1.5. Psychrometric chart

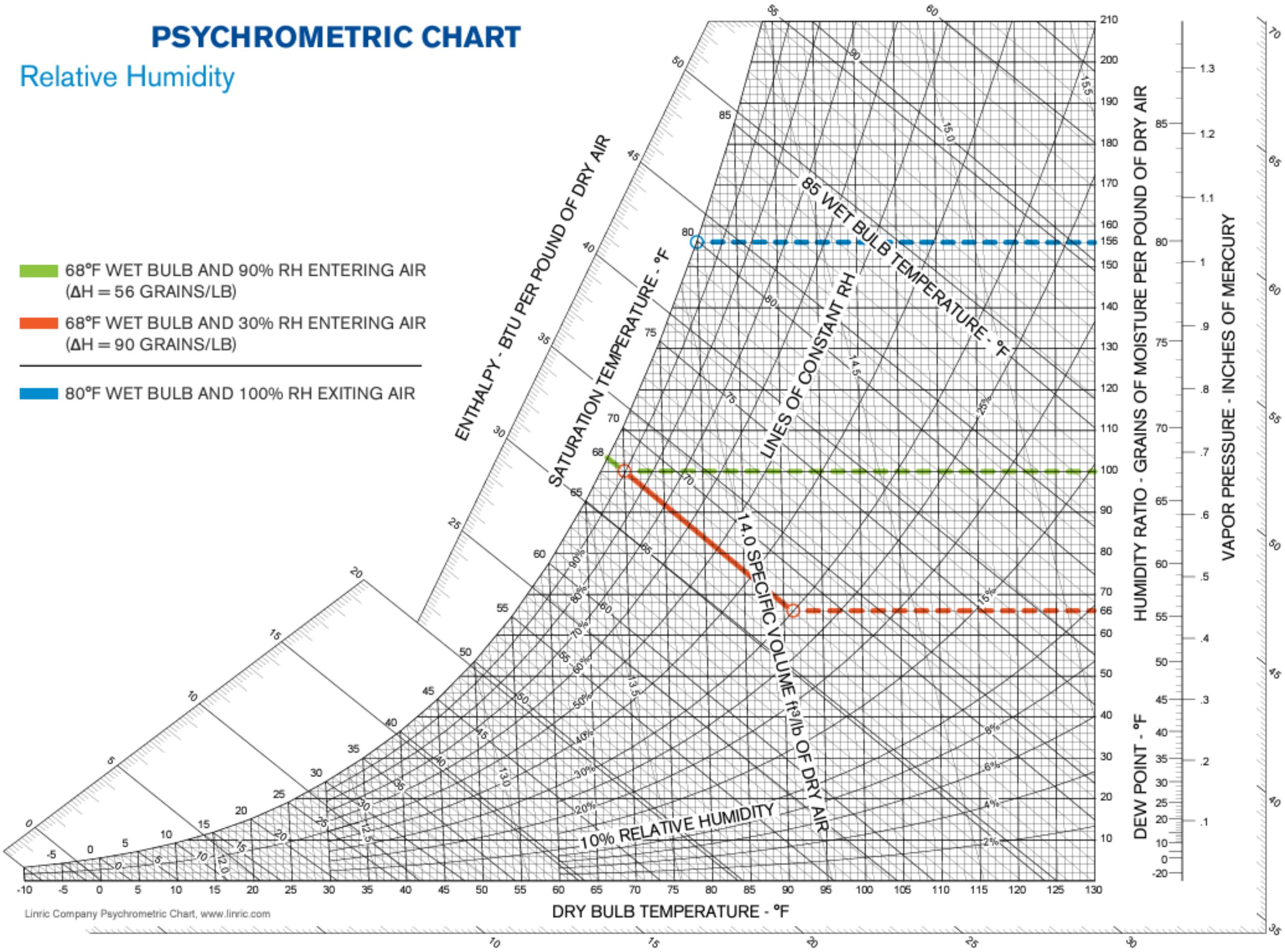

Figure 29. Psychrometric Chart of moist air (Cooling Technologies, 2018).