Universitat
Rovira i Virgili

Escola Tècnica Superior
d'Enginyeria Química

CLARIANT

EOD Heat integration

Master thesis presented by Raquel Ronquillo Moreno

to obtain the Master degree in Chemical Engineering
from the Universitat Rovira i Virgili

Company Supervisor: Daniel Pardos, Pol Aragonés

URV Tutor: Joan Manel Vallès

Tarragona, February 2024

INDEX

NOMENCLATURE

- Epoxide: aliphatic hydrocarbons in which an oxygen atom is bonded at the same time to two carbons. An example is ethylene oxide, which is of great commercial importance. Most epoxides are used in the production of paints. Although they can also be used to produce adhesives or plasticizers.
- Surfactant: substance that allows the reduction of the surface tension of liquids and facilitates the formation of emulsions or foams. They can be used in cleaning, personal care or food manufacturing applications.
- Heat-shielding: the ability of a material to thermally insulate or reduce heat transfer between two objects. It is a function of thermal conductivity (k).
- Overall heat transfer coefficient (U): the effectiveness of heat conduction through a series of resistances or resistive media. It is measured in W/m^2K and is influenced by the thickness and thermal conductivity of the media through which heat is transferred. The higher the coefficient, the easier the heat transfer.
- Plate thickness: conventional thicknesses range from 0.4 to 1 mm. It is mainly determined by the working pressure, i.e., the higher the working pressure, the greater the thickness and the higher the manufacturing cost.
- Heat energy transfer: a physical phenomenon in which energy is transferred between two systems when there is a temperature difference until thermal equilibrium is reached where temperatures are equalized. Heat can be transferred by conduction, convection and radiation. Conduction is the transfer of heat through a material or between two material that are in contact with each other causing the more energetic particles to go towards the less energetic ones due to the interaction between them. Convection is a mode of heat transfer in which energy is transferred between a fluid and a solid surface due to the movement of the fluid and heat by conduction. And, finally, radiation is known as the transfer of energy due to the emission of electromagnetic waves and can be attributed to changes in the electronic configurations of atoms.
- Specific heat (Cp): the amount of thermal energy required to raise one kilogram of a substance by 1ºC. It is measured in J/kgºC. Specific heat is proportional to the amount of energy required to produce a temperature change.
- Fouling: accumulation of solid particles on the surface of the heat exchanger impairing heat transfer as these particles generate new thermal resistance as well as increasing the pressure drop.

A	Heat transfer area	m^2
Cp	Fluid heat capacity	J/kgK
Q	Volumetric flowrate	m^3/h
v	Fluid velocity	m/s
D	Port diameter	m
T	Temperature of the fluid	°C
U	Global heat transfer coefficient	W/m^2°C
LMTD	Logarithmic mean temperature difference	°C
ΔT	Temperature difference	°C
h	Individual heat transfer coefficient of the fluid	W/m^2°C
ε	Plate thickness	m
ρ	Density	kg/m^3
μ	Dynamic viscosity	Pas
Cp	Specific heat	Ns/m^2
k	Thermal conductivity	W/m°C
Ap	Effective area of the plate	m^2
n	Total number of plates	
Le	Effective length of the plate	m
W	Width of the plate	m
VPCD	Vertical distance between the port centers	m
HPCD	Horizontal distance between the port centers	m
Sc	Area of passage per channel	m^2
b	Separation between plates	m
De	Equivalent diameter	m
ϕ	Effective heat transfer surface area expansion factor	
Nc	Number of channels per fluid	
Mc	Flow rate through each channel	kg/s
M	Total flow rate of the fluid	kg/s
m	Mass velocity in the channel	kg/sm^2
Re	Reynolds	
Pr	Prandtl	
Rf	Fouling resistance of the fluids	m^2°C/W
ΔP_c	Pressure drop in the channels	Pa
Np	Number of passages	
μ_w	Dynamic viscosity at the wall	Pas
Sp	Port passage area	m^2
Vp	Fluid velocity in the port	m/s
ΔP_p	Pressure drop in the port	Pa
ΔP	Total pressure drop	Pa
F	Correction factor	
R	Ratio of heat capacities rates	
P	Dimensionless temperature effectiveness	
Cr	Heat capacity ratio	
Ɛ	Exhanger efficiency	
NTU	Number of heat transfer units	

z	height	m
ΣF	Pressure drop	m
hm	Losses by accessories	m
h_f	Frictional losses in pipelines	m
C	Fluid heat capacity flow rate	
g	gravity	m/s^2
W	Work	J/kg
f_T	Frictional factor	
q	Heat transfer rate	W
m_x	Mass flow rate of a fluid	kg/s
Wss	Wall shear stress	N/m^2

LIST OF TABLES AND FIGURES

SUMMARY

These days, energy optimization is one of the main issues to be addressed by different companies. This is why different ways of reducing energy consumption must be studied, as is done in the Clariant company, which aims is to use the heat generated by the ethoxylation reactions to heat the water stream from the tanks without using steam.

For this purpose, a Hot Fluid will be used, which comes from the water streams used in three reactors (366, 350 and 550). In these reactors, exothermic reactions take place in which energy is generated. To avoid problems, a water stream that is in a closed circuit, is used to adsorb the heat in a closed circuit without interfering with the reaction taking place. As a result, high temperatures are obtained at the outlet of the reactor.

On the other hand, the Cold Fluid comes from a closed circuit in which water at 90ºC is taken from the tanks to three points: the isocontainers, the ethoxylation plant (ETHOX) and the high temperature multipurpose plant (HTMPP). This water helps with the transport of fatty alcohols to the ETHOX plant without them solidifying, among others.

So, in order to heat the return of the Cold Fluid back to 90ºC without entering the tanks, a gasketed plate heat exchanger will be used with the Hot Fluid. This exchanger offers higher heat transfer efficiencies, more flexibility to disassemble the equipment and takes up less space.

Therefore, there are three alternatives depending on where the exchanger is to be installed. That is, the installation of the equipment in one of the two plants mentioned above or, the third possibility is to install it next to the tanks.

To make a decision, the Cold Fluid flow rates that would be available in the three alternatives were analyzed and it was found that the best alternative is the third one since a higher Cold Fluid flow rate (16 m^3/h) passes through this point. Likewise, on the Cold Fluid side, field measurements were also taken to evaluate the temperature at which it could work, obtaining two inlet temperatures to the exchanger, 67.73 and 75ºC.

For the Hot Fluid, to select the optimum reactor to be used, the working conditions of each one were analyzed and it was established that the ideal option is reactor 366 since it works up to 26.97% during the year. Likewise, it is also determined that the flow rate that should be used for the heat exchanger of this fluid is 16 m3/h with a temperature of 95ºC since they are predominant in this reactor.

Then, two scenarios are considered, depending on the selected temperature of the Cold Fluid. In them, seven designs of the exchanger are made using the *Exchanger Design and Rating (EDR).* Of all of them, the *APV sr6gl* plate is the best option for the two scenarios since it allows to obtain the designed temperature of the Cold Fluid (90ºC) with optimum areas of 18.4 and 10.6 m^2 for the case of 67.73 and 75ºC, respectively. Similarly, the effect of increasing the flow rate of the Hot Fluid with the selected plate is evaluated, obtaining high pressure drops and a higher number of plates to be used, which could exceed the limit established by the manufacturer, and a worse heat transfer.

Finally, an economic study is carried out to estimate the necessary investment for its installation, which is 12806 €. Similarly, considering the amount of steam consumed in the tanks (280.88 tons of steam/year), it has been estimated a profit of almost 10000 €/year and a yield of 8%. In other words, thanks to the use of the exchanger, the investment would be acceptable, recovering the investment in less than two years with a Net Present Value of 63687.86 € and a positive Internal Rate of Return of 73%.

1. INTRODUCTION

Nowadays, society and the planet demand that the people and companies focus not only on the objectives of maximizing profits while maintaining quality, but also seek energy efficiency, trying to reduce emissions of polluting gases and achieve a more sustainable and cleaner market. This is why the reduction of energy consumption is a main target for industrial companies, in order to reduce carbon dioxide emissions into the environment. This target is being pursued by Clariant, a company that goes further and aims to reduce energy consumption by up to 30% by 2025 (Clariant. , 2023).

With this in mind, the company has posed a problem to which it hopes to find a solution during the course of this project. In a synthetic way, the objective will be to analyze the consumption produced in the 90ºC hot water tanks of the Tarragona site, proposing as a solution the implementation of heat exchangers to reduce energy consumption.

1.1. Problem

The alkoxylation reactions that take place at the Tarragona plant are very exothermic reactions involving the addition of an epoxide to another component for the formation of a surfactant at temperatures around 150 to 190ºC (E. Santacesariaet al. , 1995) . In this case, ethylene oxide or propylene oxide is added to alcohols, amines and phenols, in the presence of a catalyst such as sodium hydroxide (NaOH), to give different types of surfactants, producing an ethoxylation or propoxylation reaction, respectively (R. Tesser, 2021).

These surfactants are substances that allow the formation of emulsions and dispersions by decreasing the surface tension of liquids, influencing the contact surface between two phases. As these reactions are very exothermic, large amounts of energy are released and can lead to a sudden temperature increase (A. Fernandezet al. , 2004).

To prevent this from happening, water is used. This water is in a closed circuit, i.e., the water, coming from the cooling tower at 22ºC in winter and 32ºC in summer, reaches the reactors and passes through one or two coils, increasing its temperature as it passes through them. In other words, the heat that is released by the exothermic reaction, is transferred to the water entering the reactor, acquiring high temperatures at the reactor outlet. Although the outlet temperatures of this water are quite high, exceeding 70ºC in many cases, there is a loss of energy since this current is sent back to the cooling tower accompanied by cold effluents, reaching, at the tower inlet, a temperature of 25 or 35ºC, in winter and summer respectively.

1.2. Project

Knowing the problem to be addressed, the project is to see the feasibility of using the energy of the water leaving the reactors 366, 350 and 550, as mentioned above, which will be called Hot Fluid, to heat other process streams. In this case, heating the return of another fluid to reach again 90ºC. This second fluid is located in two 15 m^3 tanks near two plants of interest, the Ethoxylation and Propoxylation Plant (ETHOX) and the High Temperature Multipurpose Plant (HTMPP) as can be seen in the Figure 1.1.

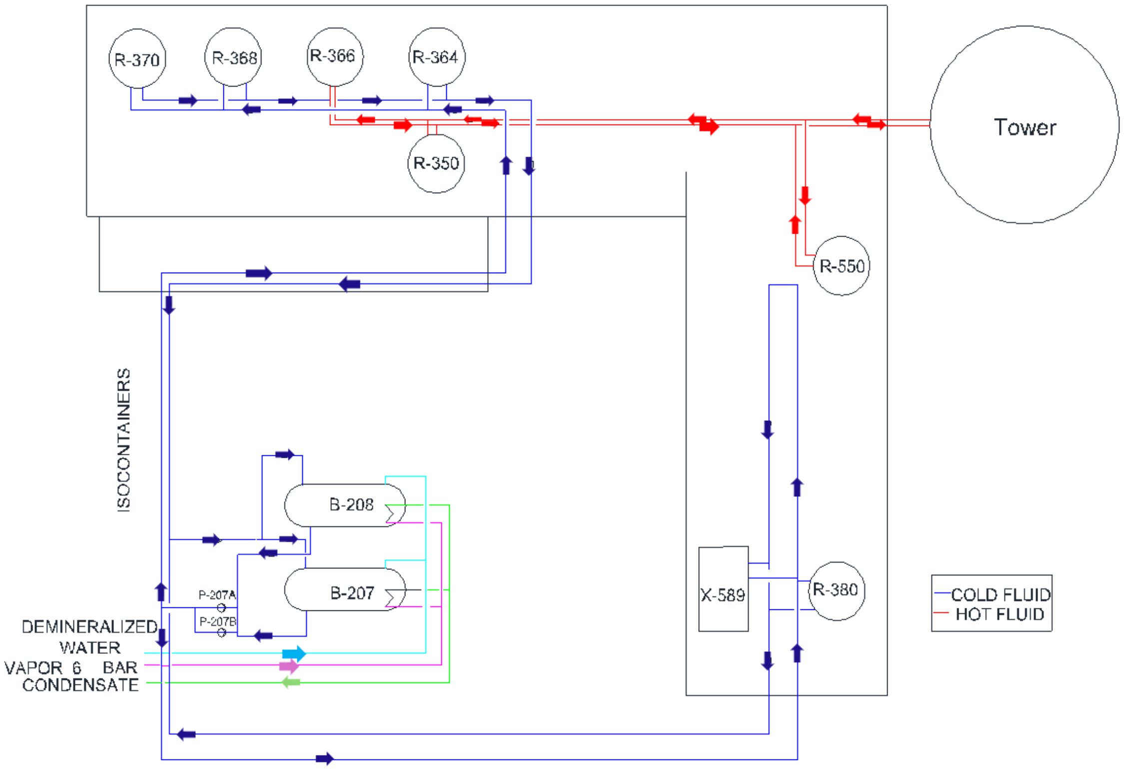

Figure 1.1. Plan of the equipment of interest (Personal compilation).

This second fluid is a water stream that also works in a closed circuit. As can be seen in Figure 1.1, this fluid, is produced by the entry of demineralized water into tanks B-207 and B-208. Thanks to the entry of saturated steam at 6 bar, this water is heated up to 90ºC. Once heated, the water is pumped by pumps and is used at 3 points in the plant; in the tanks located next to the water tanks, in the ETHOX plant to accompany the fatty alcohols to the 364, 368 and 370 reactors, and finally, in the HTMPP plant for the X-589 scrubber and the R-580 reactor when it is required.

In particular, when accompanying the alcohols, this water does not enter the reactor but allows the alcohols to remain in the reactor without solidifying. This means that the alcohols circulate in a pipe which is inside a second pipe. In this second pipe is where the water circulates. Therefore, when the alcohol reaches the relevant reactors, this water is returned to the tanks at a temperature below 90ºC without coming into play in the reactor. This return flow will be called Cold Fluid.

With these streams, it is intended to install a plate heat exchanger in these plants to produce the exchange between the Cold and Hot Fluid (M.F. Edwards and W.L. Wilkinson, 1984). This also, can be visualized in the *fatty alcohol isocontainers and hot water* tanks plan in Appendix 8.1.

However, it should be noted that the fatty alcohol lines are usually used with steam, since there were problems with solidification.

This energy exchange is intended to take advantage of the heat dissipated by the Hot Fluid to increase the temperature of the Cold fluid and thus, reduce the amount of steam used in the tanks to increase the temperature up to 90ºC. Furthermore, thanks to this 6-bar steam reduction, the environmental impact of the plant will be reduced by reducing the tons of CO_2 per ton produced, thus meeting the environmental objectives of Clariant (Y. Abdelouadoud *et al.*, 2019).

1.3. **Solutions**

To solve the problem posed, three alternatives have been proposed for consideration; since the Cold Fluid line is bifurcated in two and goes to the two plants as can be seen in Figure 1.1, the first alternative discussed is the installation of a heat exchanger at the ETHOX plant to treat the Hot Fluid from that plant, i.e., the water from the 350 and 366 reactors, each with a volume of 25 m^3. This heat exchanger is intended to heat the Cold Fluid, which accompanies the fatty alcohols to the 364. 368 and 370 reactors as can be seen in Figure 1.2. Since all the reactors are located in the same plant, the installation is proposed in that plant to reduce the final cost.

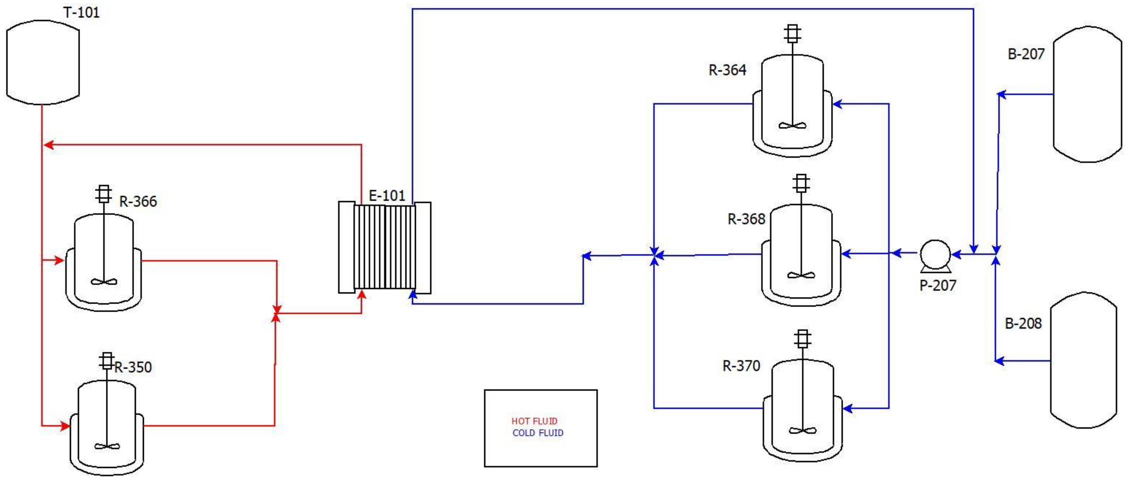

Figure 1.2. First alternative in the ETHOX plant (Personal compilation).

On the other hand, the second alternative to be evaluated is the installation of an exchanger in the HTMPP plant in order to treat the Cold Fluid. This fluid that comes from the X-589 scrubber and the 580-reactor, will be treated with the Hot Fluid coming from the 550-reactor, which is 25 m^3, as shown in Figure 1.3.

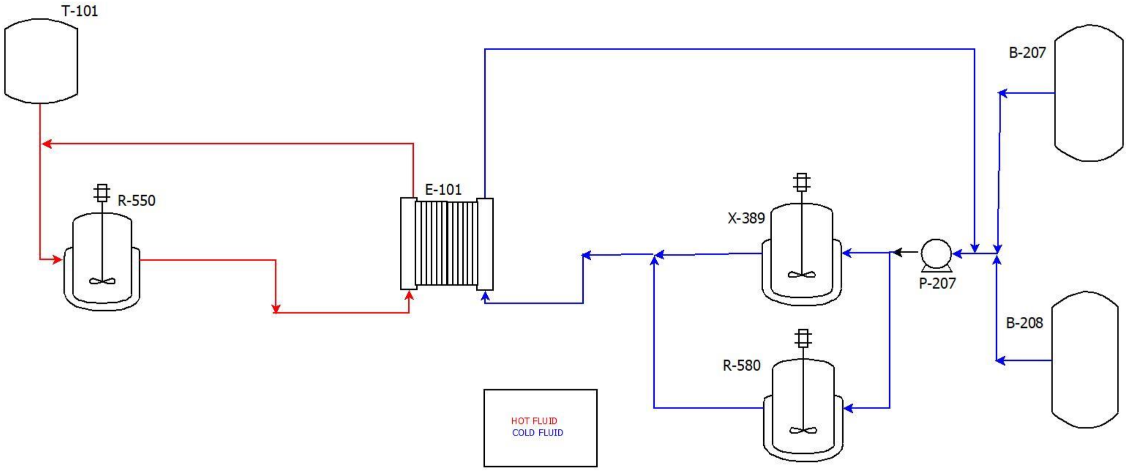

Figure 1.3. Second alternative in the HTMPP plant (Personal compilation).

Finally, the third alternative is the installation of an exchanger next to tanks B-207 and B-208. To do this, the Cold Fluid from the two plants will be treated, joining the Hot Fluid coming from the 366-reactor in the ETHOX plant as can be seen in Figure 1.4.

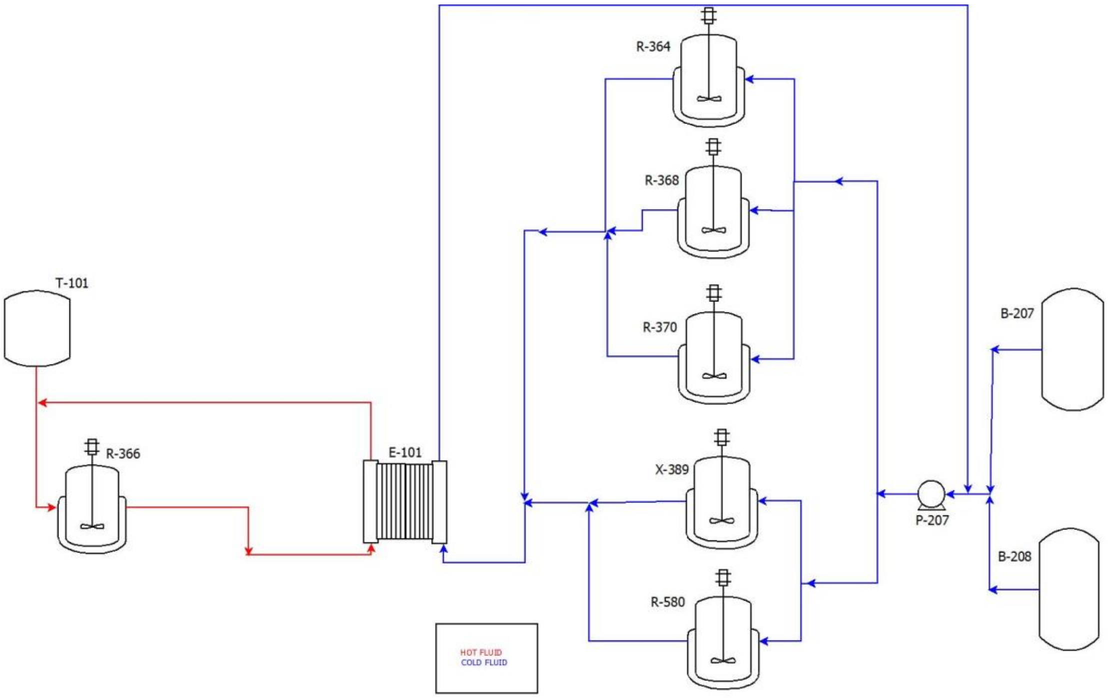

Figure 1.4. Third alternative next to the B-207 and 208 tanks (Personal compilation).

In this case, the 352-reactor will not be taken into account for the treatment, since it works by campaigns and this process is to be carried out continuously, although the reactors work discontinuously. Therefore, it will be necessary to verify the amount of energy that could be used per year in each of the alternatives, likewise, it will be evaluated which of all the alternatives would be more adequate for its installation, taking into account costs, efficiency and feasibility.

1.4. State of the art

Heat exchangers are equipment that allow the transfer of thermal energy from a high temperature fluid to a lower temperature fluid. This energy transfer can occur by direct contact when both fluids are in contact with each other or, by indirect contact between both media, in which the fluids are separated by a wall through which heat is transferred.

Different ways in which the fluids are distributed are known, either in parallel, countercurrent or crosscurrent. In parallel, the hot and cold fluids enter at the same end of the heat exchanger, circulating in the same direction, while, in countercurrent, the fluids enter at opposite ends of the exchanger circulating in opposite directions (J. Saari. , 2010).

On the other hand, cross flow can work with a single passage in which the fluids circulate perpendicular to the trajectory of the other. Or also, it can be a multiple pass when the fluid circulates in a transverse way with respect to the other fluid in an alternative way (A. Basaran and A. Yurddas, 2017).

Similarly, heat exchangers can work with two or more streams as in cryogenic processes, but the most common is to work with two fluids.

As for the types of heat exchangers, it can be differentiated between shell and tube, spiral or plate heat exchangers. Among them, plate heat exchangers stand out as they offer a large surface area for the exchange between the hot and cold fluid, having a higher heat transfer coefficient. These exchangers are composed of a movable and a fixed head, gaskets, guide bars, frame, compression nuts with fastening screws and a set of metal plates placed parallel to each other as shown in Figure 1.5 (I. Gherasim *et al.*, 2011).

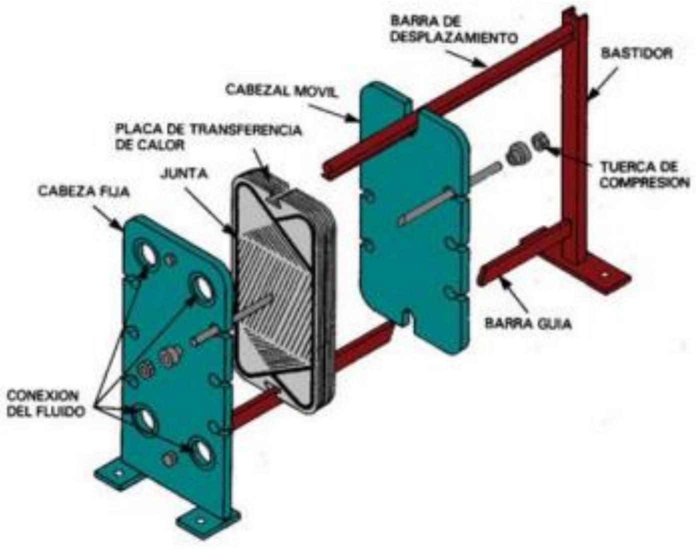

Figure 1.5. Components of a plate heat exchanger (J. P. Córdoba, 2019).

Each plate can have different patterns on its surface, and thanks to the frame, they are held together by pressure and sealed by the used of seals o gaskets leaving interconnected corridors through which fluids circulate (W. Dávila and F. Obando , 2006).

The plates are usually made of stainless steel, although depending on the fluid to be circulated, they can be made of metals. These plates have a thickness between 0.5 and 0.9 mm and the number of plates to be used in the heat exchanger depends on several factors such as the properties of the fluids to be treated, the working conditions or the heat transfer capacity, among others.

Several types of plates can be differentiated according to their corrugation angle, i.e., three types are known: H, L and M. This angle allows controlling both the flow distribution and the fluid turbulence. Therefore, when working with a very open angle (H type), a large amount of energy is recovered, but also a lot of pressure drop since it offers greater resistance due to its more obtuse angle (APV. , 2023). On the contrary, it happens with a very closed angle (L type) since there is less turbulence.

Likewise, plates with different corrugations can be mixed in the exchanger to optimize the exchanger performance as they influence both heat transfer rates and pressure drop (E. Cao. , 2010).

When it is desired to achieve an intermediate point both in heat exchanger performance and efficiency and in pressure drops, the M type is used since it offers a mixture of the two previous corrugations.

In a plate heat exchanger, the fluids usually work in countercurrent since it allows the maximum amount of heat to be recovered (Alfa Laval. , 2023). These fluids enter through the connection orifices and circulate through the channels between the plates. It is in theses plates where the heat transfer from the Hot Fluid to the Cold Fluid takes place since it acts as a barrier so that the fluids do not mix, allowing one fluid to circulate through the even channels and the other through the odd channels shown in Figure 1.6.

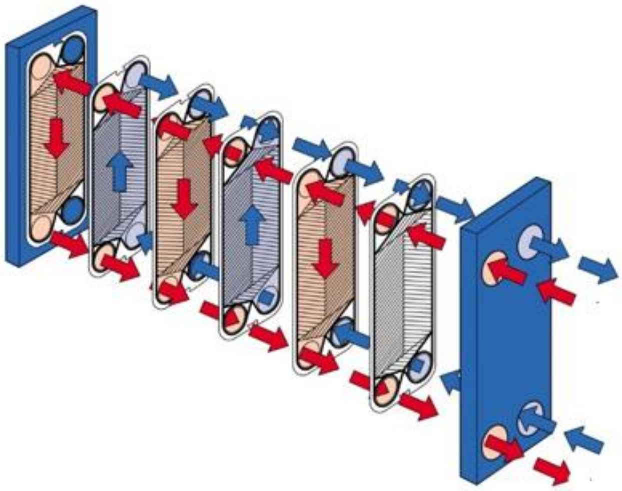

Figure 1.6. Operation of a plate heat exchanger (Spirax Sarco. , 2019).

In this case, it can be seen in Figure 1.6, that the Hot Fluid enters through the upper connection and exits through the lower one, while for the Cold Fluid the opposite occurs.

With respect to the plates, they can be joined by gaskets, or they can be welded. When gaskets, which are made of a polymeric material, are used, they are placed between the plates and act as a sealant and separator. In addition, the gaskets allow the heat exchanger to be disassembled for capacity optimization, plate addition or cleaning (SWEP. , 2023).

These gaskets are very important components for the correct performance of an exchanger since they avoid the risk of leaks, damage to the plate, etc. In addition, they can be used for long periods of time.

The main advantage of gasketed heat exchangers is their flexibility, since they allow the equipment to be easily disassembled for the addition of new plates, cleaning and maintenance, thus ensuring the highest possible efficiency of the equipment (F. Incroperaet al. , 2007).

However, the use of gaskets is restricted to operating conditions such as operating temperature up to 180ºC or pressure up to 25 bar (Jouhara *et al.*, 2018). Nevertheless, a gasketed plate heat exchanger offers an effective heat transfer that allows up to 90% of the heat to be recovered, working efficiently.

Another way in which plates can be joined together is by welding. The plates are soldered together with copper or nickel, which allows them to work in higher temperature and pressure ranges, as they offer greater resistance to these working ranges. This type is usually used in refrigeration plants (T.soluciona. , 2022).

These units are very compact and easy to install, allowing them to work between -196 and 225ºC with a nominal pressure up to 130 bar, ensuring a good connection between plates, stability and high thermal efficiency (J. Negre. , 2024).

Thanks to this equipment, stability and permanent connection between plates is ensured. The disadvantage of this equipment is its cleanability since the plates cannot be separated nor can more be added. In addition, being a more rigid structure, if it is subjected to thermal stress or temperature variations, it can cause the exchanger to fail.

On the other hand, plate heat exchangers have certain advantages compared to shell and tube heat exchangers, such as their easy of disassembly, when necessary, maintenance, cleaning and the addition of plates (G. Towler and R. Sinnot , 2008).

With this equipment, higher heat transfer coefficients are obtained, up to five times, compared to those obtained for shell and tubes due to the high turbulence, the corrugation patterns of the plates and the high velocities (R. K. Shah and D.P.Sekulic , 2003). Thanks to this, it is possible to obtain higher efficiencies than the 50% recovery that would be obtained for casing and tubes since, although tubes are the best form of duct to withstand pressure, having a small surface area per unit of flow area, optimal efficiencies are not obtained (APV. , 2023).

Likewise, thanks to the high heat transfer, its countercurrent arrangement, and the low possibility of obtaining incrustations due to its high velocity, smaller surfaces are necessary to produce the heat exchanger, occupying less space, thus reducing the cost of the equipment. This does not occur in tube heat exchangers which are usually 30 and 20% large in weight and volume, respectively, for the same heat transfer surface (B. Sundénet al. , 2007).

Therefore, plate heat exchangers can be an effective solution for the design required in this project.

2. SCOPE AND OBJECTIVES

2.1. Scope

As previously stated, the objective of this work is to see the feasibility of installing an exchanger at Clariant to try to recover the heat generated by the cooling water streams of the ethoxylation reactors. For this purpose, having known the installations of the different plants, as well as the set of reactors to be considered and their specifications, several scenarios are proposed to find the most feasible solution to the problem to be solved.

Knowing the pertinent data of the reactors 350, 366 and 550, these reactors are evaluated for their individual or group use in a heat exchanger using hot water of 90ºC of the reactors 364, 368, 370, 580 and X-589. A theoretical design of the heat exchangers will be carried out, as well as their installation cost and an economic study of the project.

2.2. Objectives

The main objective of this project is to reuse the heat generated from the ethoxylation reactions that take place in the plant to heat the return hot water up to 90ºC and thus reduce the energy losses generated in the factory. To this end, it is needed to analyze the effectiveness of this energy exchange. Considering the appropriate working conditions, the type and number of exchangers that would be necessary, as well as the appropriate place for their installation.

It is also necessary to carry out an economic study to determine the feasibility of the project, taking into account the costs involved in this project, the payback time of the investment and the gains that would be obtained by bringing it to reality since, thanks to the heat exchange that would be produced, it is expected that steam consumption in the hot water tanks will be reduced, as well as the reduction of tons of carbon dioxide per ton produced.

Specifically, it is necessary to know the operation of the reactors, study the temperatures and flow rates at which each of the reactors of interest and the hot water tanks work, verify the suitability of the site for the installation, know the operation of the non-invasive meter counter and use it to know the water and steam flow rates used. It is also appropriate to determine the heat exchanger areas of the different case studies in order to choose the most suitable case. Similarly, it is necessary to find out the total cost of the installation of such heat exchangers and to verify the benefit that could be obtained and they payback time of the necessary investment.

3. STUDENT´S ROLE IN COMPANY

3.1. Clariant

Clariant is a Swiss multinational company that manufactures specialty chemicals for different industrial sectors. Headquartered in Muttenz (Switzerland), it has more than 70 subsidiaries in 36 countries. By creating value through innovative and sustainable solutions, the company has become one of the world's leading specialty chemicals companies.

To this end, they seek to meet the specific needs of their customers by offering a wide range of products. At the same time, they are always looking to promote research to meet current challenges such as renewable raw materials or energy efficiency. Thanks to the promotion of innovation, 200 new products are created annually.

The company also has several certifications such as the *Quality Management System (ISO 9001:2008),* the *Environmental Management System (ISO 14001:2004)* and *Energy Management (ISO 22000),* among others, giving its customers the confidence to always work with them, having as one of the main priorities of the company the quality of the products and services they sell (P. Fitzgerald *et al.*, 2023).

The purpose of Clariant is "Greater chemistry-between people and planet" and to achieve this they follow a strategy based on four pillars: always taking into account the needs of the customers (Customers focus), fostering innovation (Innovation chemistry), leading the change towards sustainability (Leading in sustainability) and counting on the commitment of people (People engagement).

In addition, the values promoted in the company are to always act with integrity and agility, to innovate in pursuit of sustainability, and to be inclusive and empowering. As target for 2030, Clariant has set itself the goal of increasing female representation to 30%, encouraging the improvement of the position of women in the chemical industry.

Similarly, as environmental objectives, by 2025 Clariant aims to reduce energy consumption by up to 30% as well as CO_2 emissions. To this end, it has installed solar panels to cover the plant's electrical needs from alternative energy sources.

These are examples of measures implemented by Clariant to contribute to the *UN Sustainable Development Goals (SDGs)* (S. Dhahri *et al.*, 2024). In particular, some of the most important SDGs for Clariant are: 3. Good health and well-being, 13. Climate action and 12. Responsible consumption and production. To do so, they seek to create value with the help of their consumers by reducing their carbon footprint, eliminating waste, or encouraging the creation of products that are safe and reusable. In other words, that they are sustainable.

Clariant has three defined business areas: Care Chemical, Natural Resources and Catalysts. Care Chemical has applications such as consumer care, industrial applications, base products, food ingredients, etc. This area seeks to help meet the needs in agriculture, reduce the carbon footprint through ecological and sustainable products that do not contain harmful substances.

On the other hand, Catalysis offers a wide variety of catalysts for both fuels and the chemical industry, as well as biofuels. This business area seeks to improve the energy efficiency of chemical production as well as to find solutions to promote the circular economy and sustainable mobility.

And finally, Natural Resources works in high value-added specialty chemicals that are used in the food and oil industries, among others, as well as in additives for plastics, functions, etc.

Here, the business driver is driven by the strict regulations of the chemical industry, as well as customer expectations to drive the sustainability and circularity of plastics.

In terms of sales, the company achieved global sales of more than CHF 240 million (EUR 250 million), with Spain and Portugal contributing almost CHF 60 million. In the future, the company aims to increase its sales by 4-6% by 2024, as well as its margin by 19-21%.

Specifically in Spain, there are four sites: Sant Joan Despí, Tarragona, Yuncos and Artziniega, with the Tarragona site being the largest and with the largest number of employees. At the Yuncos site, they focus on market such as vegetable oil and ceramics. They can produce up to 55000 tons per year, with a high percentage of products being exported (up to 64%).

On the other hand, in Artziniega, they produce flocculants for industrial water treatment, binders for foundry molding, filtering agents for manufacturing paper reels, etc. At this site they also produce 51000 tons per year, most of which are domestic use, and a small percentage is exported (26%).

The site in Tarragona focuses on Care Chemical, working in various markets such as home and personal care, industrial lubricants, mining and refining. For this purpose, it has several plants within the site: Multipurpose Plant (MPP), Ethoxylation and Propoxylation (ETHOX) and High Temperature Multipurpose Plant (HTMPP), among others. It has a capacity of 106 kilotons per year with a production of 86 ktons/year, most of the products being exported (93%). Each of the plants has a capacity between 2.5 and 50 kt/year. Of these, the Multipurpose Plant and Ehoxylation and Propoxylation generate the most added value.

It is important to note that each of the plants has managed to exceed 95% of the quality index in 2021, verifying the importance Clariant attaches to the quality of the products marketed there.

They have also introduced improvements in plant safety systems such as the 5S system developed by Toyota. These 5S involve classification, order, cleanliness, standardization and discipline. All of this means that regular reviews are carried out to have the workplaces better organized and cleaner on the continuous basis. This is done to increase productivity and improve both the working environment and reduce the risk of accidents, thus improving the quality of production.

3.2. <u>Intership</u>

Once the Clariant company was known, specifically at the Tarragona site, the internship has been carried out, which has been focused on carrying out tasks for the elaboration of the Master’s Thesis. To this end, the objectives of the internship were, among others, to assume a role within a company, to learn how a company work from the inside, to adapt to the interrelationship between the different departments of and industrial company and to promote the generation of added value.

To this end, a series of tasks were carried out, as described below.

3.2.1. Updating of the Isocontainers alcohols and hot water tanks plan

The first task to be carried out is the update of the I*socontainer and 90ºC hot water* plan as there is no complete record of the water line for all plants. With the help of the production technicians, the missing line is drawn freehand on the same drawing in situ in the plant. Then, the different equipment and lines that would constitute the missing part are correctly drawn on the plan. Afterwards, the updated plan is transferred to the engineering department for the modification to be carried out on the plan, designed by them.

3.2.2. Temperature measurement of the water line from the ETHOX plant.

Another task is a temperature measurement in the water line from the ETHOX plant since this line does not have a measuring device. For this purpose, with the help of the production technicians, two points to be measured were established in two different locations. On one hand, the temperature of the Cold Fluid was measured in the line near the tanks returning from the ETHOX plant while the other measurement was carried out on the isocontainers as can be seen in Figure 1.1. This has been carried out in order to really know the temperature range in which the line works.

For the first measurement, a *Fluke Ti10 thermographic camera* as shown in Figure 3.1, from the instrumentation department and, a glass beaker are used. By opening the manual valve on the Cold Fluid line near the tanks, water is allowed to flow through, and the glass is filled for about one minute. This time is necessary for the temperature of the glass to match the temperature of the water in the pipe. Once the valve is closed, the camera is pointed in the direction of the vessel and a temperature range (from blue to red) can be seen on it, the highest temperature being the one in red. For correct measurement, two measurements are taken daily.

Figure 3.1. Fluke Ti10 Thermal Imaging Camera (Personal compilation).

Likewise, the data of the outlet temperature of the tanks is taken thanks to the temperature gauge that is located in the outlet line of the pumps as can be seen in the plan of *Alcohol isocontainers and hot water tanks* in the Appendix 8.1 under the name TI 207.19.

Once the inlet and outlet values of the Cold Fluid from the ETHOX plant are known, the temperature difference to be worked with can be known. As shown in Table 3.1. the outlet temperature of the tank is in a range between 84 and 90ºC while the Cold Fluid in the point measured is between 60 and 73ºC. By averaging the temperatures, the average temperature of the Cold Fluid will be taken as 67.73ºC.

Table 3.1. First measurement point from the ETHOX plant and tank outlet temperature measurements of the Cold Fluid.

Date	Tank outlet temperature /°C	ETHOX plant Temperature /°C	ΔT /°C
17/07/2023	90	60	30
18/07/2023	90	65	25
19/07/2023	90	63	27
20/07/2023	85	60	25
24/07/2023	87	66	21
25/07/2023	84	65	19
26/07/2023	86	65	21
27/07/2023	85	61	24
31/07/2023	88	70	18
01/08/2023	88	69	19
02/08/2023	86	67	19
07/08/2023	84	66	18
08/08/2023	85	65	20
09/08/2023	86	72	14
10/08/2023	88	68	20

Likewise, for the second measurement, as can be seen in the PID *"Alcohol iscontainers and hot water tanks",* the Cold Fluid, apart from coming back from the ETHOX plant and the HTMPP plant, also return from the isocontainers, which are arranged next to the tanks. Here, water is used so that the alcohols do not solidify, therefore, it was decided to measure the inlet and outlet temperatures of these isocontainers to verify the temperature obtained at that point.

In this case, several daily measurements of two isocontainers are made, collecting the inlet and outlet temperature values. For the inlet temperature measurement, a thermometer is used in the installation, while for the outlet temperature, a temperature probe and a glass beaker are used for the measurement. These values are shown in Table 3.2. It should be noted that for the second isocontainers, the thermometer does not work properly because it should be close to 90ºC due to the proximity to the outlet lines of the water tanks.

Table 3.2. Second measurement of temperatures in isocontainers of the Cold Fluid.

Date	Hour /h	Isocontainers	Inlet temperature /°C	Outlet temperature /°C
22/11/2023	11:15	1	92	73
		3	78	75
	13:33	1	92	75,5
		3	76	74
23/11/2023	11:08	1	93	72,4
		3	76	75,4
	13:30	1	89	73,2
		3	76	73,8
24/11/2023	10:20	1	91	74,4
		3	76	75,3
	12:42	1	88	75,2
		3	76	77,2

As can be seen in Table 3.2, the return temperatures to the tanks from the isocontainers are higher than the temperatures measured in the line from the ETHOX plant. That is, an average temperature of 75ºC is obtained from the return of the isocontainers while in the other measuring point it is 67.73ºC.

3.2.3. Measurement of steam and cold line at different points of the site.

Another tasks to be carried out is the measurement of the Cold Fluid and steam lines to know with what flow rate the exchanger could work with. For this purpose, since it is not possible to obtain a sample from each of these lines, the *Lana Sarrate* non-invasive meter is used (Lana Sarrate. , 2023). This meter is a portable ultrasonic flow meter that can measure gases, vapors and liquids. It is a non-invasive meter in which the flow rate is measured following the transit time operating principle, i.e., the emission of pulses for and against the current.

In order to know the flow rate, the velocity of the fluid passing through the pipe is estimated because this velocity is proportional to the difference between the pulses going for and against. Knowing the velocity and, knowing the inside diameter of the pipe, the area can be found, thus obtaining the flow rate by means of the following equation 3.1.

$$Q\left(\frac{m^3}{h}\right) = v(\frac{m}{s}) * A\ (m^2) \qquad (3.1.)$$

In order to perform the measurement, the type of pipe to be measured, its outer diameter or perimeter, the pipe thickness, the material, the fluid to be measured, etc. must be known.

On the other hand, it is very important to know the type of fluid to be measured because, depending on the type of fluid, the installation of the sensors is different and has more or less limitations. For example, when measuring a liquid, the sensor can be placed on top of the pipe with mineral grease while, when measuring a vapor, the pipe must be painted for a correct measurement. Also, while the sensor, when measuring a liquid, can withstand up to a temperature of 200ºC, in vapor they only allow measurement up to 180ºC, which is 9 bars of saturated vapor.

Another point to consider is the place where the meter is placed, since it must be taken into account how the section is. That is, if it is close to an elbow, at what angle, etc., as this will change the distance at which the meter should be placed from the changes in the section. Ideally, in a straight section, the sensor would be placed between ten diameters and five diameters from the accident.

Also, in order to be able to visualize the flow rates of each line, the meter has a memory that allows the data to be stored for a period of time. From the *FluxDiag* program, it is possible to collect these data and see if the measurement has been performed correctly by considering three important parameters: the sound velocity, the signal correlated noise to ratio (SCNR) and the quality of the flow rate.

With respect to the speed of sound, for example, when measuring water, the speed of sound at 20ºC is 1480 m/s. Therefore, when measuring, the value obtained must be close to or equal to that value. As far as SCNR is concerned, this data has to be above 20 dB. Normally for liquids it is around 40 dB and for gases between 25 and 35 dB.

Finally, regarding signal quality, this parameter refers to the number of shots that are used. It is usually around 98%. The number of shots refers to the numbers of shots that the sensor takes in a trajectory. This trajectory can have an even number, i.e., if the sensor is place opposite each other in line, the shots will make two trajectories, one going up towards the bottom of the pipe and the other towards the top where the other part of the sensor is. If, on the other hand, one sensor is at the top and the other at the bottom, this means that it will only make one trajectory, so it will be odd.

In this case, there are the three sensors mentioned above. These sensors are made up of two parts which, when placed in the pipe, must form an arrow for correct measurement. Likewise, the direction of the fluid to be measured must be known, otherwise the flow rate that the equipment will show would be negative.

To obtain the water and steam flow rates, the first step is to decide on the measurement location. To do so, with the help of the production technicians and the engineering department, the points to be measured were established as can be seen in Figure 3.2 considering that these points cannot be in an ATEX zone, i.e., places where flammable gases may be present with the possibility of explosive atmospheres.

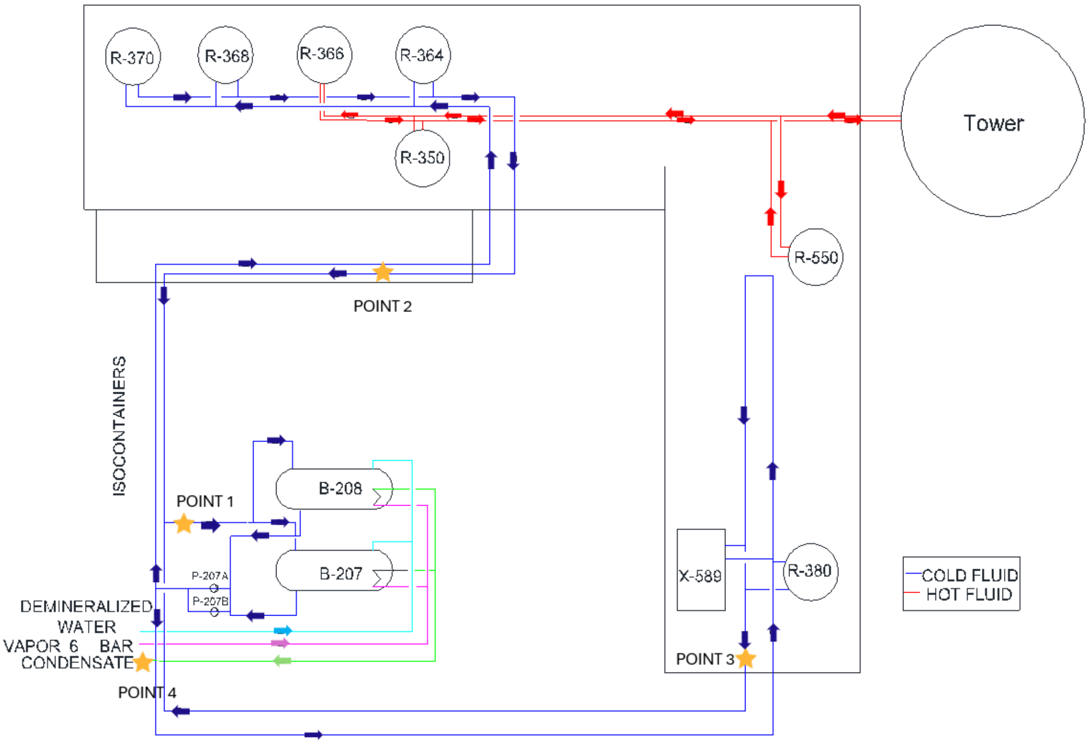

Figure 3.2. Points established to perform the steam and Cold Fluid measurements (Personal compilation).

The first is the joint Cold Fluid line from the two plants, neat the tanks (point 1). The second is the pipe with the Cold Fluid coming from the ETHOX plant (point 2).

The third point to measure is the line coming from the HTMPP plant (point 3). In this particular line, it will be possible to measure the amount of water going to the SCI gas extraction (X-589) and to the R-580 reactor. Finally, in order to know the steam consumption necessary to generate the kilocalories per hour from the tanks, the incoming steam line to tanks B-207 and B-208 will be measured (point 4).

Knowing this, thanks to the training of *Lana Sarrate* technicians, the non-invasive meter must be installed at the first point. To be able to make this measurement, the heat insulation must be removed on these lines with the help of the operators of the plants since, for a lower heat dissipation, these are protected by rock wool and an aluminum sheet behaving as a thermal insulator. Once the lines have been descaled, the non-invasive portable meter is used to measure the flow rate of each of the pipes for a given time.

Below, shown in Table 3.3. and obtained from the *FluxDiag* program, the data for each line can be seen, as well as the verification of the correct measurement.

Table 3.3. Parameters obtained from the measurement of the returning hot water and the vapor at the different points of interest in the factory.

Parameters	**Point 1**	**Point 2**	**Point 3**	**Point 4**
Flowrate /m^3/h	16.61	0.89	2.59	-
Flowrate /kg $_{vapor}$/h		-		35.11
Sound speed /m/s	1295.25	1423.06	1366.06	1566.97
SCNR /dB	27.69	45.28	22.14	36.77
Quality /%	89.79	99.78	88.51	99.60

Note: the reports of each measurement can be viewed in Appendix 8.3.

Regarding point 3, when measuring the HTMPP plant, a flow rate of 2.59 m^3/h has been established, of which 0.5 m^3/h goes to the scrubber and the rest to the 580-reactor.

On the other hand, for the steam measurement, although an attempt was made to measure this line with the sensor at a pressure between 2 and 3 bar, it was not possible to obtain a value for this line. Therefore, it is decided with the production technicians to measure the condensate line, located next to the steam line to see how much condensate is obtained (point 4). It should be noted that, in that line, depending on the opening of the steam valve, a value will be obtained or not, because as the liquid sensor are being used in the condensate, if there is a mixture of liquid and steam, no measurement will be produced. This measurement was made almost 5 days.

Therefore, the average value obtained for condensate is 22.26 L/h, which is 35.11 kg of steam per hour.

In conclusion, thanks to this internship, it has been possible to work with different departments and see how each of them works but also to encourage and initiative at work. Likewise, thanks to the tasks performed, it has been possible to understand more clearly both, the concepts and the operation of the equipment studied during the degree and the master.

In addition, all the aforementioned tasks are interrelated with the goals established by Clariant. In other words, through these practices the four pillars that make up Clariant’s purpose are being promoted, in which Clariant seeks to lead the change towards sustainability and promote innovation, since this project aims to reduce the plant’s energy demands by seeking a solution based on the use of ethoxylation reactors to reduce the company’s steam demand.

For this reason, this project is proposed not only to seek and optimize the design of the heat exchanger but also to find new ways to reduce these consumptions and to see the key points in the plant that cause these high steam demands. All this, in order to achieve the environmental objectives established by the company for the year 2025, to comply with the correct *Energy Management through ISO 50001,* as well as to contribute to the *Sustainable Development Goals*, highlighting the number 13 and 12, Climate action and Responsible consumption and production.

4. METHODS

In this project, the feasibility of the installation of a heat exchanger is evaluated. For this purpose, it is necessary to firstly know several parameters such as the temperature, pressure or flow rate of the streams of interest, to evaluate the best scenario in which the heat exchanger can be designed. Also, this section shows how to carry out the design of a plate heat exchanger.

It is worth mentioning that this project is going to be a worst-case scenario as it is going to be carried out in summer, where temperatures are higher than during the whole year. Therefore, as shown in Student's role in company, by performing several measurements, two temperatures have been obtained that will be considered in the design of the heat exchanger. In this case, 67.73 and 75ºC as inlet temperatures of the Cold Fluid.

Regarding the flow rates of the Cold Fluid, by using the non-invasive flow sensor, it was possible to determine the flow rates of water flowing at different points. In this case, 4 points were measured, 3 water measurements in the different plants and one condensate. Thanks to this, it will be possible to decide on the right place to install the meter at a later date.

4.1. Calculation of Hot fluid flow rates

In order to design an exchanger for any of the alternatives, it is first necessary to know the flow rate of the Hot Fluid, in this case, the Hot Fluid of the 350 and 366 reactors from the ETHOX plant and, from the HTMPP plant, the Hot Fluid of the 550-reactor. Knowing the working flow rate of the Hot and Cold Fluid, it will be possible to stipulate the appropriate flow rate for the heat exchanger design.

To know the flow rates of the reactors, first, the necessary TAGs of each reactor must be verified, that is to say, the points in the reactors that provide us with the necessary information to know the operation of the reactor whether it is valve opening degree, coil temperatures, etc. These points can be visualized in Appendix 8.2, specified in each of the reactors of interest. Once found out, from the company's database, the values of each of these TAGs in a given time can be obtained. In this case, it is chosen from August 2022 to July 2023.

However, in order to determine the flow rate flowing through the reactors, only the percentage of opening of the outlet valve is available, since there is no flow meter in all the reactors. To acquired it, the 204-reactor is used since it is the only one with all the available data. That is, a flow meter for the feed, a temperature indicator in the jacket, a flow meter inside the jacket and the valves for opening and closing the cooling water passing through the jacket. This reactor has a volume of 12.5 m^3. From the database and the TAGs, the cooling water outlet flow rate of this reactor is obtained.

Once these data are obtained, they must be treated with a series of conditions. In other words, the cooling water outlet valve (TIC204-01) must be at least 10% open and the flow rate must be at least 5 m^3/h or more. By performing this treatment, different Flow rates that would be used in 204-reactor are obtained.

In order to determine the flow rates with which the reactors of interest work, in this case, the R-350, R-366 and R550, assuming that the circuits are similar, it is possible to find the flow rate flowing through these reactors starting from the 204-reactor.

If for a 25% valve opening in reactor 204, a flow rate of 16 m^3/h has been acquired, in reactor 366, the same flow rate will be obtained.

Therefore, in these reactors, the flow rate is from 6.50 m^3/h to 64.97 m^3/h with a valve opening degree from 10 to 100%.

4.2. Working conditions

4.2.1. Conditionals for each reactor

Once the range of flow rates to be used in the reactors is known, in order to identify the working temperature, a series of conditions must be established according to the type of reactor since a total of 104833 data are used per reactor.

Taking into account the reactor failures, the following conditions are stipulated for the reactors of interest, i.e., 350, 366 and 550 reactors.

For the 350-reactor, which has an internal coil, as can be seen in Figure 4.1, it must be met that the inlet valve (UV 350.42) is open, that one or both of the two water outlet valves are open above 10% (TIC 350.41 and 350.53) and that the temperature of valve 41 and/or valve 53 is above 70ºC. More specifically, if valve 41 is open greater than 10% and the valve temperature is above 70ºC, it will dial that temperature. Likewise, for when only valve 53 is open. On the other hand, if both valves are open and above 70ºC, an average is made between them.

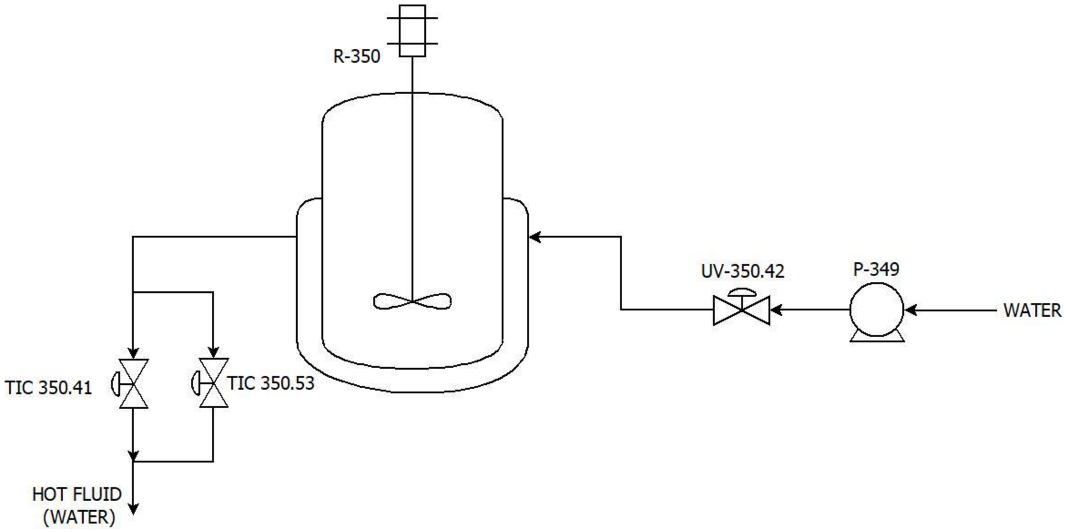

Figure 4.1. Schematic of the valves of interest of 350-reactor (Personal compilation).

Likewise, for the 366-reactor, one and/or two of the water outlet valves must be open at least 10% and the temperature must be above 70ºC. All this, having the cooling water inlet valve open.

However, for the R-550, it is necessary to add another conditioning factor since it has two cooling water inlet valves due to the fact that it has two coils as shown in Figure 4.2.

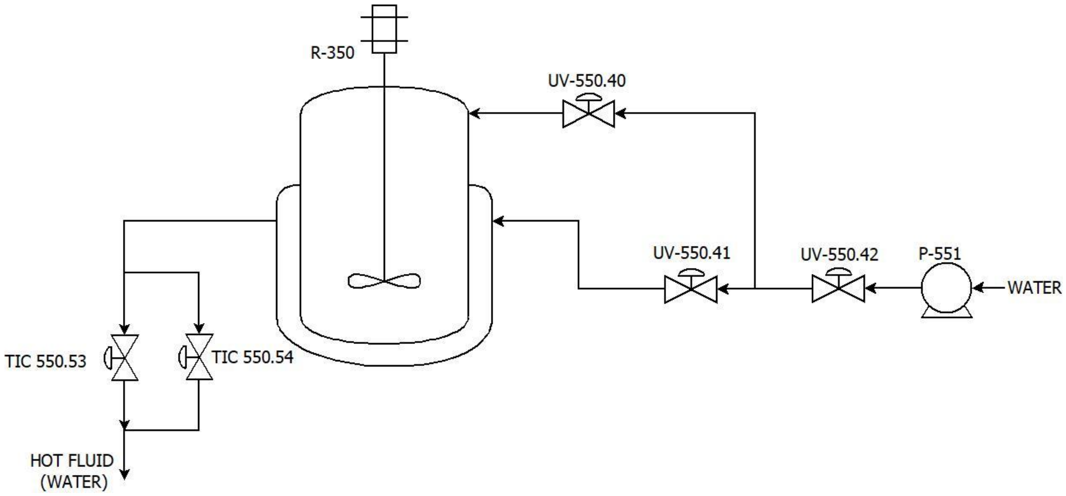

Figure 4.2. Schematic of the valves of interest of 550-reactor (Personal compilation).

Therefore, it is necessary that the water inlet valve is open (UV 550.42) and that valve 550.40 and/or 550.41 are open. Likewise, at the outlet, valve 550.53 and/or valve 550.54 must be open and their temperature must be higher than 70ºC or at least one of them must meet it. If all parameters are met, i.e., all inlet valves are open, the outlet valves are more than 10% open and the temperature is above 70ºC, the average of temperatures and opening would be performed.

4.2.2. Fluid inlet pressure

Once the temperatures and flow rates of the fluids to be treated have been established, the pressure at which the heat exchanger will work must be determined. To do this, the first step is to locate the place where the heat exchanger should be placed.

As mentioned above, the heat exchanger is to be placed in three locations: the first is in the ETHOX plant, next to the 350 and 366 reactors. In this position, the Hot Fluid, in this case the cooling water leaving the reactor, is at 3 bar. As there is not much distance, it is assumed that the pressure would be the same as at the reactor outlet.

This is the same for the second position, located in the HTMPP plant next to 550-reactor.

With respect to the Cold Fluid, it is driven by two pumps to the two plants. These pumps provide static pressure to the fluid, so, the outlet pressure will be higher than at the pump inlet. Thanks to the pressure gauge at the outlet of the pumps, the pressure at that point can be known, being 3 bar. From this value, the pressure in the ETHOX plant and HTMPP plant can be known by means of the equation of Bernoulli shown in equation 4.1 (A. Isaías *et al.*, 2014).

$$\left(\frac{v_2^2}{2}-\frac{v_1^2}{2}\right)+g*(z_2-z_1)+\left(\frac{P_2-P_1}{\rho}\right)+\Sigma F=W \tag{4.1}$$

As shown in equation 4.1, in this case, since there is no change of section, the velocities will be equal throughout the pipe so, the kinetic term is cancelled, as well as the pump work (W).

Regarding pressure drop (ΣF), pipe friction and flow accidents in the conduction fittings must be considered. To calculate the friction pressure drop, the Fanning equation is used as reflected in equation 4.2 (I.H. Shames. , 1995).

$$F_f = \frac{2 * f * v^2 * L}{D} \qquad (4.2)$$

In it, the friction factor (f) must be determined, which depends on the properties of the fluid, its velocity (v), pipe diameter (D) and internal roughness (ε). In this case, it is desired to employ a commercial steel pipe with 2-inch pipe diameter. Using the diagram of the Appendix 8.4., a relative roughness (ε/D) of 0.001 is obtained.

With respect to the fluid velocity, this parameter can be found from the use of equation 4.3.

$$v = \frac{Q(\frac{m^3}{s})}{\frac{\Pi}{4} * D^2(m^2)} \qquad (4.3)$$

Succeeding, the Reynolds number must be found in order to find out in which regime it works by applying 4.4 equation.

$$Re = \frac{v * D * \rho}{\mu} \qquad (4.4)$$

For this case we work with a flow rate of 16 m^3/h which implies a velocity of 2.19 m/s. Taking into account the properties of the fluid (μ=3.60E-04 kg/ms y ρ=972.45 kg/m^3), a turbulent regime is determined, i.e. a Reynold of 3E+05. Therefore, from the Moody diagram (Appendix 8.5.) a friction factor (f) of 6.5E-03 is established.

As for the total length (L), the length of the pipe and the length of the accessories must be quantified. To determine the length of the pipe, the distance between the two points to be joined is measured by counting the number of steps. Then, knowing the normal distance between steps, a length of 79 m is obtained.

On the other hand, for the equivalent length of the accidents, the abacuses shown in Appendix 8.6. can be used, in which, from the diameter and the type of accident, this distance can be acquired. In this example, an equivalent length of 1.5 m is determined for a large bend. For four bends, 6 m would be needed.

Another way to find the pressure drop in accidents is by using the K method in which the equation 4.5 is used.

$$F_m = \frac{k * v^2}{2} \tag{4.5}$$

Where k depends on the equivalent length (Le), the actual inside diameter of the pipe (Di) and the pipe friction factor (f_T)as shown in equation 4.6 (I. Martínet al. , 2023).

$$k = \frac{L_e}{D_i} * f_T \tag{4.6}$$

By means of the table in Appendix 8.7, it is established that Le/Di has a value of 30 and f_T is 0.019. Therefore, the pressure drop per accident is 137 J/kg, i.e., 5.46 J/kg for four 90º bends.

Consequently, once all the parameters of interest are known, frictional energy loss of 80.25 J/kg is obtained.

Then, applying equation 4.1, it is obtained that the pressure in the ETHOX plant of the cold fluid would be 1.55 bar. This same value would be used for the HTMPP plant.

$$9.81\frac{m}{s^2} * 7m + \frac{P_2 - 300000\ Pa}{972.45\frac{kg}{m^3}} + 80.25\frac{J}{kg}$$

$$P_2 = 1.55\ bar$$

With respect to the third point, it is located next to the hot water tanks. Therefore, the pressure of the Cold fluid is 1 bar while the Hot fluid has to be calculated by means of the equation of Bernoulli.

Taking into account that 16.24 m^3/h flow through the pipe, which has a density of 969.1 kg/m^3 and a viscosity of 3.39E-04 kg/ms, the above procedure is carried out, obtaining a Reynolds of 3.23E+05, a friction factor of 5.12E-03 and frictional energy losses of 83.21 J/kg.

Thus, applying equation 4.1., the pressure of the hot fluid at this location is 2.86 bar.

$$9.81\frac{m}{s^2} * (-7m) + \frac{P_2 - 300000\ Pa}{969.10\frac{kg}{m^3}} + 83.21\frac{J}{kg}$$

$$P_2 = 2.86\ bar$$

4.3. Heat exchanger design

This project seeks to obtain the area of a heat exchanger. In this case, it is a plate heat exchanger since it is much more affordable, can work in better conditions and does not require as much maintenance.

To be able to carry it out, two tools are used, which are shown below. On the one hand, as the design of a heat exchanger is an iterative process, it is better to use the *Aspen Exchanger Design and Rating (EDR)* because it offers the possibility of making different designs to be studied in a fast way (Janaun *et al.*, 2016).

But also, a theoretical design with an example is made knowing the different correlations and equations for the design of the exchanger and, thus, to be able to understand the effect that certain parameters produce in the design such as the Nusselt, the pressure drop, the velocity in the channel, etc. Thanks to this, it will be possible to understand better the values determined by the *EDR*.

From the theoretical design, to calculate the heat exchanger area, two methods are applied: the LMTD and the ε-NTU (K. Thulukkanam. , 2013).

For the LMTD method, to calculate the area of the heat exchanger, it is necessary to determine the heat transfer rate (q), the overall heat transfer coefficient (U) and the logarithmic mean temperature variation (LMTD), i.e., the calculation of the heat transfer area is given by the following equation 4.7.

$$q = U * A * LMTD \tag{4.7}$$

Regarding the heat dissipated, this can be found by knowing the mass flow rate of the Hot or Cold Fluid, the specific heat and the inlet and outlet temperature of the fluid. In this case, only all the values of these parameters are known for the Cold Fluid. Therefore, the heat dissipated by this fluid can be found according to equation 4.8.

$$q = m_x * Cp * \Delta T \tag{4.8}$$

For example, for a Cold Fluid flow rate of 16 m^3/h with working conditions of 67.73ºC and 90ºC as inlet and outlet temperature respectively, the heat required to produce this temperature increase is obtained as shown below by applying equation 4.8.

$$q = \frac{16\,\frac{m^3}{h} * \frac{1h}{3600\,s}}{972.45\,\frac{kg}{m^3}} * 4193.26\,\frac{J}{kg°\mathrm{C}}\,(90 - 67.73)°\mathrm{C}$$

$$q = 403605.22\,W$$

Subsequently, the outlet temperature of the Hot Fluid can be determined since, assuming that there are no losses between the heat exchanger and its surroundings, the heat transfer rate (q) lost by the Hot Fluid must be equal to the rate gained by the Cold Fluid. In other words,

$$q_{hot} = q_{cold} \tag{4.9}$$

By subtracting the outlet temperature, the equation 4.10 is obtained.

$$T_{hot,out} = T_{hot,in} - \frac{q_{hot}}{m_{hot}} \tag{4.10}$$

Continuing with the example, if the Hot Fluid has a flow rate of 16.24 m^3/h, that is, 4.37 kg/s, and it has an inlet temperature of 95ºC, it can be obtained a Hot Fluid outlet temperature of 73ºC by applying the equation 4.10.

$$T_{hot,out} = 95℃ - \frac{403605.22\ W}{4.37\frac{kg}{s} * 4197.43\frac{J}{kg℃}} \rightarrow T_{hot,out} = 73.01℃$$

Once these parameters are known, the logarithmic mean temperature difference can be acquired. In this case, two cases can be distinguished depending on the direction of the currents: countercurrent and parallel.

In this case, with plate heat exchangers it is usual to work mostly in countercurrent, so, in order to find it, the following equation 4.11 is applied.

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln\,(\Delta T_1/\Delta T_{2)}} \tag{4.11}$$

To determine the difference in temperatures 1 and 2, the countercurrent case is plotted as shown in Figure 4.3 (W. James. , 1996).

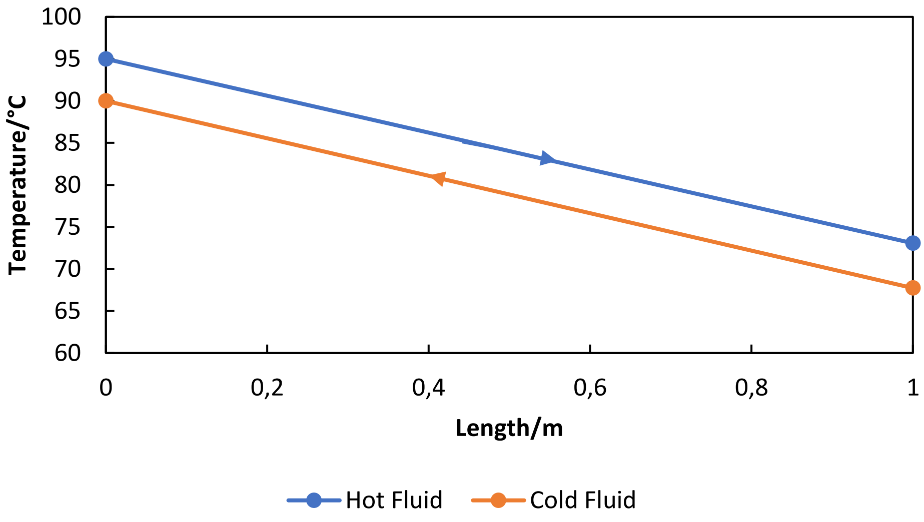

Figure 4.3. Countercurrent temperature profile (Personal compilation).

As can be seen, in countercurrent, each current goes in one direction, therefore, the temperature difference will deal with an input and an output of each current respectively, as described in equation 4.12 and 4.13.

$$\Delta T_1 = T_{hot,in} - T_{cold,out} \tag{4.12}$$

$$\Delta T_2 = T_{hot,out} - T_{cold,in} \tag{4.13}$$

Following the previous example, the logarithmic mean temperature difference for this case is shown in Table 4.1.

Table 4.1. Logarithmic mean temperature difference for the countercurrent configuration.

	Countercurrent
ΔT₁ /ºC	5.00
ΔT₂ /ºC	5.28
LMTD /ºC	5.14

Consecutively, from a given geometry, in this case provided by the manufacturer *J.C. Negre*, the effective area (Ap) can be determined from the effective length of the plate and the width of the plate as shown in equation 4.14.

$$A_p = L_e * W \tag{4.14}$$

To do so, knowing that the horizontal distance between the ports (HPCD) and the port diameter (D), i.e., 225 and 100 mm respectively, as reflected in Figure 4.4. the width of the plate can be obtained from equation 4.15.

$$W = HPCD + D + 0.015 \tag{4.15}$$

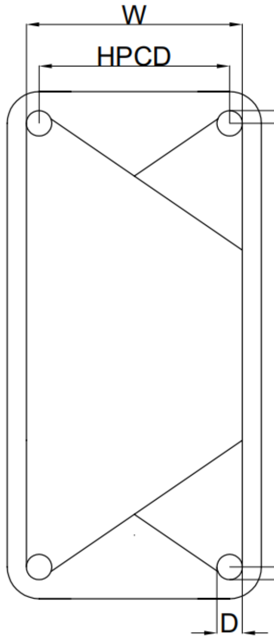

Figure 4.4. Measurement of a plate (Personal compilation).

Also, this effective area can be established by applying the following equation 4.16.

$$A = (n - 2) * A_p \tag{4.16}$$

In this case, the width and length of the plate is 340 mm and 1.5 m, respectively. So, the effective area is 0.511 m^2, obtained from equation 4.14.

Regarding the overall heat transfer coefficient (U), this value can be determined thanks to the following equation 4.17 (B. Sundénet al. , 2007).

$$\frac{1}{U} = \frac{1}{h_h} + \frac{e}{k} + \frac{1}{h_c} + R_{f,h} + R_{f,c} \tag{4.17}$$

This equation shows that the overall coefficient depends on the individual heat transfer coefficients, the thickness of the plates, the thermal conductivity of the plate material and the fouling of the fluids. *AISI 316L* stainless steel is used for this type of heat exchanger, which has a thermal conductivity of 15.05 W/mK at 100ºC and the plate thickness is given by the manufacturer, which, in this case, is 0.4 mm.

Likewise, the fluid resistance (R_f) depends on the type of fluid being worked with, in this case, the two fluids are water so, the values established for the Hot and Cold fluids are 1.70E-05 and 1E-05 m^2K/W respectively.

From the literature search to obtain a range of values for this coefficient, it has been found in *Perry´s Chemical Engineer´s handbook* that, for a gasketed plate heat exchanger, the overall heat transfer coefficient (U) working with water on the sides, the range is between 5700 and

7400 W/m^{2o}C (R. H. Perryet al. , 1934). In addition, possible manufacturers obtained U values of 7095 and 7180.69 W/m^{2o}C depending on the gaskets used in the heat exchanger.

Assuming a number of plates equal to 24, the overall heat transfer coefficient can be found.

Knowing the number of plates, the number of channels can be found from the following equation 4.18. In this case, the number of channels is 12.

$$N_c = \frac{n-1}{2} \tag{4.18}$$

Once the number of plates are known, it must be determined the individual coefficients (h) of each fluid. To do so, first, First, from the mass flow rate of the fluid (M) and the number of channels (N_c), the flow rate though each channel (M_c) is recognized by means of equation 4.19.

$$M_c = M/N_c \tag{4.19}$$

In the case of the Hot Fluid, the flow rate through each channel is 0.364 kg/s and for the Cold Fluid, M_c is equal to 0.360kg/s.

From the flow rate through each channel, the channel mass velocity (m) is established by means of the equation 4.20.

$$m = M_c/S_c \tag{4.20}$$

Where the area of passage per channel (S_c) is found from the multiplication of the width of the plates (W) and the separation between plates (b). The separation between plates can vary from 2.5 to 5 mm but, in this case the smallest distance, i.e., 2.5 mm, has been selected because in the offer from the manufacturer, this information was not available.

Then, the Reynolds (Re) can be calculated which depends on the equivalent diameter (De), the dynamic viscosity of the fluid and the mass velocity (m), as shown in equation 4.21.

$$Re = \frac{m * D_e}{\mu} \tag{4.21}$$

Once the Reynolds number is known both, the Nusselt (Nu) and the friction factor (f), can be determined. To obtain them, different correlations have been found, but, in this case, the Thonon correlation will be used in which the following two equations are applied (F. Táboas. , 2006).

$$Nu = C_1 * Re^m * Pr^{1/3} \tag{4.22}$$

$$f = C_2 * Re^{-p} \tag{4.23}$$

The constants of the correlation of Thonon can be found in Appendix 8.9. Following, the individual heat transfer coefficient (h) of each fluid can be known by applying equation 4.24.

$$h = \frac{Nu * k}{D_e} \tag{4.24}$$

For this example, the individual coefficients of the Hot and Cold Fluid are 24347.88 and 23663.33 W/m^{2o}C, respectively. This results in an overall heat transfer coefficient (U) of 7272.86 W/m^{2o}C.

The following parameter to be determined is the correction factor (F) since the number of plates is less than 50. To do so, the equation 4.7 should be reformulated in equation 4.25.

$$q = A * U * LMTD * F \tag{4.25}$$

This parameter depends on two parameters, R and P, which can be obtained from the equations 4.26 and 4.27 where M is the mass flow rate in kg/s (S. Kakaç and H. Liu , 2002).

$$R = \frac{\left(M * C_p\right)_{min}}{\left(M * C_p\right)_{max}} \tag{4.26}$$

$$P = \frac{T_{c,out} - T_{c,in}}{T_{h,in} - T_{c,in}} \tag{4.27}$$

Following the example, the properties of each fluid have been determined from the average of the inlet and outlet temperatures in the exchanger. From the application of equation 4.26 and 4.27, an R=0.99 and P=0.82 have been obtained.

$$R = \frac{4.322 \frac{kg}{s} * 4193.26\ (J\ /kg°C)}{4.373 \frac{kg}{s} * 4197.43\ \ (J\ /kg°C)} \rightarrow R = 0.99$$

$$P = \frac{90 - 67.73}{95 - 67.73} \rightarrow P = 0.82$$

Knowing these values, from the Appendix 8.8., the correction factor for this example is 0.93.

Finally, when all the parameters are acquired, the area of the heat exchanger can be obtained by applying the equation 4.25. In this case, the area is 11.61 m^2. The values obtained for each parameter can be visualized in the Appendix 8.10.

However, another way to obtain the heat exchanger area is through the number of transfer units (ε-NTU). In it, 3 dimensionless parameters have to be found out. Firstly, the heat capacity rate ratio (Cr) is defined, which is the ratio between the heat capacity rate of one of the fluids between the smallest of them as shown in equation 4.28. This parameter must be less than 1 (J. Saari. , 2010).

$$Cr = \frac{C_{min}}{C_{max}} = \frac{Q_{min} * C_{p,min}}{Q_{max} * C_{p,max}} \tag{4.28}$$

For example, for the example below, the Hot Fluid flow rate is greater than the Cold Fluid flow rate. This implies that the minimum and maximum capacity will be given by the Hot and Cold Fluid capacity, respectively. Since C is equivalent to R, from the above procedure, it has been obtained that C=0.99.

The next parameter to quantify is the exchanger efficiency (ε) (J.M. Pinto and J.A.W. Gut, 2002). This parameter represents the ratio between the actual heat transfer rate versus the maximum possible rate. To obtain it, equation 4.29 is used for the case of C=1.

$$\varepsilon = \frac{C_c * (T_{h,in} - T_{h,out})}{C_{min} * (T_{h,in} - T_{c,in})} \tag{4.29}$$

Following the above example, the efficiency of the exchanger is 0.82. Finally, the number of transfer units (NTU) can be calculated using the 4.30 equation for a countercurrent arrangement.

This value is usually between 0.5 and 4 (G. Towler and R. Sinnot , 2008). For this, from the exchanger efficiency, this parameter can be found by applying equation 4.30 since Cr is very close to 1.

$$\varepsilon = \frac{NTU}{NTU + 1} \tag{4.30}$$

For this example:

$$0.82 = \frac{NTU}{NTU + 1} \rightarrow NTU = 4.45$$

Therefore, knowing the value of the number of transfer units, the area of the exchanger can be calculated by equation 4.31. For this method, the heat dissipated (q) and the overall heat transfer coefficient (U) are calculated as above.

$$NTU = \frac{U * A}{C_{min}} \tag{4.31}$$

So, the area obtained by the ε-NTU method is 11.24 m^2., similar to the area determined by the LMTD method.

Another parameter of great importance in the design of the heat exchanger, apart from the overall coefficient, is the pressure drop (ΔP) that occurs in it since, if the pressure drop is maximized, the area will be the minimum possible, which will have an impact on the cost (B. Sundénet al. , 2007).

In order to calculate it, two parameters have to be determined: the pressure variation in the channels and ports as shown in equation 4.32.

$$\Delta P = \Delta P_c + \Delta P_p \tag{4.32}$$

With respect to the pressure variation in the channels (ΔP_c), equation 4.33 is used.

$$\Delta P_c = \frac{2 * f * m^2 * L_e * N_p}{\rho * D_e} * \left(\frac{\mu}{\mu_w}\right)^{-0.17} \tag{4.33}$$

In order to find out the viscosity at the wall, the wall temperature is estimated from the average temperatures of the fluids as shown in equation 4.34.

$$T_p = \frac{h_h * T_{mh} + T_c * T_{mc}}{h_h + h_c} \tag{4.34}$$

Once the wall temperature is known, its viscosity is determined from the table of water properties established in Appendix 8.11.

On the other hand, the pressure loss in the ports can be found out using equation 4.35 (T. M. A. Elmaatyet al. , 2017).

$$\Delta P_p = 1.5 * \frac{\rho * V_p^2}{2} \tag{4.35}$$

Where V_p is the velocity as the ports and can be found by equation 4.36, in which the passage area at the port is given by equation 4.37, with a diameter of 100 mm.

$$V_p = \frac{M}{\rho S_p} \tag{4.36}$$

$$S_p = \frac{\Pi * D^2}{4} \tag{4.37}$$

Following the previous example, pressure losses are obtained for both Cold and Hot Fluid as shown in Table 4.2. The results acquired from the procedure carried out for the determination of these values are shown in Appendix 8.10.

Table 4.2. Pressure drops in the heat exchanger with reactor 350 at the selected temperature for the example.

Fluid	ΔP_c (bar)	ΔP_p (bar)	ΔP (bar)
Hot Fluid	0.114	0.002	0.116
Cold Fluid	0.111	0.002	0.113

Finally, knowing the area and the pressure drop should be done a rating *LMTD* or *ε-NTU* method to know the temperatures at which the fluid of interest, in this case the Cold Fluid can reach at the outlet of the exchanger. For this, it must be assumed a number of plates and see if, with the plates, the temperatures of 90ºC at the Cold Fluid outlet can be obtained.

But, as mentioned before, since the design of an exchanger is an iterative process, *EDR* is used to obtain the results in a faster and more efficient way. Here, the desired plate heat exchanger can be exemplified with different plate models thanks to the database of the program and the catalog of the manufacturer.

A gasketed plate heat exchanger is used for this work because it is usually used when the thermal loafs are variable (F. Táboas. , 2006). The gaskets provide a small gap between plates which allows high fluid velocities and hence high heat transfer coefficients (E. Cao, 2010).

Different configurations can be used in the *EDR,* in this case the design is used to visualize the base case from which to start. Likewise, design with plates is used in which different plates are available from the database or you can design the plate according to established parameters. With these configurations it can be analyzed different cases to obtain the optimal heat exchanger.

Finally, the simulation is used to verify the conditions in which the fluids to be treated are going to work, both the inlet and the outlet, and to see if the desired temperature at the outlet of the cold fluid is met.

5. DISCUSSION

5.1. Comparative analysis of the employability of the reactors

In order to design the plate heat exchanger, it is first necessary to know the reactor that will be used to supply the Hot Fluid to the exchanger.

As mentioned above, there are three reactors available, R-350, R-366 and R-550. Applying the conditionals previously mentioned, a different number of data has been obtained for each of these reactors as shown in Table 5.1.

Table 5.1. Reactor steam generation and cost of the reactors of interest.

	R-350	**R-366**	**R-550**
Data	4462	28230	1449
% employed	4.26	26.93	1.38

Taking into account that if a reactor were to operate throughout the year, a number of data that would be obtained would be 104833. So, it can be stated that the reactor that would be operating for the longest time would be 366-reactor, since it would be working up to 26.93 % of the time compared to 4.26 and 1.38% of the time of reactors 350 and 550.

Therefore, reactor 366 would be chosen to supply the Hot Fluid to the heat exchanger.

In addition, in this reactor, the percentage that would be obtained if the temperature conditioner were modified from 70 to 90ºC has also been evaluated, sine the aim is for the Cold Fluid to reach this temperature at the outlet.

Analyzing the number of data obtained with a temperature higher than 90ºC as a conditional, 26376 viable data are determined, which represents 25.16% of the time used in this reactor. Consequently. There would only be a difference of 1.77% with respect to the percentage obtained in reactor 366 with the 70ºC conditions. In other words, it is confirmed that the 366-reactor works with temperatures above 90ºC, being the most suitable for the exchanger.

Likewise, in this reactor, the valve opening range where the highest number of feasible data would be obtained is evaluated. For this purpose, the reactor is evaluated according to three different valve opening ranges: from 10 to 25%, from 25 to 75% and from 75 to 100%.

Table 5.2. Data obtained according to the opening range of the R-366 reactor.

	10-25%	**25-75%**	**75-100%**
Data	8981	14835	4414
% employed	8.57	14.15	4.21

As shown in Table 5.2, the predominant working range is between 25 and 75-5 valve opening, i.e., from 16.24 m^3/h to 48.73 m^3/h since up to 14835 viable data are obtained in this range of valve opening. These data are complying with the conditionals between 70 and 160ºC.

However, if the temperature at which this reactor works is considered, the following Figure 5.1 is determined.

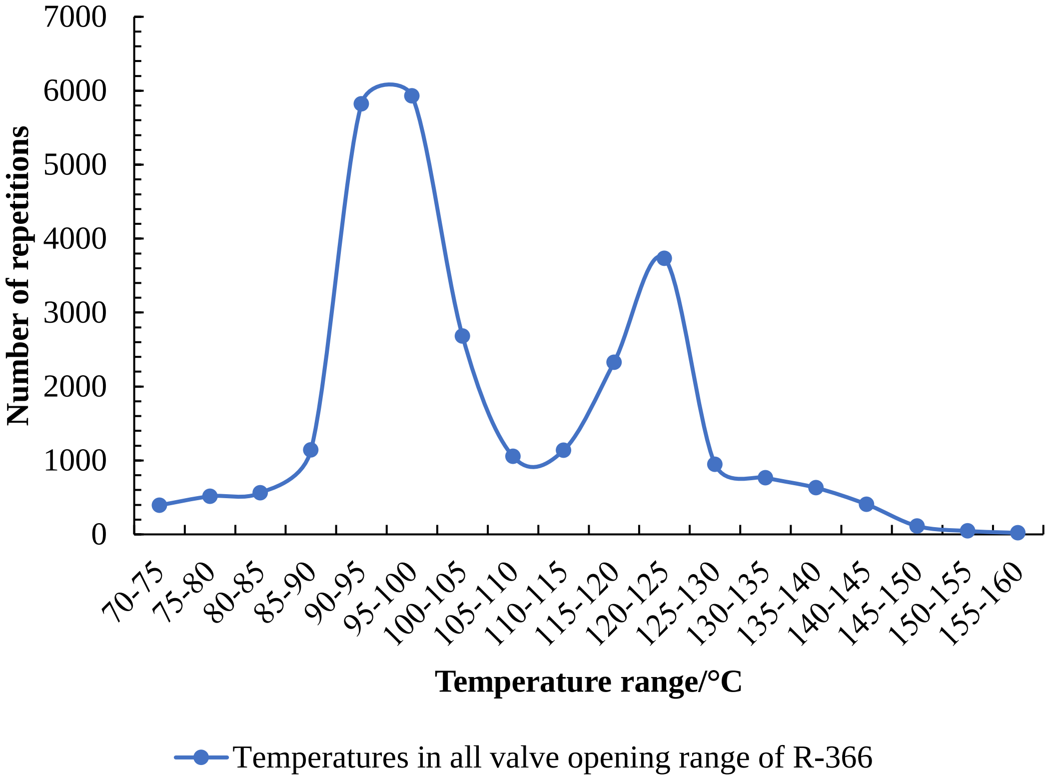

Figure 5.1. Temperatures obtained in all valves opening range of the 366-reactor (Personal compilation).

In this figure, the most prominent temperature range is between 90 and 100ºC. This would be beneficial for the design of the heat exchanger since the desired temperature at the outlet of the Cold Fluid is 90ºC. Therefore, with this temperature range, being higher than this 90ºC, this reactor could be used.

If it is represented, in a more specific way, the different ranges of valve opening previously evaluated, Figures 5.2, 5.3 and 5.4 are obtained, in which the number of repetitions in which a temperature has been obtained against different temperatures ranges is represented.

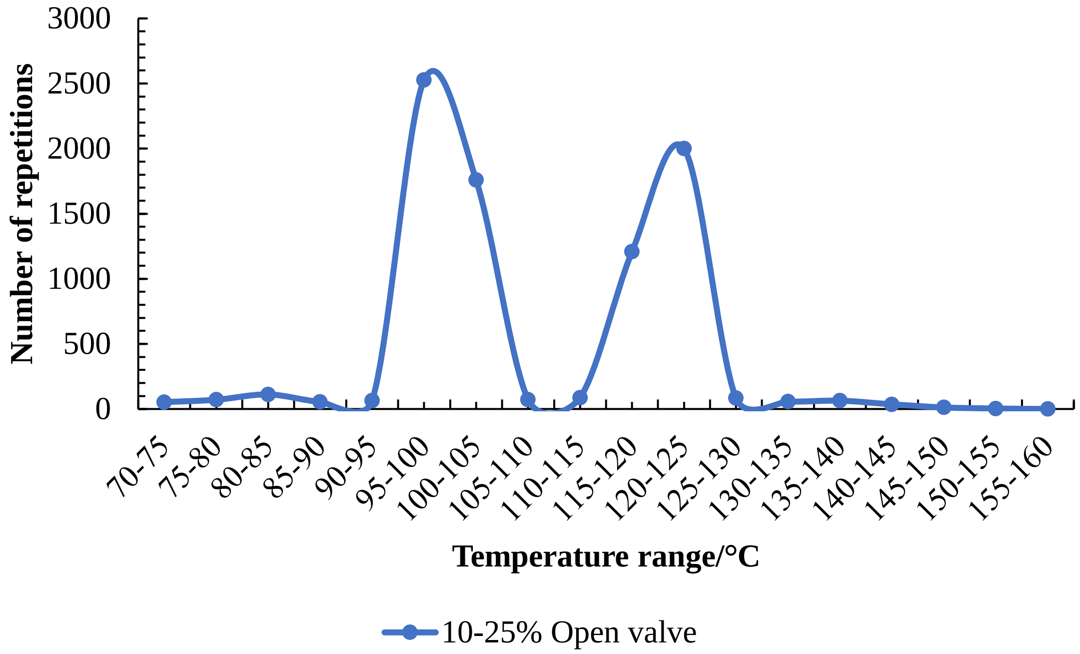

Figure 5.2. Temperatures obtained by working between 10 and 25% of valve opening of the reactor 366 (Personal compilation).

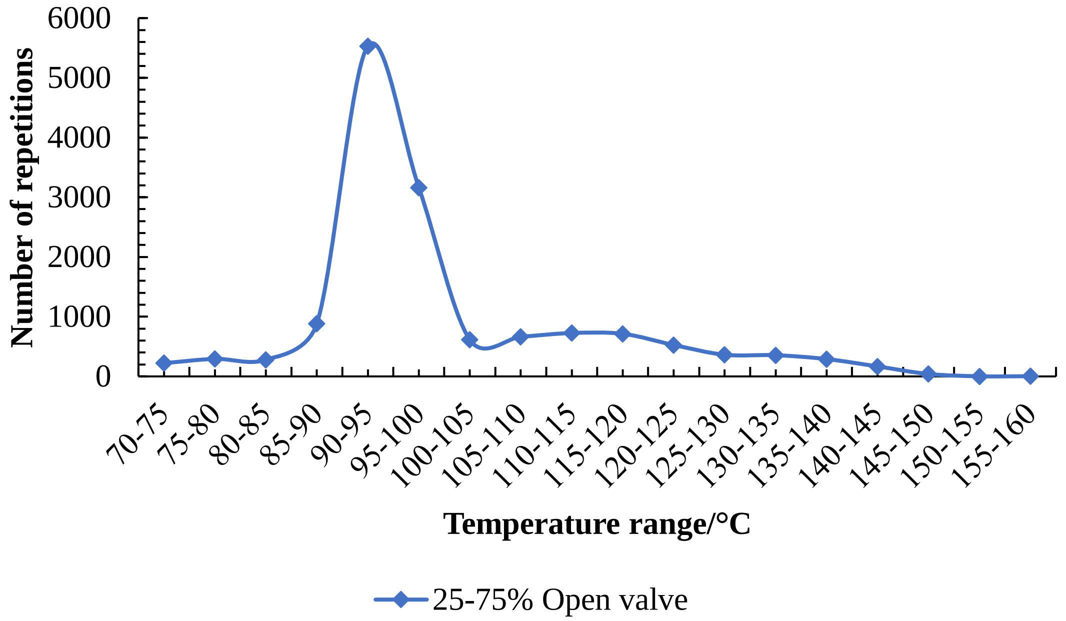

Figure 5.3. Temperatures obtained by working between 25 and 75% of valve opening of the reactor 366 (Personal compilation).

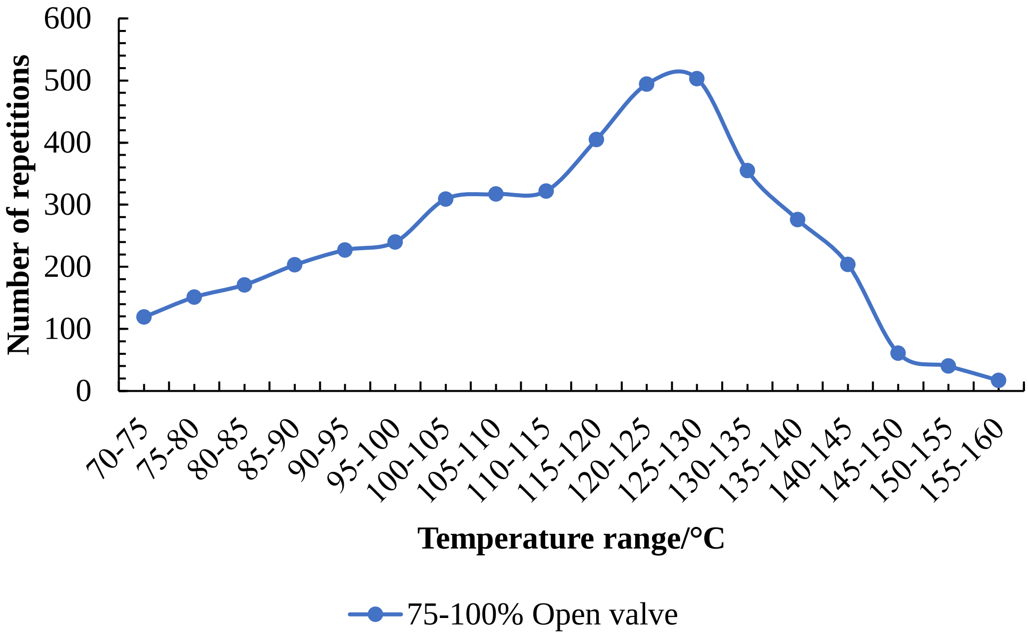

Figure 5.4. Temperatures obtained by working between 75 and 100% of valve opening of the reactor 366 (Personal compilation).

As can be seen, in all the ranges of valve opening, the highest number of repetitions is obtained in high temperatures ranges, above 90ºC.

Specifically, in the predominant valve opening range in this reactor, i.e., between 25 and 75%, 14835 data are obtained as shown in Table 5.3, with a predominant temperature range between 90 and 95ºC.

Table 5.3. Temperatures obtained for the R-366 reactor.

	10-25%	**25-75%**	**75-100%**
Temperature range/ºC	95-125	90-95	110-125
Average temperature/ºC	109.63	100.12	114.50
Number of data	8981	14835	4414

Therefore, for the Hot Fluid of the heat exchanger, the flow rate should be between 16 and 48.73 m^3/h, and it would work with a temperature of 95ºC since this range of valve opening works predominantly with this temperature.

Similarly, in 366-reactor, the percentage in which the reactor would work with the heating temperatures, i.e., higher than 95ºC is analyzed. To do this, the amount of data in the entire reactor that is between 70 and 95ºC is counted, being in this case 8437 data. This value is then divided by the ideal number of data, i.e. 104833 data. Hence, it is determined that 8.05% of the time the reactor works between 70 and 95ºC.

From this, knowing the total percentage of the time that the reactor operates, the percentage used for heating can be found. So, reactor 366, from working 26.93% of the time between temperatures of 70 and 160ºC, would work 18.88% of the time with temperatures higher than 95ºC.

Likewise, since it has been shown how much percentage the reactor would work in ideal conditions for the exchanger, the percentage of the valve opening range of interest is also shown in Table 5.4.

Table 5.4. Data obtained working with a temperature above 95ºC in a range between 25 to 75% valve opening in reactor 366.

	25-75%
Data	7626
kcal/year	2.26E+08
% employed	7.28
$\mathbf{kg_{steam}}$/year	4.59E+05
$\mathbf{t_{steam}}$/year	458.98
$\mathbf{€_{steam}}$/year	41308.02

That is to say, of the 18.88% that the reactor works with a temperature above 95ºC, 7.28% is in the range of valve opening that has been selected, 25 and 75%.

Thank to this, energy of 2.26E+08 kcal/year could be acquired. This value has been obtained thanks to the heat dissipated in the heat exchanger. That is, if a theoretical calculation is made using the equation 4.8, having a water flow rate of 16 m^3/h with a temperature difference of 67.73ºC to 90ºC, 356320 kcal/h are determined.

Knowing the number of data available, in this case 7626 data, the kcal/year can be found by means of the equation 5.1.

$$7626\,\frac{data}{year} * \frac{5\,min}{data} * \frac{1\,h}{60\,min} * 356320\frac{kcal}{h} = 2.26E + 08\frac{kcal}{year} \qquad (5.1)$$

Also, the kilograms of steam that could be generated by using these kilocalories can be obtained. Knowing that the latent heat at 6 bar is 493.36 kcal per kilogram of steam, the kilograms of steam that could be generated per year can be found as shown in equation 5.2.

$$\frac{2.26E+08\,\frac{kcal}{year}}{493.36\,\frac{kcal}{kg_{steam}}}=4.59E+05\,\frac{kg_{steam}}{year} \tag{5.2}$$

Then, knowing the tons of steam generated, it can be determined the cost of these tons of steam, i.e., in the case of working with 7626 data, it can be generated 458.98 tons of steam per year, which implies about 41308 € per year, if it were purchased, as exemplified in equation 5.3, knowing that the price of steam is around 90 €/ton.

$$458.98\,\frac{t_{steam}}{year} * \;90\,\frac{€}{t_{steam}}=41308\,\frac{€}{year} \tag{5.3}$$

Consequently, the 366-reactor is the ideal choice for supplying the Hot Fluid to the exchanger since it works up to 7.28% per year at temperatures above 90ºC with flow rates of 16 m^3/h or more.

5.2. Optimal location of the exchanger

Once the conditions under which the Hot Fluid can work are known, the optimum location of the heat exchanger must be established.

As previously mentioned, three locations have been recognized for the installation of the heat exchanger as can be seen in Figure5.5.

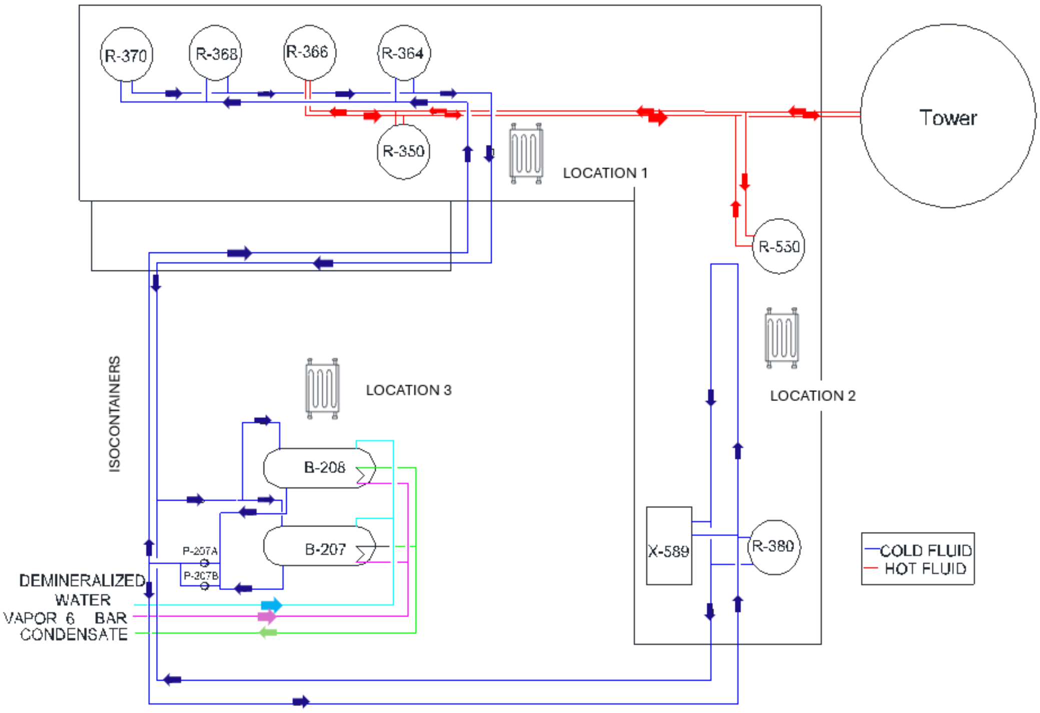

Figure 5.5. Three heat exchanger locations (Personal compilation).

Once the flow rates and pressures of the Cold Fluid, all of which are shown in Table 5.5., are known, it has been determined that the best location for the heat exchanger is the third one.

Table 5.5. Working parameters at each location.

		Location 1 (ETHOX)	**Location 2 (HTMPP)**	**Location 3**
Hot fluid	**Pressure (bar)**	3	3	2.86
	Flow rate (m^3/h)		16	
Cold fluid	**Pressure (bar)**	1.55	1.55	1
	Flow rate (m^3/h)	0.89	2.5	16

As can be seen in Table 5.5., in the ETHOX plant (location 1) only 0.89 m^3/h of Cold Fluid is available. This implies that, even if there are working flows of the Hot Fluid from 16 to 48 m^3/h, it is not possible to produce a large amount of heat since the fluid that limits the transfer is the cold one.

The objective of this heat exchanger is to increase the temperature of the Cold Fluid. So, working with 0.89 m^3/h, only 22.45 kW could be generated. This heat has been obtained by using this water flow with a temperature difference of 67.73 ºC to 90ºC.

The same happens in the HTMPP plant (location 2) because, although there is a higher flow rate compared to situation 1, the heat dissipated is not very high either (63 kW).

Therefore, location 3, located next to the tanks as shown in Figure 5.6, is the best option since 16 m^3/h of the Cold Fluid is available at that point, which implies that a good exchange with the Hot Fluid can be performed at this location and up to 407 kW can be generated.

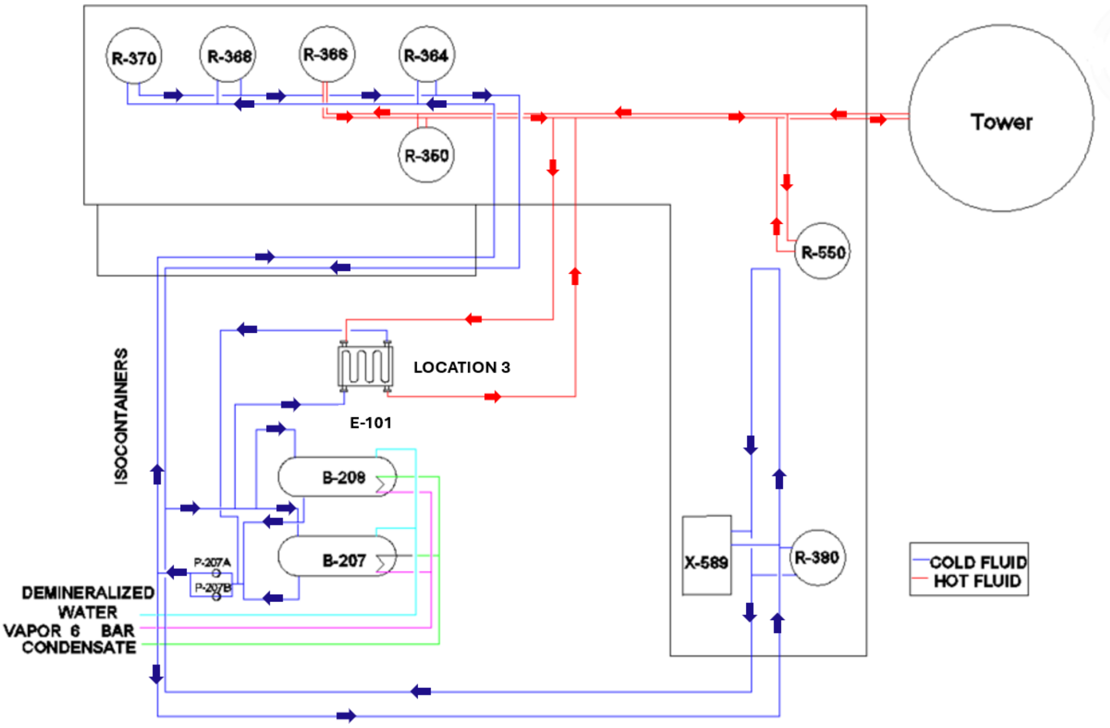

Figure 5.6. Heat exchanger at the selected location (Personal compilation).

Knowing this, as mentioned in section 5.1, from the 366-reactor, a flow rate of 16 m^3/h, as well as the Cold Fluid, has been selected since the temperature at this flow rate is above 95ºC. So, it will be used these conditions to design the heat exchanger.

5.3. Comparison of different plate heat exchangers

In order to know the optimum heat exchanger for the treatment of the relevant fluids, the Hot Fluid and the Cold Fluid, two case studies are proposed. As mentioned before, as the Cold Fluid is at different temperatures at the two selected measurement points, the design of the heat exchanger will be studied at these temperatures, i.e., 67.73ºC and 75ºC.

Also, as mentioned above, the flow rates to be used are 16 m^3/h in both fluids since the selected reactor, R-366, would work with this flow rate most of the time with a minimum temperature of 95ºC and the location selected works with that flow rate.

In addition, it will be evaluated in the two cases to be treated how the increase in the flow rate of the Hot Fluid affects the design of the exchanger.

5.3.1. Scenario 1: 67.73ºC of the Cold Fluid

All the cases to be visualized, the *EDR* has been used because, as the design of a heat exchanger is an iterative process, *EDR* allows to obtain the design faster than with correlations (C. Gulenogluet al. , 2014).

- **Optimum plate selection of Scenario 1**

First, for the exchanger, two streams are used which are in different conditions both in terms of pressure and temperature as shown in Table 5.6. In this first case to be treated, the Cold Fluid works with an inlet temperature of 67.73ºC.

Table 5.6. Conditions of the fluids to be treated in Scenario 1.

	Hot side	**Cold side**
Flow rate (m^3/h)	16.24	16.00
Flow rate (kg/s)	4.37	4.32
Inlet temperature (°C)	95	67.73
Outlet temperature (°C)	73.01	90
Inlet pressure (bar)	2.86	1

By applying these conditions in the program, an area of 26.1 m^2 is obtained with 77 plates and a low pressure drop of 0.054 and 0.053 bar for both, the hot and cold fluids, respectively.

As low pressure drops of less than 1 bar are acquired, different cases are analyzed in which several plates from different manufacturers are used to evaluate the change that occurs in both, the heat exchanger area and the pressure drop and, thus, optimize the heat exchanger area by adjusting the heat transfer and pressure drops.

Among the manufacturers included in the *EDR (Alfa Laval, Tranter and APV)* only three designs fit the current to be treated. On the other hand, the company contacted the manufacturer *J. Negre* to estimate the cost of the exchanger with other data. From the catalog of the latter manufacturer, several plates are established which may be suitable for the design of this exchanger. In this case, *S-17, S-19A, S-37* and *S-31A.* In them, only a permissible pressure drop of 0.5 and 0.29 bar in the Hot and Cold Fluid is allowed, since if it is increased above these values, the exchanger design will not be adequate or it will result in exchangers with a double number of steps.

For proper heat transfer and adequate pressure drop, several parameters must be taken into account such as heat transfer, plate geometry with the corrugation angle used, the established pressure drops, especially port losses, the outlet temperature obtained in the Cold Fluid, the risk of maldistribution, wall shear stress and, finally, the cost (E. Cao. , 2010).

Exchanger plates can have different types of corrugation in them, i.e. depending on the angle of the plate (A. Jafari *et al.*, 2022). Three types of corrugation can be differentiated: H, L and M, but for these cases, the most optimal plate should have an H type angle, in which a very open angle is used, allowing a more efficient exchange, i.e., a higher transfer, but also a higher pressure drop (J. Negre. , 2024).

If working with a smaller chevron angle (L), this would cause less turbulence which would imply a less efficient exchange but there would be lower pressure drops.

For all the cases studies in this section, all work with an angle type H (30º), with respect to the horizontal, which allows a balance between pressure drop and heat transfer, reaching values of the global heat transfer coefficient close to 5000 W/m^{2}K.

Knowing this, starting from the base case, 7 designs are made with the above-mentioned plates as shown in Table 5.7.

Table 5.7. Plates evaluated for the case of 67.73ºC.

	Base Case		**S-17**		**S- 37**		**S-31A**	
	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side
Q(m^3/h)	16,24	16	16,24	16	16,24	16	16,24	16
T_{in} (ºC)	95	67,73	95	67,73	95	67,73	95	67,73
T_{out} (ºC)	73,01	90	73,14	90	73,14	90	73,14	90
ΔP (bar)	0,05	0,05	0,18	0,18	0,28	0,28	0,28	0,28
ΔP_p (bar)	0,01	0,01	0,04	0,04	0,00	0,00	0,01	0,01
ΔP_c (bar)	0,05	0,05	0,15	0,15	0,28	0,27	0,27	0,27
m (m/s)	0,13	0,12	0,22	0,22	0,27	0,26	0,26	0,26
q (W)	403891		401569		401569		401569	
LMTD (ºC)	5,14		5,2		5,2		5,2	
U (W/m^{2}K)	3047,2		4731,9		5256,2		5239,3	
A(m^2)	26,1		16,3		17,6		17,8	
h (W/m^{2}K)	7763,2	7548,1	12865,2	12496,5	14850,8	14423	14784,6	14358,7
Re	2052,84	1447,63	2437,75	1719,06	2946,22	2077,63	2928,9	2065,42
n	77		87		53		69	
A_p (m^2)	0,348		0,192		0,345		0,265	
Angle (º)	30		30		30		30	
ε (mm)	0,6		0,4		0,4		0,4	
V_p (m/s)	1,03	1,01	2,31	2,28	0,9	0,89	1,37	1,35
Nc	38	38	43	43	26	26	34	34
L (mm)	1167,85		927,5		1224,42		1119,82	
VPCD (mm)	1077,9		800		1050		1050	
W (mm)	322,5		240		328,42		252,63	
HPCD (mm)	232,5		112,5		154		182,8	
D_p (mm)	75		50		80		65	
Cost (€)	5064		3739		3641		3792	
A/A_d	1,01		1		1,2		1,21	
Risk	No		no		no		no	
Wss (N/m^2)	13,32	13,17	18,67	18,45	26,25	25,95	25,97	25,68

Table 5.7. Plates evaluated for the case of 67.73ºC "(cont.)"

	S19A		**ALFA LAVAL M6**		**TRANTER GC-16**		**APV SR6GL**	
	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side
Q(m^3/h)	16,24	16	16,24	16	16,24	16	16,24	16
T_{in} (ºC)	95	67,73	95	67,73	95	67,73	95	67,73
T_{out} (ºC)	73,14	90	73,14	90	73,14	90	73,14	90
ΔP (bar)	0,08	0,08	0,08	0,08	0,09	0,09	0,13	0,13
ΔP_p (bar)	0,01	0,01	0,02	0,02	0,03	0,03	0,00	0,00
ΔP_c (bar)	0,07	0,07	0,06	0,06	0,06	0,06	0,13	0,13
m (m/s)	0,16	0,16	0,15	0,15	0,14	0,14	0,17	0,17
q (W)	401569		401569		401569		401569	
LMTD (ºC)	5,2		5,2		5,2		5,2	
U (W/m^2K)	3900,7		3682		3627,3		4243,8	
A(m^2)	20		21,2		21,5		18,4	
h (W/m^2K)	10006,4	9723	9306,7	9044,8	9417	9151,9	12024,4	11676,6
Re	1747,06	1232	1535,44	1082,77	1379,01	972,45	3331,19	2349,1
n	115		143		161		35	
A_p (m^2)	0,177		0,15		0,135		0,557	
Angle (º)	30		31		30		25	
ε (mm)	0,4		0,4		0,5		0,6	
V_p (m/s)	1,37	1,35	1,61	1,58	1,91	1,88	0,56	0,55
Nc	57	57	71	71	80	80	17	17
L (mm)	769,82		716		682		1369,06	
VPCD (mm)	700		640		592		1254,8	
W (mm)	252,63		216		225		427,99	
HPCD (mm)	182,8		140		135		313,7	
D_p (mm)	65		60		55		101,6	
Cost (€)	4523		4955		5173		3666	
A/A_d	1,01		1,01		1,01		1,01	
Risk	No		No		Yes		No	
Wss (N/m^2)	10,25	10,13	9,12	9,01	8,6	8,51	18,03	17,82

Of all of them, the *APV sr6gl* plate stands out. This type of plate works with a corrugation angle of 25º with respect to the horizontal, i.e., it is an H-type plate, with a geometry as shown in Figure 5.7.

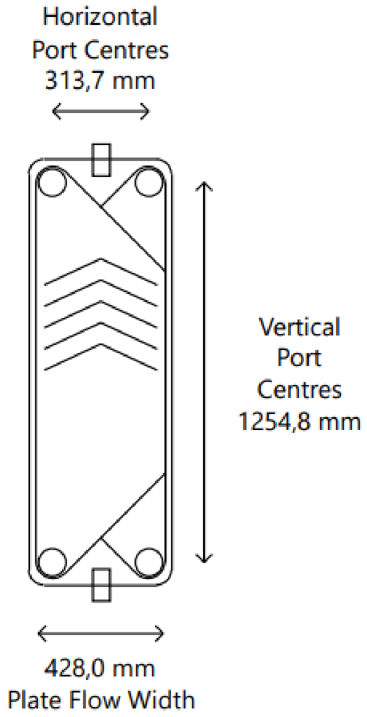

Figure 5.7. Sr6gl APV plate design of scenario 1(From *EDR*).

This type of plate allows to obtain a better efficiency in the heat exchanger. However, this improvement in heat transfer also leads to an increase in pressure drop because they are directly proportional. But, as can be seen in Table 5.7, for this type of plate, the calculated pressure drops are lower than the admissible ones, i.e., 0.13 bar compared to the admissible 0.5 and 0.29 bar.

In addition, although working with a larger plate geometry than in all cases with a geometry of 1369.06 x 428 mm and a number of passes of 1, it is possible to reduce the velocity in the port to 0.56 m/s when using a pipe diameter of 101.6 mm. if a smaller geometry were used, as can be seen in the case of plate *S-17* or *S-19A*, this would cause the diameter in the of the pipe in the port to be smaller, considerably increasing the number of plates to be used. This could reach in a number that the manufacturer does not allow.

Thanks to this speed, pressure drops in the port are determined to be less than 15% of the total pressure drop, i.e., 0.0014 bar compared to 0.02 bar of 15% of the total. So, taking into account this, there are no distribution problems (SPX. , 2008).

Likewise, by using a larger plate size than in all cases, the number of plates to be used is considerably reduced to 35 plates, allowing to work with a channel velocity of 0.17 m/s.

Thanks to this velocity in the channel, it is possible to improve the individual heat transfer coefficients (h). This is due to the influence that the velocity of the fluid in the channel has on the Reynolds, and, therefore, on the Nusselt and the individual heat transfer coefficient.

The velocity in the channel (m) depends on the flow rate through the channel, the flow area per channel (Sc) and the number of channels of each fluid (Nc). On the part of the flow rate through the channel, this value is kept constant, i.e., 16 m^3/h.

Similarly, the area passing through the channel (Sc) varies depending on the width of the plate and the separation between plates set. With the same flow rate passing through each channel (Mc), the larger the area passing through the channel, the lower the velocity in the channel (m).

On the other hand, the velocity in the channel also varies according to the number of channels used. This parameter is influenced by the number of plates to be used, i.e., the greater the number of plates, the greater the number of channels to be established as shown in equation 4.18. For the same flow rate, the greater the number of channels, the lower the flow rate through each channel (Alrwashdeh *et al.*, 2022).

That is, the obtained value of velocity in the channel in the *APV* plate is 0.17 m/s. By obtaining a higher velocity than in the base case (0.13 m/s), this causes an increase in the Reynolds number to 3331.19 and 2349.1 with respect to the Hot and Cold Fluid compared to the base case by the relationship establish in equation 4.21.

Similarly, since the Nusselt is proportional to the Reynolds raised to a power as observed in the Thonon correlation in equation 4.22, an increase of the parameter is observed as the Reynolds increases. Likewise, from equation 4.24, the influence of the Nusselt on the individual heat transfer coefficient is observed since this parameter is directly proportional to the coefficient.

However, the influence of the equivalent diameter (De) on both, Reynolds and individual heat transfer coefficients, must also be taken into account. The equivalent diameter depends on the enlargement factor of the effective heat transfer surface area (φ) and the plate spacing (b) (B. Saleh and L. Sundar, 2021).

While De is directly proportional to Reynolds, the individual heat transfer coefficient is inversely proportional to the equivalent diameter. But even though there is a decrease in this parameter, when there is an increase in the Reynolds number, there is also an increment in the individual coefficient as visualized in the values obtained for the *APV* plate.

Therefore, with the Reynolds values mentioned above, there is an increase in the individual heat transfer coefficient to 12024.4 and 11676.6 W/m^2K for the Hot and Cold Fluid respectively, compared to that obtained in the base case (7763.2 and 7548.1 W/m^2K).

As for the overall transfer coefficient, it depends on the individual coefficients of the fluids, the conductivity of the plate and its thickness and the fouling resistance of the fluids as shown in equation 4.17. In each of the cases, the same fluid fouling resistance have been used in all cases, 1.70E-05 and 1E-05 m^2K/W. The difference between these selected values is due to the origin of the waters, i.e., the Hot Fluid comes from the tower water and, therefore, has a higher value while the Cold Fluid comes from a stream of demineralized water. Also, plate thicknesses between 0.4 and 0.6 mm and conductivities around 15 W/mK are used.

Consequently, the individual coefficients affect the overall coefficient (U) to a greater extent as can be seen in the case of the *APV* plate where, as there is an increase in the individual coefficients, this also causes an increment in the U to 4243.8 W/m^2K compared to the base case of 3047.2 W/m^2K.

With respect to the actual area obtained on this plate, the heat exchanger area has been reduced to 18.4 m^2. This is because, having the same heat dissipated (402 kW) and logarithmic mean temperature difference of 5.2 ºC as the other plates, there is a considerable increase in the overall heat transfer coefficient.

Likewise, the ratio between the actual area and the required area (A/A_d) is less than 1.2, in this case 1.01, which implies that the design is being made to comply with the heat transfer and not with the pressure drop (G. D. Ulrich. , 1984).

In reference to the Wall shear stress (Wss), although typical values of 40 N/m^2 are not achieved for this parameter, values are higher than most of the cases studied are obtained, in this case, 18.03 and 17.82 N/m^2 for the Hot and Cold Fluids, respectively (W. Dávila and F. Obando , 2006).

As for the cost of the heat exchanger, there is a reduction of more than 1000 € compared to the base case, in addition to being one of the cheapest designs of all those evaluated, valued at 3666 €.

Finally, using the *"Simulation"* in the *EDR* with this plate, it is verified that the outlet temperature of the fluid of interest, in this case the Cold Fluid, is close to the established value, i.e., an outlet temperature of 89.97 ºC is obtained, being close to 90 ºc.

Therefore, the plate to be used to work with a temperature difference of 67.73 ºC to 90ºC, is the *APV sr6gl* plate with which a heat exchanger of 18.4 m^2 is acquired.

- **Effect of an increase of the Cold Fluid flow rate on the design of the heat exchanger of scenario 1.**

Once the plate to be used was known, it was analyzed how it would affect a change in the flow rate of the Hot Fluid, in this case the fluid at 95ºC coming from the 366-reactor. For this purpose, the *EDR* is used with the selected plate configuration and the flow rate is varied to 48 and 64 m^3/h and can be seen in the Table 5.8.

Table 5.8. Change of the Hot Fluid flow rate in the APV plate in scenario 1.

	APV SR6GL		**48 m^3/h**		**64 m^3/h**	
	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side
Q(m^3/h)	16,24	16	48,73	16	64.79	16
T$_{in}$ (ºC)	95	67,73	95	67,73	95	67,73
T$_{out}$ (ºC)	73,14	90	87,69	90	89,52	90
ΔP (bar)	0,13	0,13	0,47	0,07	0,49	0,04
ΔP$_p$ (bar)	1,43E-03	1,39E-03	1,37E-02	1,49E-03	2,59E-02	1,59E-03
ΔP$_c$ (bar)	0,13	0,13	0,46	0,06	0,47	0,04
m (m/s)	0,17	0,17	0,35	0,12	0,35	0,09
q (W)	401569		401569		401569	
LMTD (ºC)	5,2		10,81		11,4	
U (W/m^{2}K)	4243,8		4414,8		3969,9	
A(m^2)	18,4		27,3		36,2	
h (W/m^{2}K)	12024,4	11676,6	21466,3	8824,9	21743,8	7176,5
Re	3331,19	2349,1	6760,92	1597,39	6824,62	1210,14
n	35		51		67	
A$_p$ (m^2)	0,557		0,557		0,557	
Angle (º)	25		25		12,5	
ε (mm)	0,6		0,6		0,6	
V$_p$ (m/s)	0,56	0,55	1,67	0,55	2,23	0,55
Nc	17	17	25	25	33	33
L (mm)	1369,06		1369,06		1369,06	
VPCD (mm)	1254,8		1254,76		1254,76	
W (mm)	427,99		427,99		427,99	
HPCD (mm)	313,7		313,7		313,7	
D$_p$ (mm)	**101,6**		**101,6**		**101,6**	
Cost (€)	3666		5069		6471	
A/A$_d$	1,01		3,25		4,09	
Risk	No		No		No	
Wss (N/m^2)	18,03	17,82	63,66	8,90	64,66	5,40

From these designs it is observed that the pressure drop for the Hot Fluid increase significantly, becoming close to the allowable pressure drop for this fluid, i.e., 0.47 and 0.49 bar for the case of 48 and 64 m^3/h, respectively. Having such close values, the design would not be carried out to comply with the heat transfer, it would be carried out to comply with the pressure drop. This can also be visualized in the ratio between the actual and required area, since values greater than 1.2 are achieved. Therefore, these designs would not be adequate.

The opposite occurs for the Cold Fluid since there is a drop in pressure drop from 0.13 bar in the case of 16 m^3/h with the *APV* plate to 0.07 and 0.04 bar for the other flow rates. This is due to the increase in the velocities in the port per equation 4.35. This parameter is influence by the total flow rate of fluid entering the exchanger and the area of passage through the port, in which it depends on the port diameter (Incroperaet al. , 2020).

So, when working with such a large port diameter, the passage area is increased, which implies that, although the flow rate of the hot fluid is increased, the velocity in the port is also increased because the section for the three cases is the same, i.e., there is an increase from 0.56

m/s to 1.67 and 2.23 m/s for 48 and 64 m^3/h respectively. Consequently, the pressure drop at the port is more than doubled to 0.014 and 0.026 bar.

However, for the Cold Fluid, the velocity at the port is maintained at 0.55 m/s in all three cases, with a slight increase in the pressure drop at the port for the 48 and 64 m^3/h cases due to the density used, i.e. a loss of 0.015 and 0.016 bar is determined, respectively.

Another important point in the comparison of the different flow rates is that, although a plate with the same dimensions has been used, the number of plates required has been increased (Alrwashdeh *et al.*, 2022). Then, the velocity between the plates would also be increased to 0.35 m/s and the space occupied by the exchanger would be larger.

Similarly, by means of the equations, when there is an increase in the velocity in the channel, the Reynolds would also be affected in the same way, going from a transient regime of 3000 to 6000, which would cause greater turbulence. As a result, a wall shear stress greater than 40 N/m^2 is determined in the hot fluid.

Nevertheless, although there is a large increase in the individual coefficient in the Hot Fluid, there is a decrease in the Cold Fluid. Therefore, the overall heat transfer coefficient is decreased by increasing the flow rate of the hot fluid.

Also, using the *Simulation* configuration in the *EDR*, it is estimated that the heat to be exchanged is much higher than what was thought in the Design, i.e., a transfer of 491 kW instead of 402 kW would be produced and a higher outlet temperature than expected, almost 95ºC would be obtained. This would occur because EDR seeks to comply with the pressure drop as discussed above (B. Sundénet al. , 2007).

Thus, an increase in the flow rate should consider that there would be a significant increase in both, the size of the heat exchanger and the head losses that occur in the exchanger, in addition to a decrease in the overall heat transfer coefficient.

If the same equipment were used, i.e., 18.4 m^2, but with a higher flow rate of Hot Fluid, there would be a lot of turbulence which would cause a poor heat transfer and higher pressure drops, even very close to the permitted limit, which would not be beneficial for the equipment.

5.3.2. Scenario 2: 75ºC of the Cold Fluid

- **Optimum plate selection of Scenario 2**

In the second case to be considered, the working conditions must be as shown in Table 5.9. The difference with the previous case is the inlet temperature of the cold fluid, in this case 75ºC since this temperature is the closest point to the place where the heat exchanger would be placed.

Table 5.9. Conditions of the second scenario to be treated.

	Hot side	**Cold side**
Flow rate (m^3/h)	16.24	16.00
Flow rate (kg/s)	4.37	4.32
Inlet temperature (°C)	95	75
Outlet temperature (°C)	73.01	90
Inlet pressure (bar)	2.86	1.00

From these conditions, as a base case, an area of 16.1 m^2 is obtained, being less than that was obtained in the previous case. Sixty-five plates are required with a pressure drop of 0.12 bar per stream. So, the same procedure as above is performed to optimize the required area of the heat exchanger without deliberately increasing the pressure drop.

In addition, by working with a heat of 268 kW, lower than in the previous case, much higher hot fluid outlet temperatures are achieved, up to 90.43ºC. This causes that, even though the same logarithmic mean temperature difference is achieved, having a similar overall heat transfer coefficient, the area is significantly reduced.

For these cases, a pressure drops of 0.5 and 0.4 bar has been established for the Hot and Cold Fluid, respectively. It is worth mentioning that all the plates considered use an angle of 30º, i.e. type H, which allows an efficient exchange, but a considerable pressure drop.

As done in the previous case, a total of 7 plates from manufacturers such as *Alfa Laval, J.C. Negre, APV* and *Tranter* are studied as shown in Table 5.10.

Table 5.10. Plates evaluated for the case of 75ºC.

	Base Case		**S-17**		**S- 37**		**S-31A**	
	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side
Q(m^3/h)	16,24	16	16,24	16	16,24	16	16,24	16
T_{in} (ºC)	95	75	95	75	95	75	95	75
T_{out} (ºC)	80,19	90	80,43	90	80,43	90	80,43	90
ΔP (bar)	0,115	0,113	0,399	0,394	0,374	0,370	0,395	0,390
ΔP_p (bar)	0,034	0,033	0,032	0,031	0,004	0,004	0,011	0,010
ΔP_c (bar)	0,082	0,081	0,367	0,363	0,369	0,365	0,384	0,379
m (m/s)	0,18	0,18	0,36	0,36	0,31	0,31	0,32	0,32
q (W)	272200		267909		267909		267909	
LMTD (ºC)	5,1		5,21		5,21		5,21	
U (W/m^2K)	3838,9		6296,3		5839,6		5904,5	
A(m^2)	16,1		9,8		14,8		14,6	
h (W/m^2K)	10466,3	10181,7	19264,7	18716,6	17232,2	en	17512,2	17015,2
Re	2966,7	2308,39	4031,66	3137,04	3481,9	2709,27	3556,52	2767,33
n	65		53		45		57	
A_p (m^2)	0,256		0,192		0,345		0,265	
Angle (º)	30		30		30		30	
ε (mm)	0,6		0,4		0,4		0,4	
V_p (m/s)	2,31	2,28	2,31	2,28	0,9	0,89	1,37	1,35
Nc	32	32	26	26	22	22	28	28
L (mm)	1023,63		927,5		1224,42		1119,82	
VPCD (mm)	966,6		800		1050		1050	
W (mm)	265		240		328,42		252,63	
HPCD (mm)	205		112,5		154		182,8	
D_p (mm)	50		50		80		65	
Cost (€)	3521		2488		3177		3229	
A/A_d	1,16		1,20		1,68		1,68	
Risk	No		No		No		No	
Wss (N/m^2)	23,04	22,75	45,87	45,32	65,23	34,81	36,60	36,17

Table 5.10. Plates evaluated for the case of 75ºC “(cont.)”

	S-19A		**ALFA LAVAL M6**		**TRANTER GC-16**		**APV SR6GL**	
	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side
Q(m^3/h)	16,243	16	16,243	16	16,243	16	16,243	16
T_{in} (ºC)	95	75	95	75	95	75	95	75
T_{out} (ºC)	80,43	90	80,43	90	80,43	90	80,43	90
ΔP (bar)	0,375	0,371	0,351	0,346	0,303	0,299	0,338	0,334
ΔP_p (bar)	0,010	0,010	0,015	0,014	0,022	0,022	0,001	0,001
ΔP_c (bar)	0,365	0,361	0,336	0,332	0,281	0,277	0,336	0,332
m (m/s)	0,39	0,39	0,38	0,38	0,34	0,33	0,29	0,29
q (W)	267909		267909		267909		267909	
LMTD (ºC)	5,21		5,21		5,21		5,21	
U (W/m^2K)	6525,2		6287,2		5950,3		5653,2	
A(m^2)	8		8,2		8,8		10,6	
h (W/m^2K)	20341,3	19761,8	19222,4	18676,2	18797,8	18264	18416,8	17889,7
Re	4329,68	3368,93	3893,44	3029,48	3343,05	2601,23	5663,02	4406,4
n	47		57		67		21	
A_p (m^2)	0,177		0,15		0,135		0,557	
Angle (º)	30		31		30		25	
ε (mm)	0,4		0,4		0,5		0,6	
V_p (m/s)	1,37	1,35	1,61	1,58	1,91	1,88	0,56	0,55
Nc	23	23	28	28	33	33	10	10
L (mm)	769,82		716		682		1369,06	
VPCD (mm)	700		640		592		1254,8	
W (mm)	252,63		216		225		427,99	
HPCD (mm)	182,8		140		135		313,7	
D_p (mm)	65		60		55		101,6	
Cost (€)	2166		2295		2462		2432	
A/A_d	1,01		1,01		1,02		1,16	
Risk	No		No		No		No	
Wss (N/m^2)	52,15	51,53	48,35	47,78	42,08	41,58	46,55	46,00

In this case, the plate to be highlighted is the *APV sr6gl*. In it, on the heat transfer side, a quite high overall heat transfer coefficient (U) is achieved, 5653.2 W/m^2K, thanks to obtaining individual coefficients close to 18000 W/m^2K. In other words, the overall coefficient is increased by almost 2000, compared to those obtained in the base case, 3838.9 W/m^2K. Thus, working with the same heat dissipated (268 kW) and a logarithmic mean temperature difference of 5.21ºC, the area is reduced to 10.6 m^2.

To obtain these coefficients, they are highly dependent on the velocity in the channel. This plate works with a channel velocity of 0.29 m/s, since the number of channels to be used in this exchange is 10, which is much lower than all the previous cases. This is due to the increase in the size of the plate to be used as can be seen in Figure 5.8, which works with a corrugation angle of 25º and a number of passes of 1.

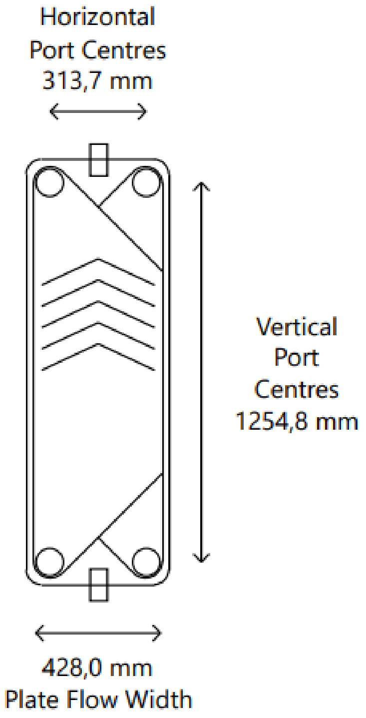

Figure 5.8. *Sr6gl APV* plate design for the second scenario (From *EDR*).

From a plate geometry of 428 x 1369 mm with a diameter of 101.6 mm, for an area of 10.6 m^2, the number of plates has been reduced to 21 compared to the 65 plates required in the base case. Therefore, by means of the equation 4.19., the velocity in the channel is reduced.

By working with the lower number of channels obtained compared to the other cases, i.e. 10 channels for the *APV* plate, a higher flow rate will pass through each channel. As a result, although a transition regime has been obtained in all the plates, with this plate, it is possible to reach a Reynolds close to 6000. Consequently, there is a significant increase in the individual coefficients and, by default, in the overall heat transfer coefficient.

Similarly, working with a DN 100, it is possible to reduce the velocity at the port to 0.56 m/s, much lower than that obtained with *Tranter and Alfa Laval* plates, 1.91 and 1.61 m/s, respectively. As a result, port pressure drops do not exceed 15% of the total, i.e., 0.001 bar compared to 0.33 bar for 15%. Therefore, there are no distribution problems.

Likewise, taking into account the channel pressure drop, which are always higher than those of the port, a total pressure drop of 0.34 bar is obtained with the *APV* plate, having a difference with the allowable pressure drop (0.5 and 0.4 bar).

This, for example, for the *J.C. Negre* plates does not occur since, as mentioned before, their obtained port velocities are high, which causes an increase in the port pressure drop. That is, while with the *APV* plate a port pressure drop of 0.001 bar is acquired, with the *S-17* plate a much higher value of 0.032 bar is determined.

Also, the *APV* plate has a Wall shear stress (Wss) of 46 N/m^2 due to the use of larger port diameter, which is above what is expected in a plate heat exchanger (40 N/m^2). Similarly, the actual area to required area ratio (A/A_d) is less than 1.2, which means that the design is being made to meet heat transfer and not to meet pressure drop.

Finally, comparing the required costs, thanks to the *APV* plate, the cost is reduced to 2432 € compared to 3521 € in the original case.

Then, with the *APV sr6gl* plate, although it does not achieve the highest heat transfer coefficients, it does allow a good heat transfer, obtaining 5653.2 W/m^{2}K (IWOFR. , 2021). In addition, since it works with smaller velocities due to the use of a larger geometry, acceptable pressure drop are acquired, around 0.34 bar, allowing a margin between the allowed and calculated pressure drop.

In conjunction, by performing a "*Simulation*" in the *EDR* with this plate, it is verified that the temperature achieved at the outlet of the exchanger by the fluid of interest, in this case, the Cold Fluid, is above 90ºC, almost reaching 91ºC.

Therefore, the plate to be used to work with a temperature difference of 75 ºC to 90ºC, is the *APV sr6gl* plate with which a heat exchanger of 10.6 m^2 is acquired.

- **Effect of an increase of the Cold Fluid flow rate on the design of the heat exchanger of scenario 2.**

Next, the effect on the heat exchanger with the selected *APV* plate is studied when the flow rate is increased. That is, when working with a flow rate of 48 or 64 m^3/h of the Hot Fluid while using the Cold Fluid with a flow rate of 16 m^3/h, several changes occur as can be seen in Table 5.11.

Table 5.11. Change of the Hot Fluid flow rate in the APV plate for the second scenario.

	APV SR6GL		**48 m^3/h**		**64 m^3/h**	
	Hot side	Cold side	Hot side	Cold side	Hot side	Cold side
Q(m^3/h)	16,24	16	48,73	16	64,79	16
T_{in} (ºC)	95	75	95	75	95	75
T_{out} (ºC)	80,43	90	90,13	90	91,34	90
ΔP (bar)	0,338	0,334	0,473	0,065	0,492	0,040
ΔP_p (bar)	0,001	0,001	0,014	0,001	0,026	0,002
ΔP_c (bar)	0,336	0,332	0,459	0,064	0,466	0,039
m (m/s)	0,29	0,29	0,35	0,12	0,35	0,09
q (W)	267909		267909		267909	
LMTD (ºC)	5,21		9,15		9,58	
U (W/m^{2}K)	5653,2		4464,9		4014,3	
A(m^2)	10,6		27,3		36,2	
h (W/m^{2}K)	18416,8	17889,7	21647	8989,3	21886,6	7303,5
Re	5663,02	4406,4	6760,92	1762,56	6824,64	1335,27
n	21		51		67	
A_p (m^2)	0,557		0,557		0,557	
Angle (º)	25		25		25	
ε (mm)	0,6		0,6		0,6	
V_p (m/s)	0,56	0,55	1,67	0,55	2,23	0,55
Nc	10	10	25	25	33	33
L (mm)	1369,06		1369,06		1369,06	
VPCD (mm)	1254,8		1254,8		1254,8	
W (mm)	427,99		427,99		427,99	
HPCD (mm)	313,7		313,7		313,7	
D_p (mm)	101,6		101,6		101,6	
Cost (€)	2432		5069		6471	
A/A_d	1,16		4,16		5,20	
Risk	No		No		No	
Wss (N/m^2)	46,55	46,00	63,54	8,84	64,56	5,36

Firstly, although the heat dissipated remains constant, 268 kW, the logarithmic mean temperature difference varies in each case. While with a flow rate of 16 m^3/h per stream a LMTD of 5.21ºC is found, with a higher flow rate, 9.15ºC is obtained. This difference is because, according to equation 4.8, as the outlet temperature of the Hot Fluid depends on the limiting fluid, in this case the Cold Fluid, with the same q, increasing the flow rate produces an increment in the outlet temperature (Sebastián Castiñeiras. , 2023). In this case of 48 m^3/h, an outlet temperature of 88.44ºC is achieved in the Hot Fluid.

This logarithmic average temperature difference causes the required area to be greater than in the case of *APV* with 16 m^3/h in which 10.6 m^2 are obtained compared to the 27.3 m^2 acquired in the latter case, when applying the 4.25 equation.

Likewise, the overall heat transfer coefficient (U) must be considered for this equation. This parameter is decreased with respect to the original *APV* case, 4464.9 W/m^{2}K versus 5653.2 W/m^{2}K. This is due to the individual heat transfer coefficients.

That is, since while for the Hot Fluid a value of de 21647 W/m^{2}K is obtained, for the Cold Fluid, there is a decrease compared to the original case, i.e., from 17889.7 W/m^{2}K to 8989.3 W/m^{2}K since the velocities in the channel are different for the two fluids, 0.35 and 0.12 m/s for the Hot and Cold Fluids, respectively. This difference causes this large difference between the individual coefficients and, therefore, in the overall coefficient.

Furthermore, there is a difference between the fluids because while the Hot Fluid works in a transition regime, around 7000, the Cold Fluid is in laminar regime, less than 2000, which affects the coefficients due to the difference in velocity.

Another point to consider in this difference in flow rates is that, although the same geometry as above is used, the number of plates required increases as the flow rate growth, having up to 67 plates for a flow rate of 64 m^3/h for the Hot Fluid.

Therefore, there is a variation of both, the velocities in the channel and in the port, obtaining calculated pressure drop by the fluid very close to the allowed values, as in the case of 64 m^3/h, where a loss of 0.49 bar is obtained for the Hot Fluid with an admissible pressure drop of 0.5 bar. For example, in the case of 48 m^3/h, the velocity at the Hot Fluid port is three times the Cold Fluid, i.e. 1.67 m/s and 0.55 m/s, which is not beneficial for the heat exchanger (I. Lipovic and S.N. Kazi , 2015).

Also, with this difference in velocities, it causes an increase in the pressure drop in the port compared to the original *APV* case, going from 0.001 bar to 0.014 bar at 48 m^3/h. But, although these losses increase as well as the flow rate, they do not exceed 15% of the total losses, for example, for 48 m^3/h, 15% of the total loss of the Hot Fluid is 0.071 bar, so there are no maldistribution problems.

Regarding the ratio between the actual and required area, for the two cases considered (48 and 64 m^3/h), the ratio is above 1.2, which gives preference to comply with pressure drop instead of heat transfer.

However, when performing a *Simulation* in the *EDR*, it is obtained that the fluid outlet temperatures would be above the temperatures achieved in the original case of *APV*, i.e., for 64 m^3/h, 90 and 95ºC would be obtained for the Hot and Cold Fluids, respectively and, the heat available would be higher than previously mentioned, reaching 363 kW.

Similarly, the Wall shear stress obtained is always higher for the Hot Fluid, giving values above 40 N/m^2 compared to values below 10 N/m^2 for the Cold Fluid, since it works with a lower flow rate.

Likewise, the price of the exchanger for these changes in flow rate would also have varied from 2432 € to 6471 € with the highest possible flow rate. Therefore, such an increase in flow rate would cause, in addition to an increase in the size of the exchanger due to the need for a greater number of plates, a decrease in the efficiency of the exchanger and it would work with pressure drop by the Hot Fluid very close to what is allowed, which would be dangerous.

Finally, the technical data sheets of the selected heat exchangers are shown in the Appendix 8.12 and 8.13.

5.4. <u>Investment</u>

Based on the evaluation of the different cases, an estimate is made of the cost of installing the heat exchanger at the Tarragona site for the second case.

For this purpose, the cost of the heat exchanger itself, labor, piping, etc., must be taken into account, as shown in Table 5.12.

Table 5.12. Cost of exchanger implementation.

Concept		Prices /€
Material	Heat exchanger	2432
	Pipelines	5100
	Te	600
	Reductions	400
	Control valve	300
	Temperature probe	274
	Safety alarm	300
	Pump	400
	Total	9806
Manpower		3000
TOTAL		12806

The pipes to be used in the heat exchanger are DN 100 stainless steel. But the pipes from the 366-reactor are 80 mm and the pipes that carry the cooling fluid are DN 50. Also, a return line must be installed to return to the cooling water to the cooling tower.

As mentioned above, 100 passages are assumed, i.e. 79 meters distance between the exchanger arrangement and the ETHOX plant in which the 366-reactor is located. As two lines are to be used, one outgoing and one return line, 170 meters of piping would be required for the cooling water line leaving the reactor (hot fluid), taking into account the relevant elbows.

For an AISI 316L DN 100 stainless steel pipe, this would be 30 € per meter. Therefore, for 170 meters, 5100 € would be necessary (Paratureforma. , 2023).

In the same line, fittings such as tees, elbows and reductions would be needed. In this case, a tee to divide the outgoing flow from the reactor to the cooling tower and to the exchanger, i.e., to allow only 16 m^3/h to pass to the second point (Inoxpres, 2023). For this purpose, a flow regulating valve would be installed so that, in addition to allowing this flow to pass, there would be an adequate temperature in the line to reach 95ºC in the exchanger (ikPresPCal. , 2024). Also, a temperature indicator would be installed to know the temperature circulating in the line.

It would also be necessary to use a pump to drive the Hot Fluid, i.e., cooling water, to the cooling tower, after the point where it has been extracted (Electrobombas Jávea. , 2023). Therefore, it would also be necessary to install another tee to join the water that has been previously let through plus the outflow fromm the exchanger.

With respect to the Cold Fluid, there are already lines close to the point where the exchanger is to be installed, so only 10 meters of piping would be necessary.

From the return line of the cold fluid, two tees are required to introduce the current into the exchanger and to join the outlet current of the exchanger with the outlet current of the tanks, before the tank pumps.

Also, a temperature indicator would be needed on this return line to know the operating temperature. Consequently, the final cost would be estimated at 9806 €.

On the other hand, labor must be taken into account, which represents 30% of the cost of the necessary material, i.e. about 3000 €. So, the investment to be made would be about 13000 €.

5.5. Economic feasibility

In order to know the profitability of this project, the profit that would be obtained by carrying out this installation is calculated. To do this, it is necessary to know the kilos of steams, both theoretical and real.

With respect to the theoretical kilograms of steam (Q_t), these can be found from the heat exchanged in the heat exchanger. For example, for the 75-90ºC case, 268 kW, i.e. 230438.52 kcal/h, is required. Knowing that the enthalpy of condensation at 1 bar is 525.79 kcal/kg steam, 438.27 kg steam/h are obtained.

Taking into account that 8000 h are worked in a year and that the selected reactor, in this case R-366, works 11% per year, it can be obtained the kilograms of steam per year that could be generated as shown in equation 5.4.

This 11% has been determined from the data obtained in 366-reactor at shown in section 5.1, taking into account that the 16 m^3/h can be obtained from, at least, a valve opening degree of 25%. In other words, even if a higher flow comes out of the reactor, only 16 m^3/h will reach the exchanger. Therefore, with a temperature of 95ºC, the reactor 366 can be operated up to 11% of time.

$$438.27\frac{kg}{h} * 8000\frac{h}{year} * 0.11 = 385677.6\, kg\frac{steam}{year} \tag{5.4}$$

Knowing that the price of steam is 90 €/ton, 34711 €/year are obtained using 366-reactor.

On the other hand, in order to know the actual kilograms of steam (Q_R), the condensate measurement has been carried out, obtaining 35.11 kg steam/h. So, the cost implied by these tons of steam is 25280 €/year as reflected in equation 5.5.

$$\begin{gathered} 35.11\frac{kg}{h} * 8000\frac{h}{year} = 280880\, kg\frac{steam}{year} \\ 280.88\, \frac{t_{steam}}{year} * \frac{90€}{t} = 25280\frac{€}{year} \end{gathered} \tag{5.5}$$

Consequently, the Benefit to be obtained is 9431 €/year. In other words, thanks to the heat exchanger, the steam requirements in the hot water tanks would be covered. In addition, a yield of 8% would be obtained using equation 5.6.

$$\text{ꞑ}(\%) = \frac{Q_R}{Q_t} * 100 \tag{5.6}$$

$$\text{ꞑ}(\%) = \frac{35.11 \frac{kg_{steam}}{h}}{438.27 \frac{kg_{steam}}{h}} * 100 \rightarrow \text{ꞑ} = 8\%$$

In reference to the depreciation of the equipment, this can be calculated from the previously calculated investment (P), the depreciation time (t) and the residual value of the equipment (R) as shown in equation 5.7. The residual value is estimated at approximately 10% of the investment, therefore:

$$F = \frac{P - R}{t}$$

$$F = \frac{12806 - 0.1 * 12806}{10} = 1153\ €/year \tag{5.7}$$

In addition, the payback time of the investment made is analyzed through the 5.8 equation.

$$t_R = \frac{P}{B}$$

$$t_R = \frac{12806}{9431} \rightarrow t_R = 1.36\ years \tag{5.8}$$

This result implies that in less than two years, the company would recover the disbursement made in the implementation of the project.

Other criteria for the economic viability of a project are also analyzed, such as the *Internal Rate of Return (IRR)* and the *Net Present Value (NPV)* (Mete, 2014). The *NPV* is an indicator that represents the direct viability of a project and to calculate it, it is necessary to apply equation 5.9.

$$VAN = -P + Q * \frac{1 - \frac{1}{(1+k)^n}}{k} \tag{5.9}$$

Knowing the investment (P), the cash flow (Q), the interest (k) and the payback period (n), an *NPV* of 63687.86 € is obtained. This value was estimated considering an interest rate of 4% (PWC, 2023).

$$VAN = -12806 + 9431 * \frac{1 - \frac{1}{(1+0.04)^{10}}}{0.04}$$

Regarding the *IRR*, this parameter refers to the interest rate that causes the Net Present Value to be zero, i.e., according to the above equation, the NPV is zero. For this, applying the equation 5.10, it can be obtained an *IRR* of 73%.

$$0 = -P + Q * \frac{1 - \frac{1}{(1+TIR)^{n}}}{TIR} \tag{5.10}$$

Taking into account the results acquired by applying the economic data indicated, this investment would be accepted since both, the *NPV* and *IRR*, are positive and, in the specific case of the *IRR*, it is greater than the cost of money (J. Pasqual, 2007).

On the other hand, seeing that the steam measurement is not correct since the condensates are being measured instead of the steam, a contingency plan is proposed in which it is required to stop the part of the plant that requires the use of steam in order to install a steam meter and thus, be able to verify the steam consumption in the hot water tanks.

It should be considered that if the plant is shut down, the isocontainers will solidify, the heat insulation must be removed from the pipes, painted and the meter installed. In addition, it should be connected to the central panel of the tanks to have a record of the values obtained. Also, tests should be carried out and, when everything is ready, the isocontainers should be left to de-solidify. This operation may take more than a week, but the steam consumption of the tanks, which could be the highest steam consumption of the entire plant, could be truly known.

6. CONCLUSIONS

Throughout the work, a series of conclusions have been obtained, which are summarized below:

Among the reactors discussed, the 366-reactor stands out since it is the reactor that operates for the longest period of time, up to 11%, and manages to work with the desired temperature range, higher than 95ºC up to 27%.

Regarding the selection of the ideal location, it is established that the ideal location for the installation of the plate heat exchanger is the third one, since it works in the limiting current with the highest possible flow, 16 m^3/h.

According to the analysis of the heat exchanger, working with an inlet temperature of the cold fluid of 67.73ºC, the most suitable plate would be the *APV sr6gl.* With this plate, an area of almost 19 m^2 is acquired, allowing to obtain a cold fluid outlet temperature of 90ºC.

In the case of working with 75ºC as initial temperature, a heat exchanger with the APV sr6gl plate is necessary but a smaller area is needed, 10.6 m^2 in this case. Such heat exchangers would be between 2000 and 3000 €.

Therefore, the investment required for the installation of the heat exchanger would be about 13000 €.

Thanks to this, a profit of almost 10000 € per year and a yield of 8% could be achieved. This means, thanks to the use of the heat exchanger, the steam requirements of the tanks would be covered.

So, taking into account other economic viability criteria, thanks to the positive values of both, the Internal Rate of Return and the Net Present Value, the investment would be acceptable.

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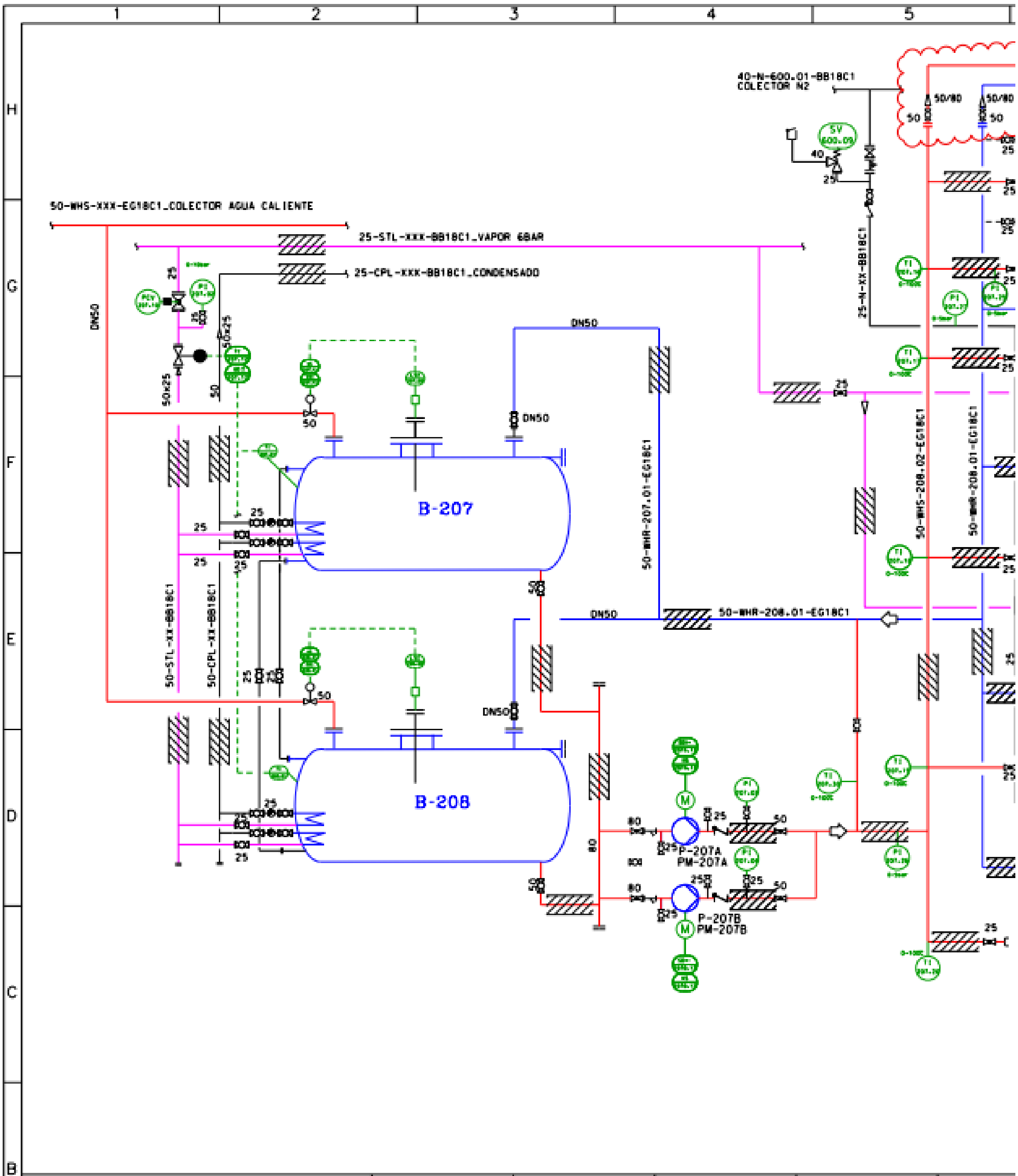
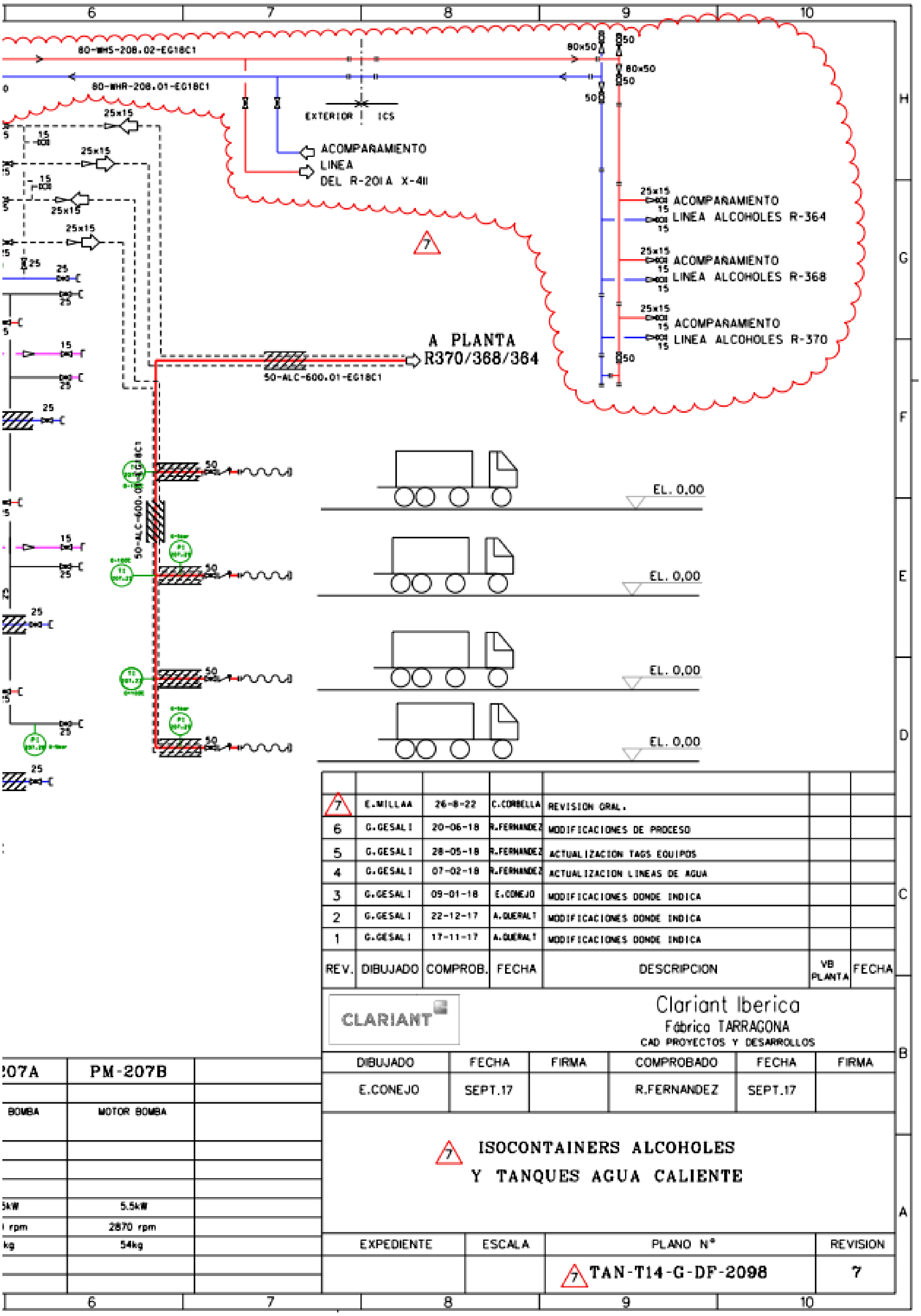
8. APPENDIX

8.1. Plan of alcohol isocontainers and hot water tanks



			B-207	B-208	P-207A	P-207B	PM-2
SIMBOLO DEL APARATO			B-207	B-208	P-207A	P-207B	PM-2
DENOMINACION			DEPOSITO INTERMEDIO	DEPOSITO INTERMEDIO	BOMBA	BOMBA	MOTOR
PRESION DISEÑO (BAR)	I	E	ATM.	ATM.			
TEMPERATURA DISEÑO (°C)	I	E					
MATERIAL			ALUMINIO	ALUMINIO			
DATOS TECNICOS	1		Ø 2000 × 2000	Ø 2000 × 2000	30m^3/h	30m^3/h	5.5
	2						2870
	3						54
	4						
	5						


6
7
8
9
10
80-WHS-208.02-EG18C1
80-WHR-208.01-EG18C1
80x50
50
80x50
50
50
EXTERIOR
ICS
25x15
15
25x15
15
25x15
25x15
25
25
ACOMPAÑAMIENTO
LINEA
DEL R-201 A X-411
25x15
15
ACOMPAÑAMIENTO
LINEA ALCOHOLES R-364
15
25x15
15
ACOMPAÑAMIENTO
LINEA ALCOHOLES R-368
15
25x15
15
ACOMPAÑAMIENTO
LINEA ALCOHOLES R-370
15
50
7
A PLANTA
R370/368/364
50-ALC-600.01-EG18C1
50-ALC-600.01-EG18C1
50
50
50
50
EL. 0,00
EL. 0,00
EL. 0,00
EL. 0,00
H
G
F
E
D
C
B
A
7
E.MILLAA
26-8-22
C.CORBELLA
REVISION GRAL.
6
G.GESALI
20-06-18
R.FERNANDEZ
MODIFICACIONES DE PROCESO
5
G.GESALI
28-05-18
R.FERNANDEZ
ACTUALIZACION TAGS EQUIPOS
4
G.GESALI
07-02-18
R.FERNANDEZ
ACTUALIZACION LINEAS DE AGUA
3
G.GESALI
09-01-18
E.CONEJO
MODIFICACIONES DONDE INDICA
2
G.GESALI
22-12-17
A.QUERALT
MODIFICACIONES DONDE INDICA
1
G.GESALI
17-11-17
A.QUERALT
MODIFICACIONES DONDE INDICA
REV.
DIBUJADO
COMPROB.
FECHA
DESCRIPCION
VB PLANTA
FECHA
CLARIANT
Clariant Iberica
Fábrica TARRAGONA
CAD PROYECTOS Y DESARROLLOS
DIBUJADO
FECHA
FIRMA
COMPROBADO
FECHA
FIRMA
E.CONEJO
SEPT.17
R.FERNANDEZ
SEPT.17
207A
PM-207B
BOMBA
MOTOR BOMBA
5kW
5.5kW
rpm
2870 rpm
kg
54kg
7
ISOCONTAINERS ALCOHOLES
Y TANQUES AGUA CALIENTE
EXPEDIENTE
ESCALA
PLANO Nº
REVISION
7
TAN-T14-G-DF-2098
7

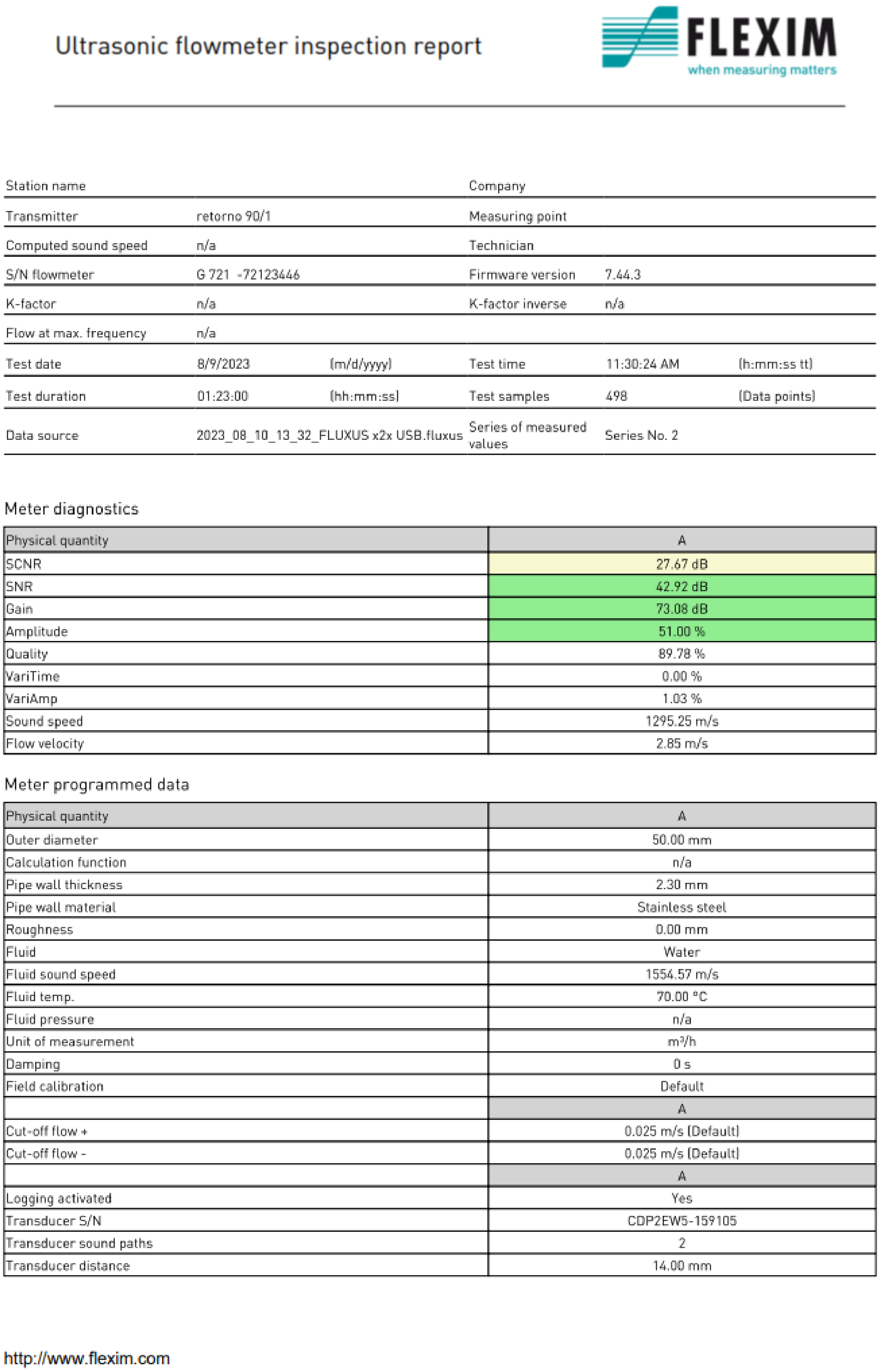
8.2. TAGs list

REACTORES OXI			
TAG	**REACTOR**	**DESCRIPTION**	**CODE**
UV-200-42	R-200	UV-200-42 Salida agua refrigeración R-200	UV-200-42
TIC 200-01	R-200	TIC-200-01 Temperatura serpentín interior R-2	TIC-200-01
HY 200-01	R-200	TIC-200-01 Temperatura serpentín interior R-2	TIC-200-01
TIC 200-05	R-200	TIC-200-05 Temperatura interior R-200	TIC-200-05
UV-201-42	R-201	UV-201-42 Salida agua refrigeración reactor R-201	UV-201-42
TIC-201-01	R-201	TIC-201-01 Temperatura serpentín interior R-2	TIC-201-01X
HY 201-01	R-201	TIC-201-01 Apertura serpentín interior R-2	TIC-201-01Y
TIC 201-05/PID1/PV.CV	R-201	TIC-201-05 Temperatura interior R-201	TIC-201-05
UV-202-42	R-202	UV-202-42 Salida agua refrigeración reactor R-202	UV-202-42
TIC-202-01	R-202	TIC-202-01 Temperatura serpentín interior R-2	TIC-202-01X
HY 202-01	R-202	TIC-202-01 Apertura serpentín interior R-2	TIC-202-01Y
TIC 202-05	R-202	TIC-202-05 Temperatura interior R-202	TIC-202-05
UV-203-42	R-203	UV-203-42 Salida agua refrigeración reactor R-203	UV-203-42
TIC 203-01	R-203	TIC-203-01 Temperatura serpentín interior R-2	TIC-203-01X
TIC 203-05	R-203	TIC-203-05 Temperatura interior R-203	TIC-203-05
HY 203-01	R-203	TIC-203-01 Apertura serpentín interior R-2	TIC-203-01Y
UV-204-42	R-204	UV- 204-42 Entrada agua refrigeración R-204	UV- 204-42
TIC-204-01	R-204	TIC-204-01 Temperatura serpentín interior R-2	TIC-204-01X
TI 204-05	R-204	TI-204-05 Temperatura fondo Reactor R-204	TI-204-05
HY 204-01	R-204	TIC-204-01 Apertura serpentín interior R-2	TIC-204-01.Control.Y
FIC 204-08	R-204	FIC-204-08 Caudal serpentín interior	FIC-204-08.Control.X
UV-350-42	R-350	UV-350-42 Entrada agua serpentín interior R-350	UV-350-42.BValve.FC
TIC-350-41	R-350	TIC-350-41 Temperatura salida agua refrigeración serpentín interior	TIC-350-41.Control.X
HY-350-41	R-350	TIC-350-41 Apertura salida agua refrigeración serpentín interior	TIC-350-41.Control.Y
TIC-350-53	R-350	TIC-350-53 Temperatura salida agua refrigeración serpentín interior	TIC-350-53.Control.X
HY-350-43	R-350	TIC-350-53 Apertura salida agua refrigeración serpentín interior	TIC-350-53.Control.Y
UV-350-30	R-350	UV-350-30 Entrada agua refrigeración serpentín exterior R-350	UV-350-30.BValve.FC
HY-350-33	R-350	HY-350-33 Salida agua refrigeración R-350	HY-350-33.BValve.FC
TIC-350-01	R-350	TIC-350-01 Lazo maestro temperatura interior	TIC-350-01.Control.X
UV-350-45	R-350	UV-350-45 Recirculación bomba aceleración	UV-350-45.BValve.FC

TAG	REACTOR	DESCRIPTION	CODE
UV-366-42	R-366	UV-366-42 Entrada agua refrigeración R-366	UV-366-42.BValve.FC
UV-366-30	R-366	UV-366-30 Entrada Agua refrigeración serpentín exterior R-366	UV-366-30.BValve.FC
TIC-366-53	R-366	TIC-366-53 Temperatura salida agua refrigeración interior	TIC-366-53.Control.X
HY-366-43	R-366	TIC-366-53 Apertura salida agua refrigeración interior	TIC-366-53.Control.Y
TIC-366-54	R-366	TIC-366-54 Temperatura salida agua refrigeración interior	TIC-366-54.Control.X
HY-366-46	R-366	TIC-366-54 Apertura salida agua refrigeración interior	TIC-366-54.Control.Y
HY-366-33	R-366	UV-366-33 Salida agua refrigeración	HY-350-33.BValve.FC
TIC-366-01	R-366	TIC-366-01 Temperatura Interior R-366	TIC-366-01.Control.X
UV-550-42	R-550	UV-550-42 Entrada agua refrigeración interior R-550	UV-550-42
UV-550-33	R-550	UV-550-33 Entrada agua refrigeración serpentín exterior R-550	UV-550-33
UV-550-41	R-550	UV-550-41 Entrada agua serpentín interior R-550	UV-550-41
UV-550-40	R-550	UV-550-40 Entrada agua serpentín interior R-550	UV-550-40
TIC-550-53	R-550	TIC-550-53 Temperatura salida agua refrigeración serpentín interior	TIC-550-53
TIC-550-53	R-550	TIC-550-53 Apertura salida agua refrigeración serpentín interior	TIC-550-53
TIC-550-54	R-550	TIC-550-54 Temperatura salida agua refrigeración serpentín interior	TIC-550-54
TIC-550-54	R-550	TIC-550-54 Apertura salida agua refrigeración serpentín interior	TIC-550-54
HY-550-30	R-550	HY-550-30 Salida agua refrigeración R-550	HY-550-30
TIC 550-01	R-550	TIC-550-01 PID Control module master	TIC-550-01

8.3. Report obtained from the Lana Sarrate flowmeter

8.3.1. Hot water return line from the two plants (point 1)



Ultrasonic flowmeter inspection report

Station name			Company		
Transmitter	retorno 90/1		Measuring point		
Computed sound speed	n/a		Technician		
S/N flowmeter	G 721 -72123446		Firmware version	7.44.3	
K-factor	n/a		K-factor inverse	n/a	
Flow at max. frequency	n/a				
Test date	8/9/2023	(m/d/yyyy)	Test time	11:30:24 AM	(h:mm:ss tt)
Test duration	01:23:00	(hh:mm:ss)	Test samples	498	(Data points)
Data source	2023_08_10_13_32_FLUXUS x2x USB.fluxus		Series of measured values	Series No. 2	

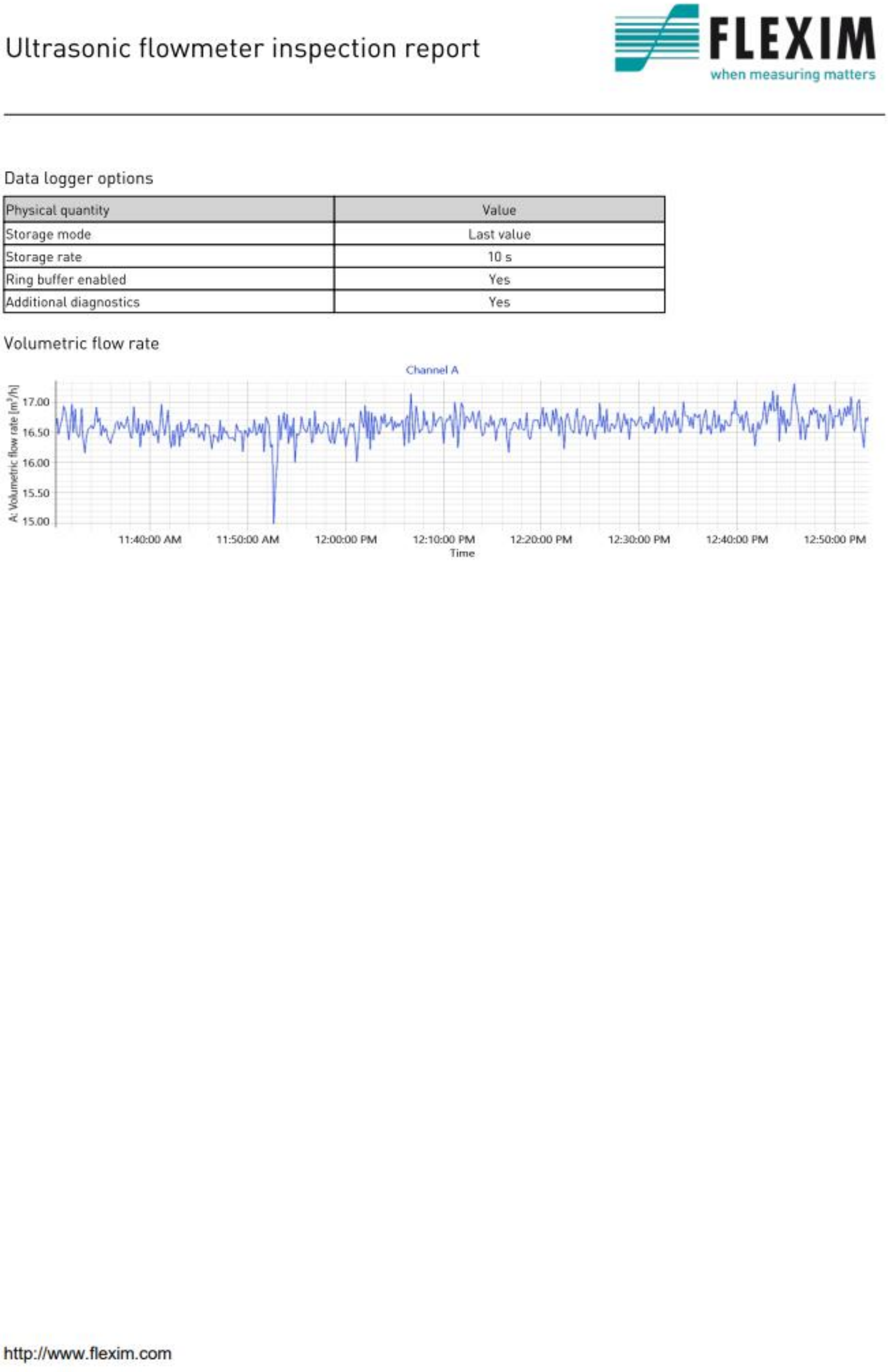
Meter diagnostics

Physical quantity	A
SCNR	27.67 dB
SNR	42.92 dB
Gain	73.08 dB
Amplitude	51.00 %
Quality	89.78 %
VariTime	0.00 %
VariAmp	1.03 %
Sound speed	1295.25 m/s
Flow velocity	2.85 m/s

Meter programmed data

Physical quantity	A
Outer diameter	50.00 mm
Calculation function	n/a
Pipe wall thickness	2.30 mm
Pipe wall material	Stainless steel
Roughness	0.00 mm
Fluid	Water
Fluid sound speed	1554.57 m/s
Fluid temp.	70.00 °C
Fluid pressure	n/a
Unit of measurement	m³/h
Damping	0 s
Field calibration	Default
	A
Cut-off flow +	0.025 m/s (Default)
Cut-off flow -	0.025 m/s (Default)
	A
Logging activated	Yes
Transducer S/N	CDP2EW5-159105
Transducer sound paths	2
Transducer distance	14.00 mm

http://www.flexim.com



Ultrasonic flowmeter inspection report

FLEXIM
when measuring matters

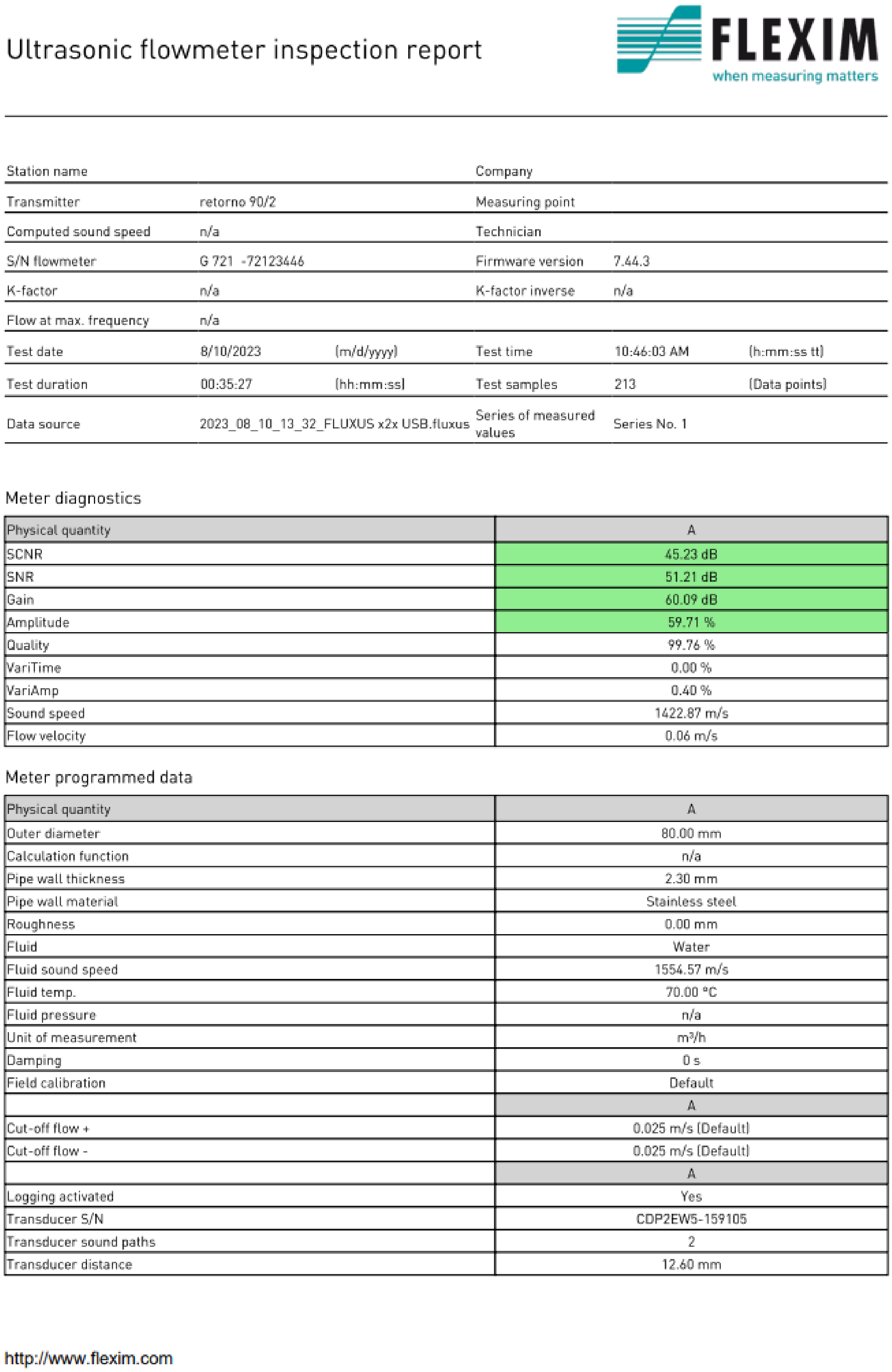
Data logger options

Physical quantity	Value
Storage mode	Last value
Storage rate	10 s
Ring buffer enabled	Yes
Additional diagnostics	Yes

Volumetric flow rate

http://www.flexim.com

8.3.2. Hot water return line from the ETHOX plant (point 2)



Ultrasonic flowmeter inspection report

FLEXIM
when measuring matters

Station name			Company		
Transmitter	retorno 90/2		Measuring point		
Computed sound speed	n/a		Technician		
S/N flowmeter	G 721 -72123446		Firmware version	7.44.3	
K-factor	n/a		K-factor inverse	n/a	
Flow at max. frequency	n/a				
Test date	8/10/2023	(m/d/yyyy)	Test time	10:46:03 AM	(h:mm:ss tt)
Test duration	00:35:27	(hh:mm:ss)	Test samples	213	(Data points)
Data source	2023_08_10_13_32_FLUXUS x2x USB.fluxus		Series of measured values	Series No. 1	

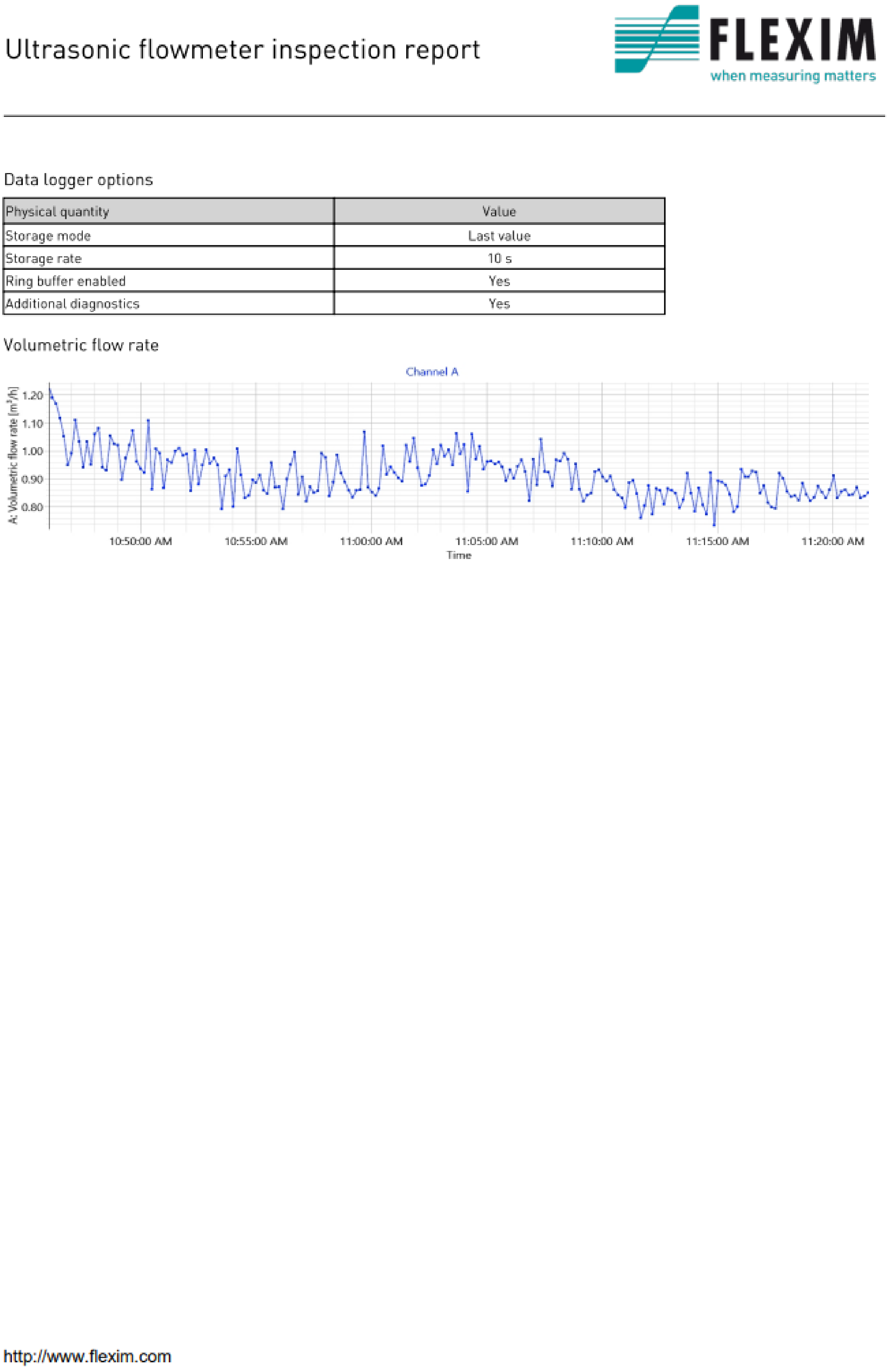
Meter diagnostics

Physical quantity	A
SCNR	45.23 dB
SNR	51.21 dB
Gain	60.09 dB
Amplitude	59.71 %
Quality	99.76 %
VariTime	0.00 %
VariAmp	0.40 %
Sound speed	1422.87 m/s
Flow velocity	0.06 m/s

Meter programmed data

Physical quantity	A
Outer diameter	80.00 mm
Calculation function	n/a
Pipe wall thickness	2.30 mm
Pipe wall material	Stainless steel
Roughness	0.00 mm
Fluid	Water
Fluid sound speed	1554.57 m/s
Fluid temp.	70.00 °C
Fluid pressure	n/a
Unit of measurement	m³/h
Damping	0 s
Field calibration	Default
	A
Cut-off flow +	0.025 m/s (Default)
Cut-off flow -	0.025 m/s (Default)
	A
Logging activated	Yes
Transducer S/N	CDP2EW5-159105
Transducer sound paths	2
Transducer distance	12.60 mm

http://www.flexim.com



Ultrasonic flowmeter inspection report

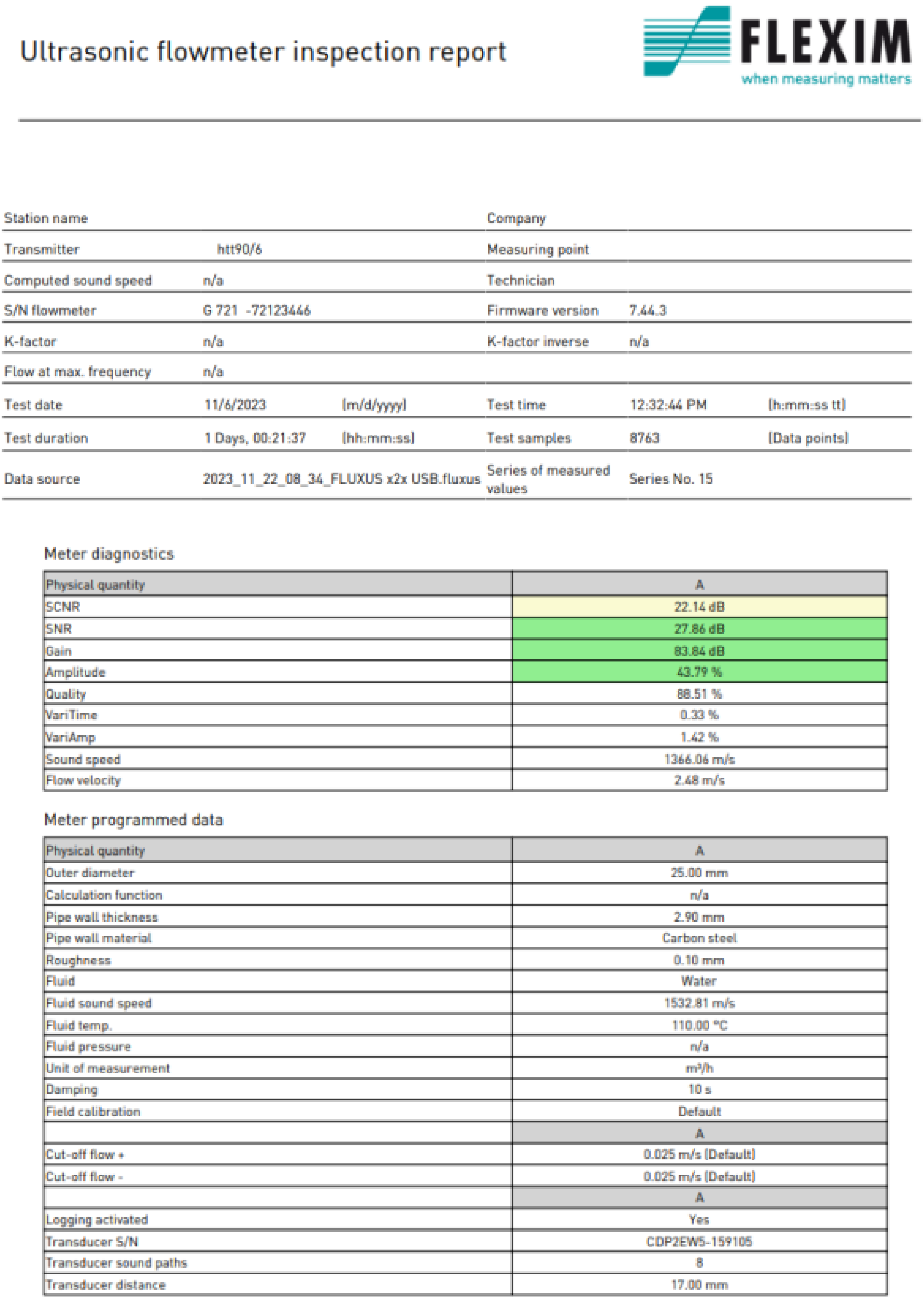
Data logger options

Physical quantity	Value
Storage mode	Last value
Storage rate	10 s
Ring buffer enabled	Yes
Additional diagnostics	Yes

Volumetric flow rate

http://www.flexim.com

8.3.3. Hot water return line from HTMPP plant (point 3)



Ultrasonic flowmeter inspection report

FLEXIM
when measuring matters

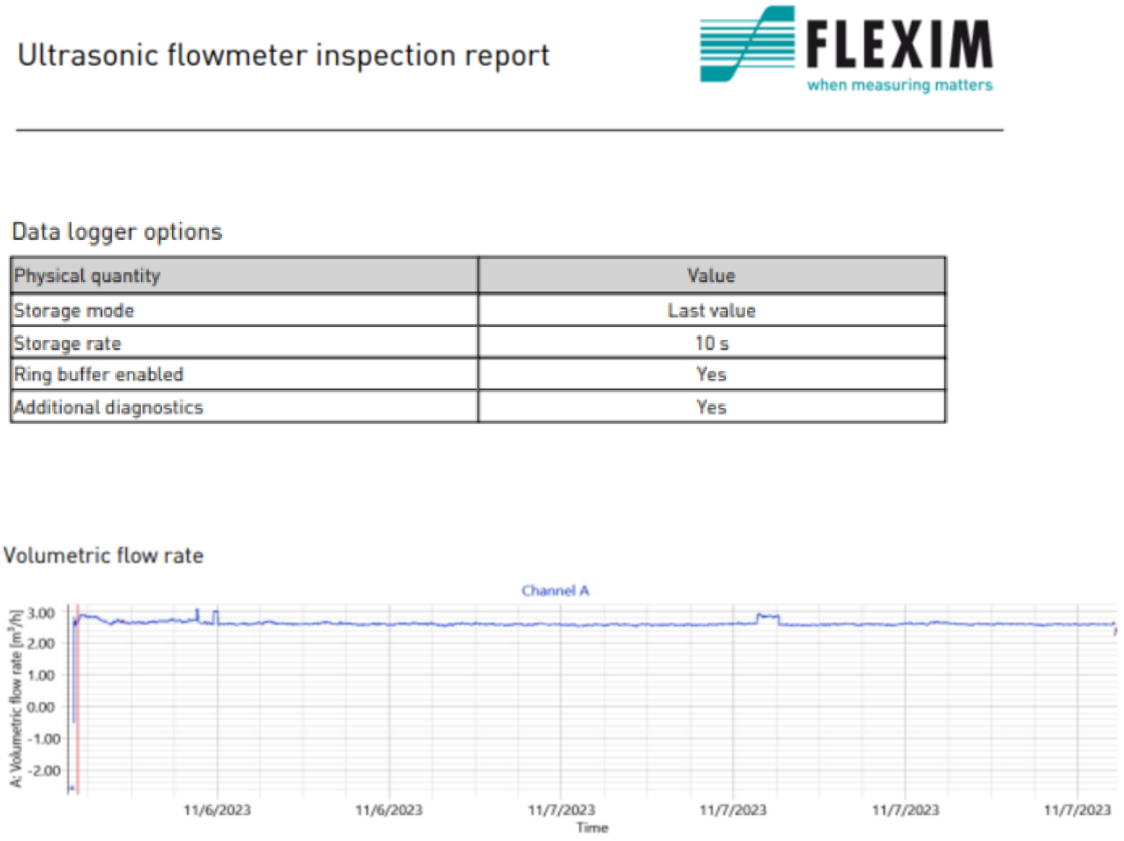
Station name			Company		
Transmitter	htt90/6		Measuring point		
Computed sound speed	n/a		Technician		
S/N flowmeter	G 721 -72123446		Firmware version	7.44.3	
K-factor	n/a		K-factor inverse	n/a	
Flow at max. frequency	n/a				
Test date	11/6/2023	[m/d/yyyy]	Test time	12:32:44 PM	[h:mm:ss tt]
Test duration	1 Days, 00:21:37	[hh:mm:ss]	Test samples	8763	[Data points]
Data source	2023_11_22_08_34_FLUXUS x2x USB.fluxus		Series of measured values	Series No. 15	

Meter diagnostics

Physical quantity	A
SCNR	22.14 dB
SNR	27.86 dB
Gain	83.84 dB
Amplitude	43.79 %
Quality	88.51 %
VariTime	0.33 %
VariAmp	1.42 %
Sound speed	1366.06 m/s
Flow velocity	2.48 m/s

Meter programmed data

Physical quantity	A
Outer diameter	25.00 mm
Calculation function	n/a
Pipe wall thickness	2.90 mm
Pipe wall material	Carbon steel
Roughness	0.10 mm
Fluid	Water
Fluid sound speed	1532.81 m/s
Fluid temp.	110.00 °C
Fluid pressure	n/a
Unit of measurement	m^3/h
Damping	10 s
Field calibration	Default
	A
Cut-off flow +	0.025 m/s (Default)
Cut-off flow -	0.025 m/s (Default)
	A
Logging activated	Yes
Transducer S/N	CDP2EW5-159105
Transducer sound paths	8
Transducer distance	17.00 mm



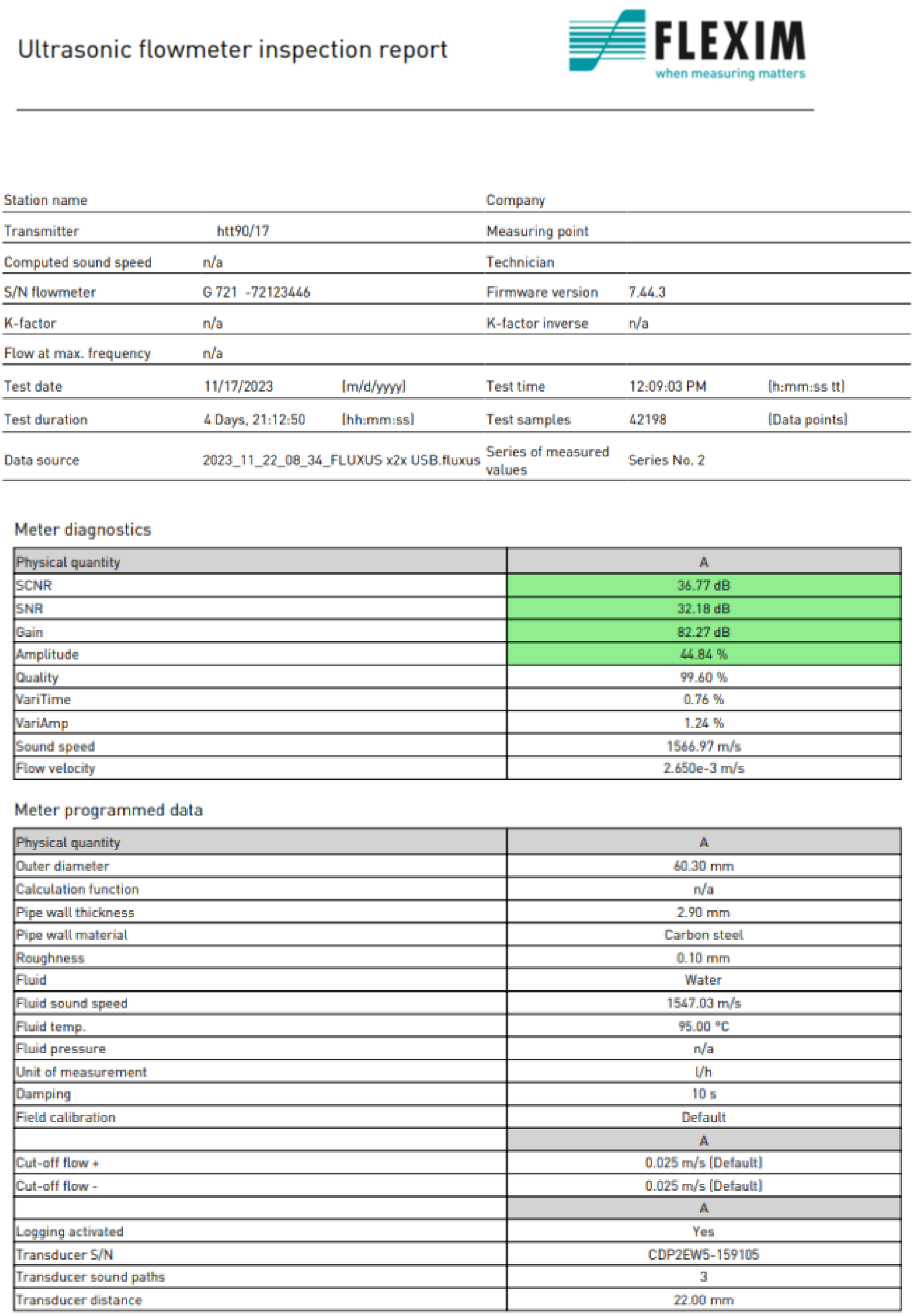
Ultrasonic flowmeter inspection report

Data logger options

Physical quantity	Value
Storage mode	Last value
Storage rate	10 s
Ring buffer enabled	Yes
Additional diagnostics	Yes

Volumetric flow rate

8.3.4. Steam line (point 4)



Ultrasonic flowmeter inspection report

FLEXIM
when measuring matters

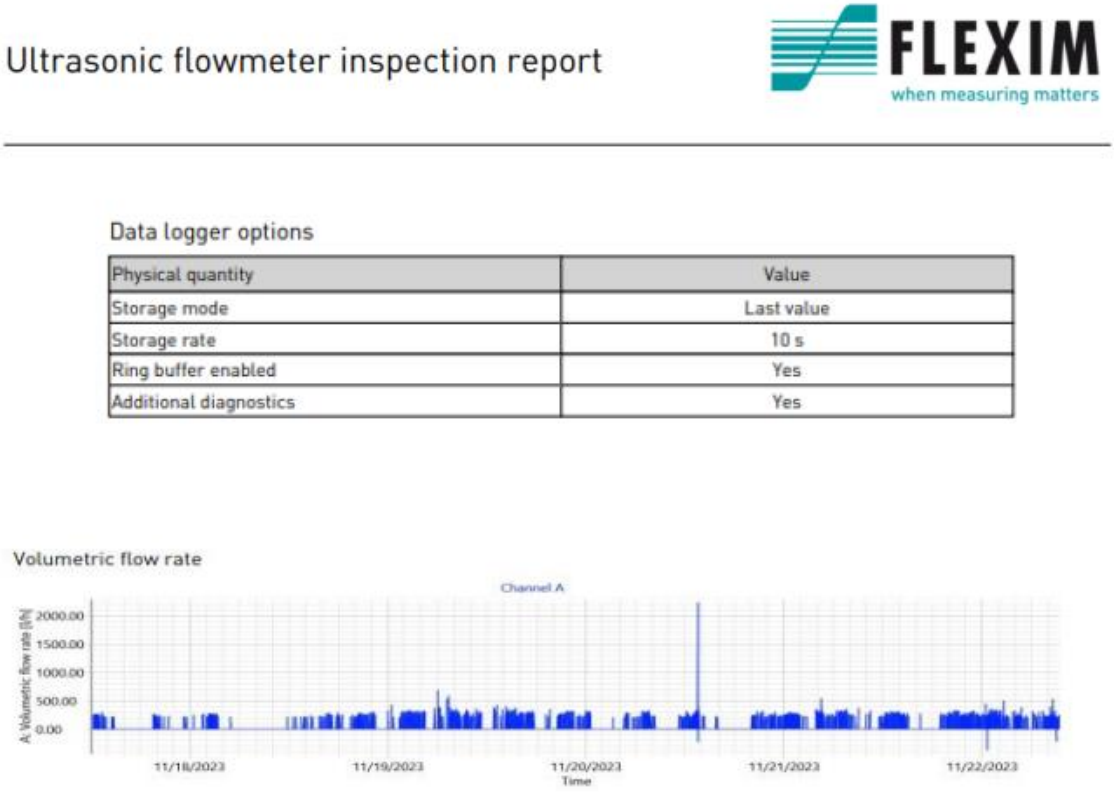
Station name			Company		
Transmitter	htt90/17		Measuring point		
Computed sound speed	n/a		Technician		
S/N flowmeter	G 721 -72123446		Firmware version	7.44.3	
K-factor	n/a		K-factor inverse	n/a	
Flow at max. frequency	n/a				
Test date	11/17/2023	[m/d/yyyy]	Test time	12:09:03 PM	[h:mm:ss tt]
Test duration	4 Days, 21:12:50	[hh:mm:ss]	Test samples	42198	[Data points]
Data source	2023_11_22_08_34_FLUXUS x2x USB.fluxus		Series of measured values	Series No. 2	

Meter diagnostics

Physical quantity	A
SCNR	36.77 dB
SNR	32.18 dB
Gain	82.27 dB
Amplitude	44.84 %
Quality	99.60 %
VariTime	0.76 %
VariAmp	1.24 %
Sound speed	1566.97 m/s
Flow velocity	2.650e-3 m/s

Meter programmed data

Physical quantity	A
Outer diameter	60.30 mm
Calculation function	n/a
Pipe wall thickness	2.90 mm
Pipe wall material	Carbon steel
Roughness	0.10 mm
Fluid	Water
Fluid sound speed	1547.03 m/s
Fluid temp.	95.00 °C
Fluid pressure	n/a
Unit of measurement	l/h
Damping	10 s
Field calibration	Default
	A
Cut-off flow +	0.025 m/s (Default)
Cut-off flow -	0.025 m/s (Default)
	A
Logging activated	Yes
Transducer S/N	CDP2EW5-159105
Transducer sound paths	3
Transducer distance	22.00 mm



Ultrasonic flowmeter inspection report

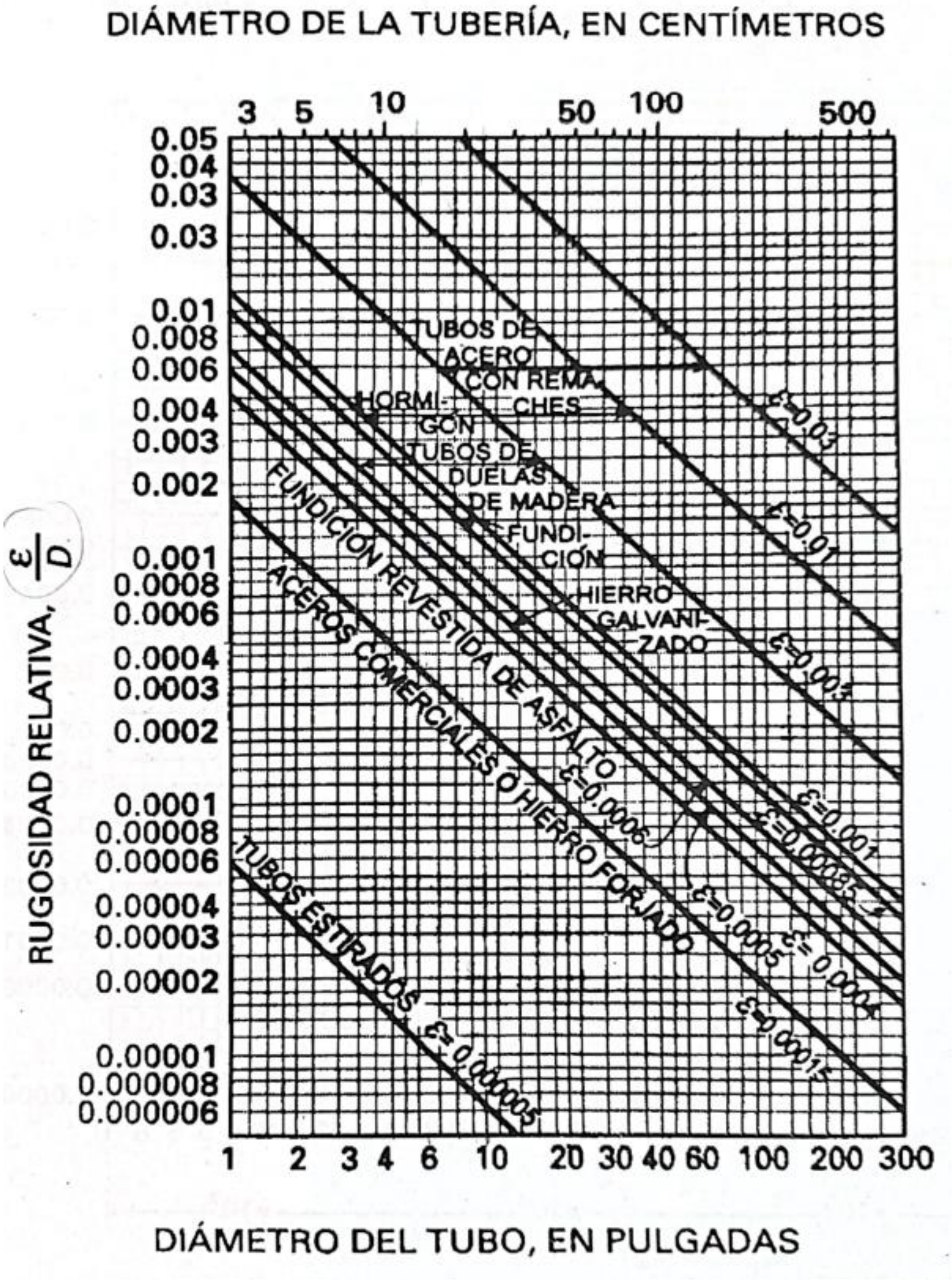
FLEXIM
when measuring matters

Data logger options

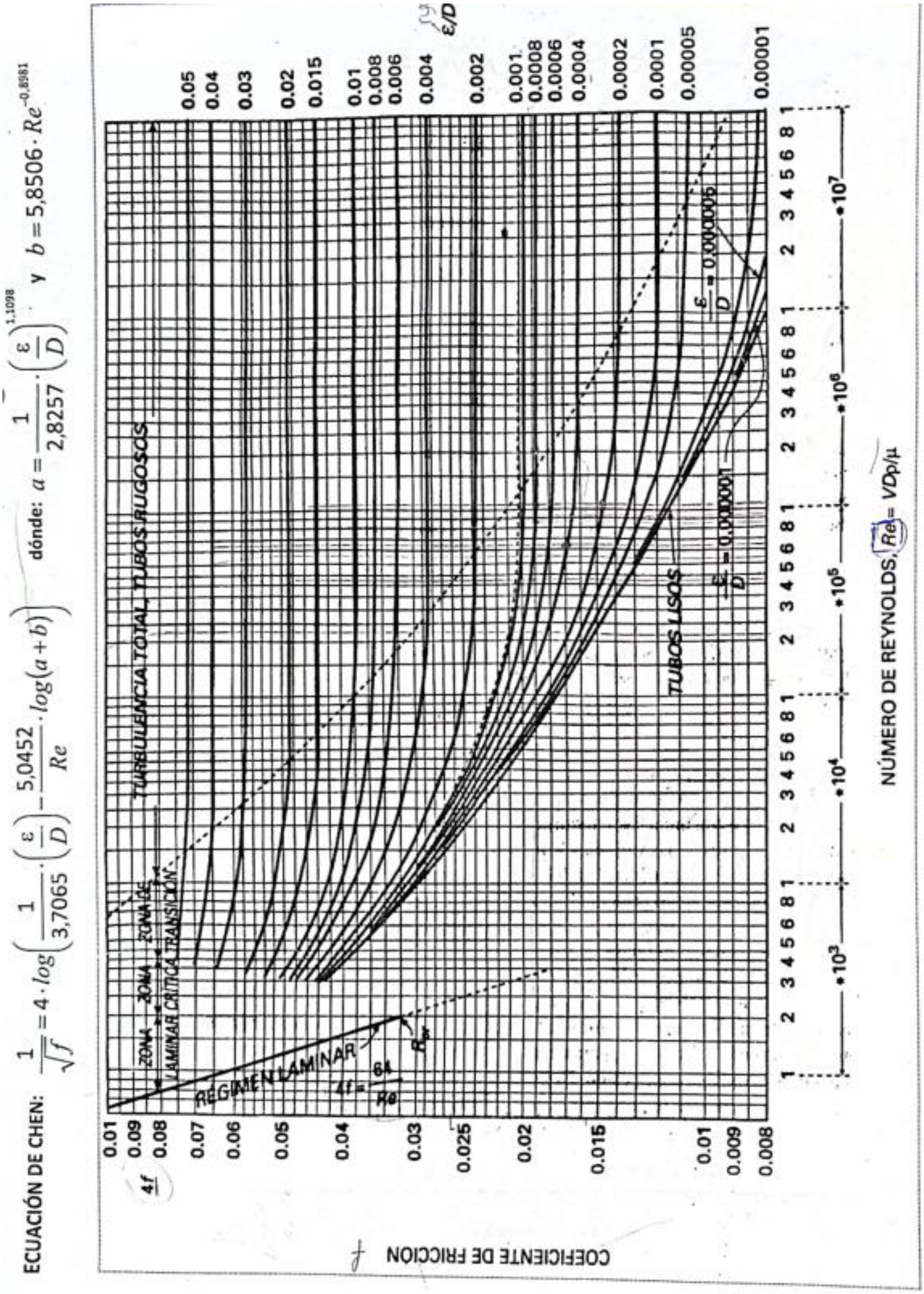
Physical quantity	Value
Storage mode	Last value
Storage rate	10 s
Ring buffer enabled	Yes
Additional diagnostics	Yes

Volumetric flow rate

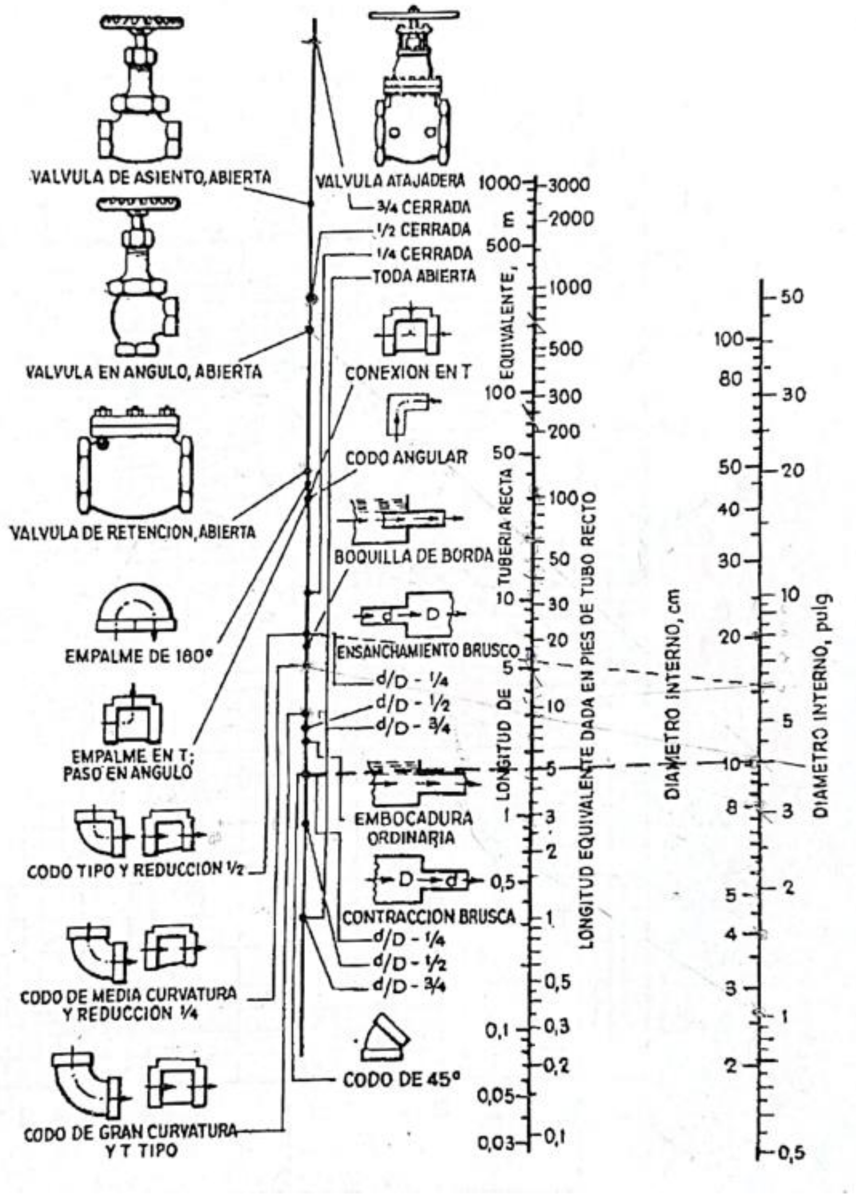
8.4. Diameter and relative roughness diagram



8.5. Moody’s diagram

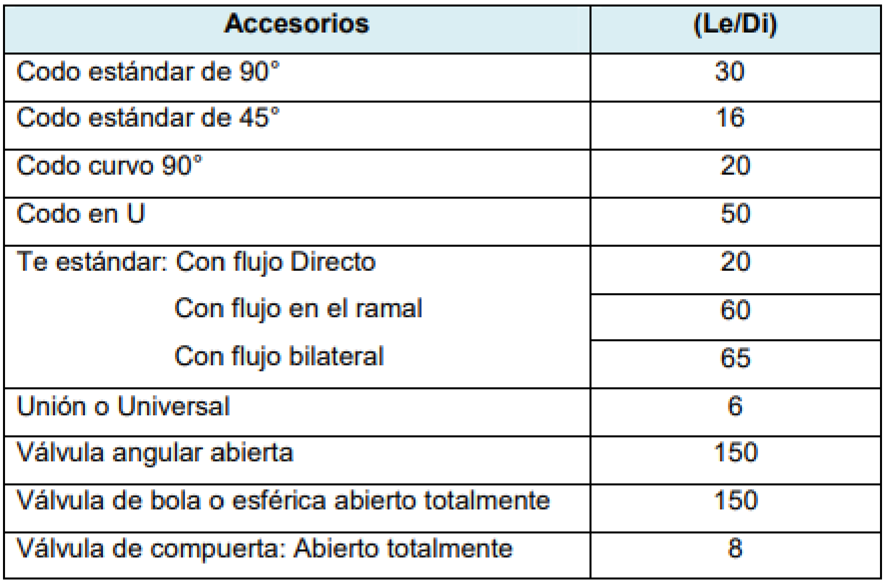


8.6. Equivalent length diagram for accidents

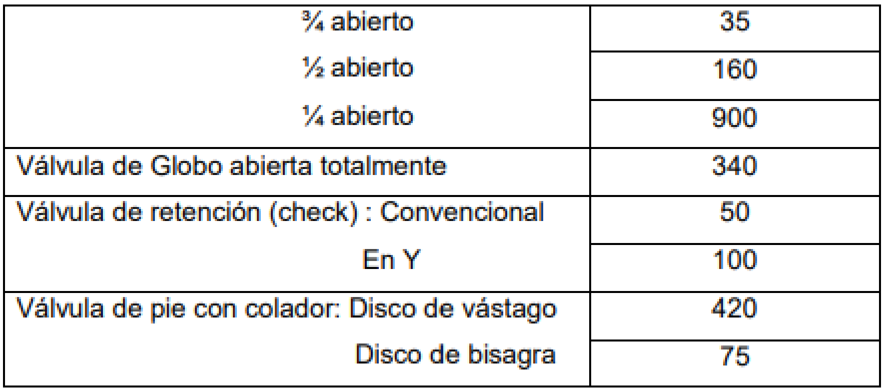


8.7. <u>Tables for calculating pressure drop due to accidents</u>

8.7.1. Resistance of equivalent length in number of pipe diameter (Le/Di)

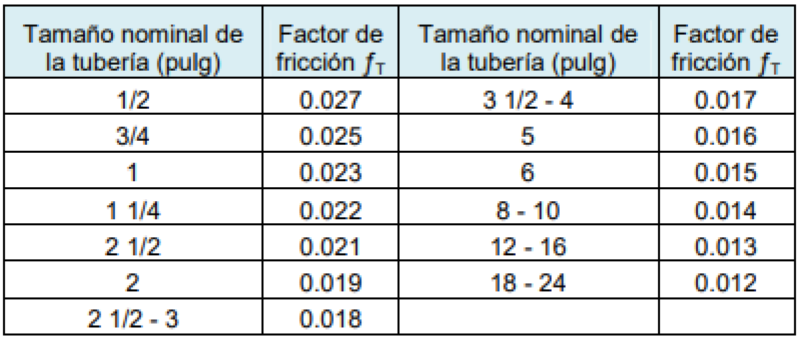


Accesorios	(Le/Di)
Codo estándar de 90°	30
Codo estándar de 45°	16
Codo curvo 90°	20
Codo en U	50
Te estándar: Con flujo Directo	20
Con flujo en el ramal	60
Con flujo bilateral	65
Unión o Universal	6
Válvula angular abierta	150
Válvula de bola o esférica abierto totalmente	150
Válvula de compuerta: Abierto totalmente	8



¾ abierto	35
½ abierto	160
¼ abierto	900
Válvula de Globo abierta totalmente	340
Válvula de retención (check) : Convencional	50
En Y	100
Válvula de pie con colador: Disco de vástago	420
Disco de bisagra	75

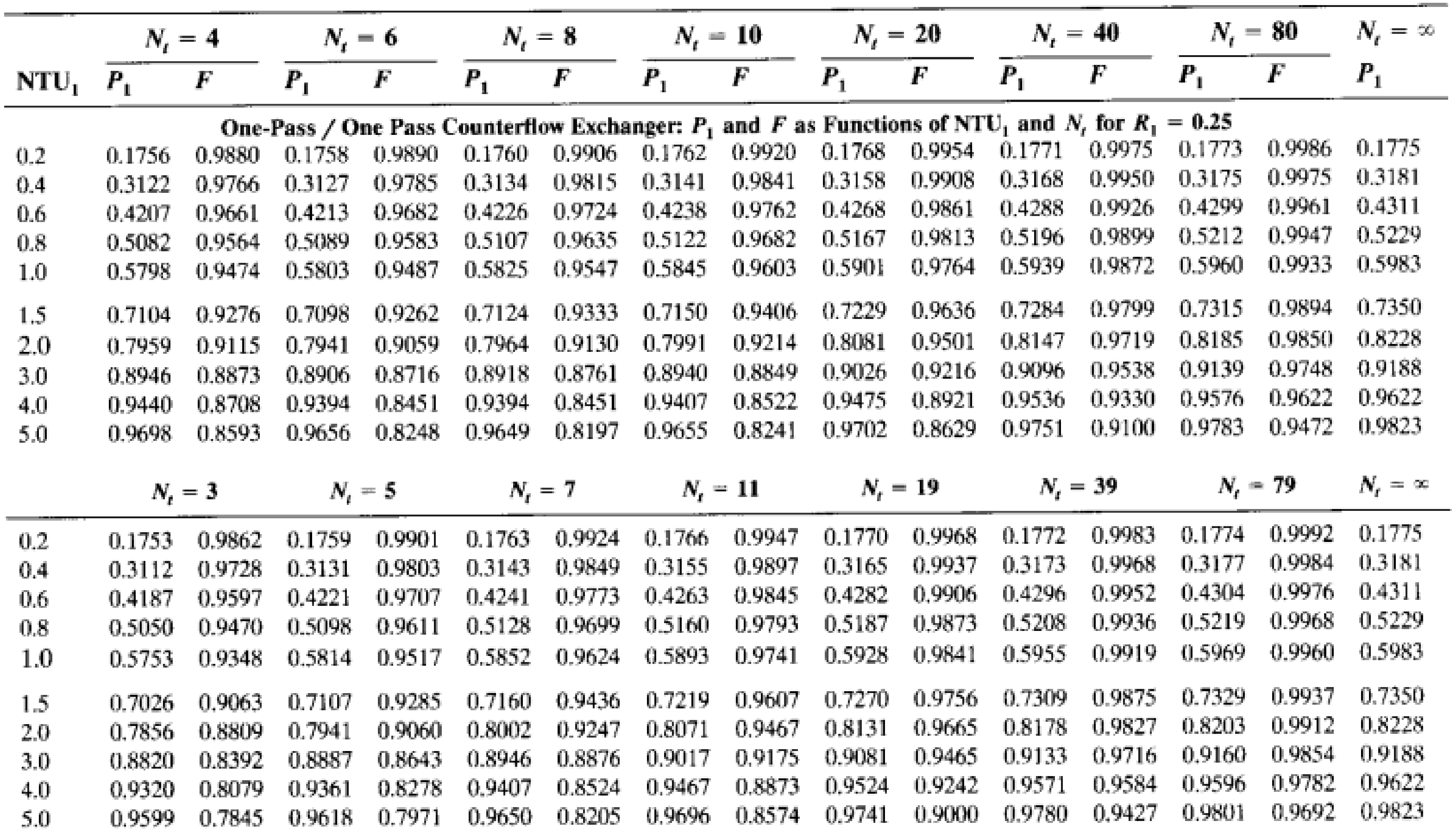
8.7.2. Frictional factor



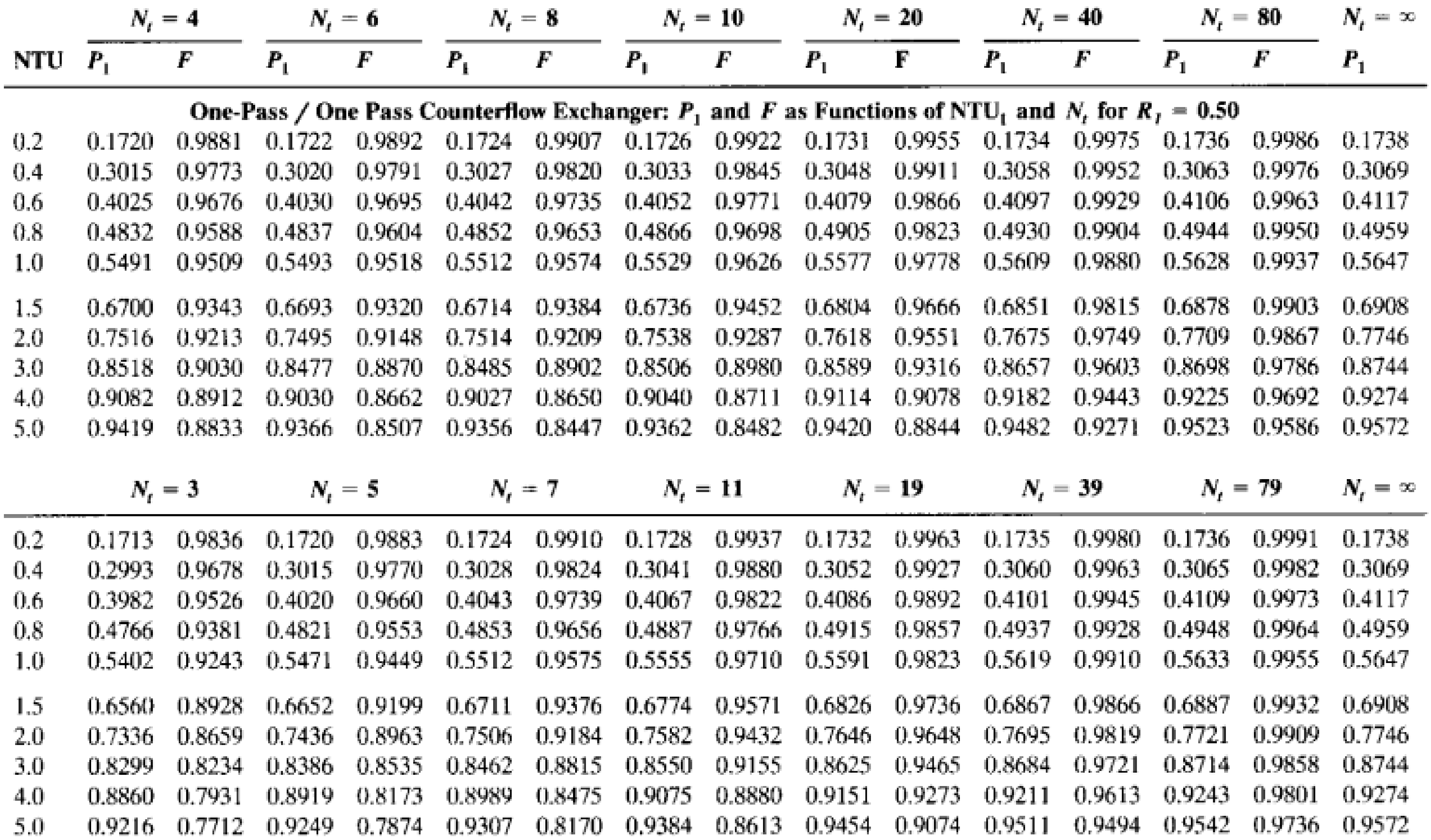
Tamaño nominal de la tubería (pulg)	Factor de fricción f_T	Tamaño nominal de la tubería (pulg)	Factor de fricción f_T
1/2	0.027	3 1/2 - 4	0.017
3/4	0.025	5	0.016
1	0.023	6	0.015
1 1/4	0.022	8 - 10	0.014
2 1/2	0.021	12 - 16	0.013
2	0.019	18 - 24	0.012
2 1/2 - 3	0.018		

8.8. Correction factor tables

Table 8.1. Thermal Performance of Single-Pass Heat Exchanger with N_t Plates



	$N_t = 4$		$N_t = 6$		$N_t = 8$		$N_t = 10$		$N_t = 20$		$N_t = 40$		$N_t = 80$		$N_t = \infty$
NTU_1	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1
One-Pass / One Pass Counterflow Exchanger: P_1 and F as Functions of NTU_1 and N_t for $R_1 = 0.25$															
0.2	0.1756	0.9880	0.1758	0.9890	0.1760	0.9906	0.1762	0.9920	0.1768	0.9954	0.1771	0.9975	0.1773	0.9986	0.1775
0.4	0.3122	0.9766	0.3127	0.9785	0.3134	0.9815	0.3141	0.9841	0.3158	0.9908	0.3168	0.9950	0.3175	0.9975	0.3181
0.6	0.4207	0.9661	0.4213	0.9682	0.4226	0.9724	0.4238	0.9762	0.4268	0.9861	0.4288	0.9926	0.4299	0.9961	0.4311
0.8	0.5082	0.9564	0.5089	0.9583	0.5107	0.9635	0.5122	0.9682	0.5167	0.9813	0.5196	0.9899	0.5212	0.9947	0.5229
1.0	0.5798	0.9474	0.5803	0.9487	0.5825	0.9547	0.5845	0.9603	0.5901	0.9764	0.5939	0.9872	0.5960	0.9933	0.5983
1.5	0.7104	0.9276	0.7098	0.9262	0.7124	0.9333	0.7150	0.9406	0.7229	0.9636	0.7284	0.9799	0.7315	0.9894	0.7350
2.0	0.7959	0.9115	0.7941	0.9059	0.7964	0.9130	0.7991	0.9214	0.8081	0.9501	0.8147	0.9719	0.8185	0.9850	0.8228
3.0	0.8946	0.8873	0.8906	0.8716	0.8918	0.8761	0.8940	0.8849	0.9026	0.9216	0.9096	0.9538	0.9139	0.9748	0.9188
4.0	0.9440	0.8708	0.9394	0.8451	0.9394	0.8451	0.9407	0.8522	0.9475	0.8921	0.9536	0.9330	0.9576	0.9622	0.9622
5.0	0.9698	0.8593	0.9656	0.8248	0.9649	0.8197	0.9655	0.8241	0.9702	0.8629	0.9751	0.9100	0.9783	0.9472	0.9823
	$N_t = 3$		$N_t = 5$		$N_t = 7$		$N_t = 11$		$N_t = 19$		$N_t = 39$		$N_t = 79$		$N_t = \infty$
0.2	0.1753	0.9862	0.1759	0.9901	0.1763	0.9924	0.1766	0.9947	0.1770	0.9968	0.1772	0.9983	0.1774	0.9992	0.1775
0.4	0.3112	0.9728	0.3131	0.9803	0.3143	0.9849	0.3155	0.9897	0.3165	0.9937	0.3173	0.9968	0.3177	0.9984	0.3181
0.6	0.4187	0.9597	0.4221	0.9707	0.4241	0.9773	0.4263	0.9845	0.4282	0.9906	0.4296	0.9952	0.4304	0.9976	0.4311
0.8	0.5050	0.9470	0.5098	0.9611	0.5128	0.9699	0.5160	0.9793	0.5187	0.9873	0.5208	0.9936	0.5219	0.9968	0.5229
1.0	0.5753	0.9348	0.5814	0.9517	0.5852	0.9624	0.5893	0.9741	0.5928	0.9841	0.5955	0.9919	0.5969	0.9960	0.5983
1.5	0.7026	0.9063	0.7107	0.9285	0.7160	0.9436	0.7219	0.9607	0.7270	0.9756	0.7309	0.9875	0.7329	0.9937	0.7350
2.0	0.7856	0.8809	0.7941	0.9060	0.8002	0.9247	0.8071	0.9467	0.8131	0.9665	0.8178	0.9827	0.8203	0.9912	0.8228
3.0	0.8820	0.8392	0.8887	0.8643	0.8946	0.8876	0.9017	0.9175	0.9081	0.9465	0.9133	0.9716	0.9160	0.9854	0.9188
4.0	0.9320	0.8079	0.9361	0.8278	0.9407	0.8524	0.9467	0.8873	0.9524	0.9242	0.9571	0.9584	0.9596	0.9782	0.9622
5.0	0.9599	0.7845	0.9618	0.7971	0.9650	0.8205	0.9696	0.8574	0.9741	0.9000	0.9780	0.9427	0.9801	0.9692	0.9823



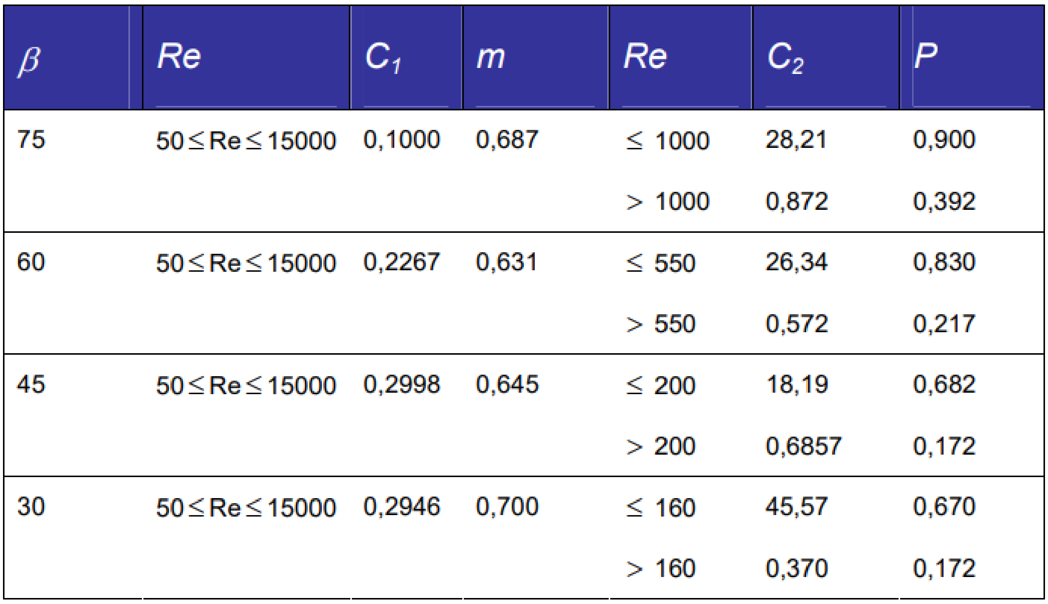
	$N_t = 4$		$N_t = 6$		$N_t = 8$		$N_t = 10$		$N_t = 20$		$N_t = 40$		$N_t = 80$		$N_t = \infty$
NTU	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1
	One-Pass / One Pass Counterflow Exchanger: P_1 and F as Functions of NTU_1 and N_t for $R_1 = 0.50$														
0.2	0.1720	0.9881	0.1722	0.9892	0.1724	0.9907	0.1726	0.9922	0.1731	0.9955	0.1734	0.9975	0.1736	0.9986	0.1738
0.4	0.3015	0.9773	0.3020	0.9791	0.3027	0.9820	0.3033	0.9845	0.3048	0.9911	0.3058	0.9952	0.3063	0.9976	0.3069
0.6	0.4025	0.9676	0.4030	0.9695	0.4042	0.9735	0.4052	0.9771	0.4079	0.9866	0.4097	0.9929	0.4106	0.9963	0.4117
0.8	0.4832	0.9588	0.4837	0.9604	0.4852	0.9653	0.4866	0.9698	0.4905	0.9823	0.4930	0.9904	0.4944	0.9950	0.4959
1.0	0.5491	0.9509	0.5493	0.9518	0.5512	0.9574	0.5529	0.9626	0.5577	0.9778	0.5609	0.9880	0.5628	0.9937	0.5647
1.5	0.6700	0.9343	0.6693	0.9320	0.6714	0.9384	0.6736	0.9452	0.6804	0.9666	0.6851	0.9815	0.6878	0.9903	0.6908
2.0	0.7516	0.9213	0.7495	0.9148	0.7514	0.9209	0.7538	0.9287	0.7618	0.9551	0.7675	0.9749	0.7709	0.9867	0.7746
3.0	0.8518	0.9030	0.8477	0.8870	0.8485	0.8902	0.8506	0.8980	0.8589	0.9316	0.8657	0.9603	0.8698	0.9786	0.8744
4.0	0.9082	0.8912	0.9030	0.8662	0.9027	0.8650	0.9040	0.8711	0.9114	0.9078	0.9182	0.9443	0.9225	0.9692	0.9274
5.0	0.9419	0.8833	0.9366	0.8507	0.9356	0.8447	0.9362	0.8482	0.9420	0.8844	0.9482	0.9271	0.9523	0.9586	0.9572
	$N_t = 3$		$N_t = 5$		$N_t = 7$		$N_t = 11$		$N_t = 19$		$N_t = 39$		$N_t = 79$		$N_t = \infty$
0.2	0.1713	0.9836	0.1720	0.9883	0.1724	0.9910	0.1728	0.9937	0.1732	0.9963	0.1735	0.9980	0.1736	0.9991	0.1738
0.4	0.2993	0.9678	0.3015	0.9770	0.3028	0.9824	0.3041	0.9880	0.3052	0.9927	0.3060	0.9963	0.3065	0.9982	0.3069
0.6	0.3982	0.9526	0.4020	0.9660	0.4043	0.9739	0.4067	0.9822	0.4086	0.9892	0.4101	0.9945	0.4109	0.9973	0.4117
0.8	0.4766	0.9381	0.4821	0.9553	0.4853	0.9656	0.4887	0.9766	0.4915	0.9857	0.4937	0.9928	0.4948	0.9964	0.4959
1.0	0.5402	0.9243	0.5471	0.9449	0.5512	0.9575	0.5555	0.9710	0.5591	0.9823	0.5619	0.9910	0.5633	0.9955	0.5647
1.5	0.6560	0.8928	0.6652	0.9199	0.6711	0.9376	0.6774	0.9571	0.6826	0.9736	0.6867	0.9866	0.6887	0.9932	0.6908
2.0	0.7336	0.8659	0.7436	0.8963	0.7506	0.9184	0.7582	0.9432	0.7646	0.9648	0.7695	0.9819	0.7721	0.9909	0.7746
3.0	0.8299	0.8234	0.8386	0.8535	0.8462	0.8815	0.8550	0.9155	0.8625	0.9465	0.8684	0.9721	0.8714	0.9858	0.8744
4.0	0.8860	0.7931	0.8919	0.8173	0.8989	0.8475	0.9075	0.8880	0.9151	0.9273	0.9211	0.9613	0.9243	0.9801	0.9274
5.0	0.9216	0.7712	0.9249	0.7874	0.9307	0.8170	0.9384	0.8613	0.9454	0.9074	0.9511	0.9494	0.9542	0.9736	0.9572

Table 8.1 (continued).

	$N_t = 4$		$N_t = 6$		$N_t = 8$		$N_t = 10$		$N_t = 20$		$N_t = 40$		$N_t = 80$		$N_t = \infty$
NTU	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1
	One-Pass / One Pass Counterflow Exchanger: P_1 and F as Functions of NTU$_1$ and N_t for R_1 = 0.75														
0.2	0.1685	0.9883	0.1686	0.9894	0.1689	0.9909	0.1691	0.9923	0.1695	0.9955	0.1698	0.9976	0.1700	0.9986	0.1702
0.4	0.2913	0.9780	0.2916	0.9797	0.2923	0.9825	0.2928	0.9850	0.2942	0.9913	0.2951	0.9953	0.2956	0.9976	0.2961
0.6	0.3849	0.9690	0.3854	0.9707	0.3864	0.9746	0.3873	0.9780	0.3897	0.9872	0.3912	0.9932	0.3920	0.9964	0.3930
0.8	0.4588	0.9611	0.4592	0.9624	0.4605	0.9670	0.4617	0.9713	0.4650	0.9832	0.4672	0.9909	0.4684	0.9953	0.4697
1.0	0.5187	0.9542	0.5188	0.9546	0.5203	0.9599	0.5218	0.9648	0.5259	0.9792	0.5287	0.9887	0.5302	0.9942	0.5319
1.5	0.6283	0.9401	0.6275	0.9374	0.6293	0.9432	0.6311	0.9495	0.6368	0.9692	0.6407	0.9831	0.6429	0.9912	0.6454
2.0	0.7030	0.9297	0.7011	0.9229	0.7026	0.9283	0.7046	0.9353	0.7112	0.9596	0.7160	0.9775	0.7187	0.9880	0.7218
3.0	0.7979	0.9157	0.7942	0.9006	0.7949	0.9031	0.7966	0.9101	0.8038	0.9404	0.8097	0.9658	0.8132	0.9816	0.8171
4.0	0.8553	0.9072	0.8505	0.8848	0.8502	0.8834	0.8514	0.8889	0.8583	0.9218	0.8645	0.9538	0.8685	0.9748	0.8730
5.0	0.8930	0.9017	0.8879	0.8736	0.8869	0.8680	0.8875	0.8713	0.8934	0.9040	0.8998	0.9415	0.9039	0.9675	0.9088
	$N_t = 3$		$N_t = 5$		$N_t = 7$		$N_t = 11$		$N_t = 19$		$N_t = 39$		$N_t = 79$		$N_t = \infty$
0.2	0.1674	0.9809	0.1682	0.9865	0.1687	0.9896	0.1691	0.9928	0.1696	0.9957	0.1698	0.9977	0.1700	0.9989	0.1702
0.4	0.2879	0.9627	0.2903	0.9735	0.2917	0.9798	0.2931	0.9863	0.2943	0.9916	0.2952	0.9958	0.2957	0.9979	0.2961
0.6	0.3787	0.9455	0.3829	0.9612	0.3852	0.9702	0.3877	0.9798	0.3898	0.9877	0.3914	0.9938	0.3922	0.9969	0.3930
0.8	0.4496	0.9292	0.4554	0.9492	0.4588	0.9611	0.4623	0.9736	0.4652	0.9839	0.4674	0.9919	0.4686	0.9960	0.4697
1.0	0.5066	0.9139	0.5138	0.9377	0.5181	0.9521	0.5225	0.9674	0.5262	0.9801	0.5290	0.9899	0.5304	0.9950	0.5319
1.5	0.6099	0.8798	0.6194	0.9102	0.6255	0.9305	0.6320	0.9525	0.6372	0.9708	0.6413	0.9852	0.6433	0.9925	0.6454
2.0	0.6798	0.8515	0.6900	0.8848	0.6974	0.9099	0.7053	0.9379	0.7118	0.9617	0.7168	0.9805	0.7193	0.9902	0.7218
3.0	0.7694	0.8087	0.7783	0.8399	0.7868	0.8714	0.7965	0.9097	0.8046	0.9437	0.8108	0.9710	0.8140	0.9854	0.8171
4.0	0.8252	0.7795	0.8314	0.8031	0.8396	0.8368	0.8501	0.8827	0.8591	0.9258	0.8659	0.9612	0.8695	0.9803	0.8730
5.0	0.8636	0.7591	0.8670	0.7737	0.8744	0.8064	0.8848	0.8571	0.8941	0.9080	0.9013	0.9512	0.9051	0.9751	0.9088

	$N_t = 4$		$N_t = 6$		$N_t = 8$		$N_t = 10$		$N_t = 20$		$N_t = 40$		$N_t = 80$		$N_t = \infty$
NTU	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1	F	P_1
One-Pass / One Pass Counterflow Exchanger: P_1 and F as Functions of NTU$_1$ and N_t for $R_1 = 1$															
0.2	0.1651	0.9885	0.1652	0.9895	0.1654	0.9910	0.1656	0.9924	0.1661	0.9956	0.1663	0.9976	0.1665	0.9986	0.1667
0.4	0.2813	0.9786	0.2817	0.9802	0.2822	0.9830	0.2827	0.9854	0.2840	0.9916	0.2848	0.9954	0.2853	0.9977	0.2857
0.6	0.3680	0.9703	0.3683	0.9719	0.3692	0.9755	0.3700	0.9789	0.3721	0.9877	0.3735	0.9935	0.3742	0.9966	0.3750
0.8	0.4352	0.9632	0.4355	0.9642	0.4366	0.9686	0.4376	0.9727	0.4405	0.9840	0.4423	0.9914	0.4433	0.9955	0.4444
1.0	0.4890	0.9571	0.4891	0.9573	0.4904	0.9622	0.4916	0.9668	0.4951	0.9804	0.4973	0.9894	0.4986	0.9945	0.5000
1.5	0.5864	0.9451	0.5856	0.9422	0.5870	0.9475	0.5885	0.9534	0.5931	0.9718	0.5963	0.9846	0.5981	0.9920	0.6000
2.0	0.6520	0.9367	0.6504	0.9302	0.6516	0.9350	0.6531	0.9413	0.6584	0.9637	0.6621	0.9799	0.6643	0.9895	0.6667
3.0	0.7353	0.9260	0.7325	0.9126	0.7329	0.9147	0.7342	0.9209	0.7399	0.9483	0.7444	0.9709	0.7471	0.9846	0.7500
4.0	0.7863	0.9198	0.7828	0.9008	0.7826	0.8997	0.7835	0.9046	0.7889	0.9343	0.7937	0.9621	0.7967	0.9798	0.8000
5.0	0.8208	0.9159	0.8170	0.8928	0.8163	0.8887	0.8168	0.8917	0.8217	0.9215	0.8266	0.9536	0.8298	0.9749	0.8333
	$N_t = 3$		$N_t = 5$		$N_t = 7$		$N_t = 11$		$N_t = 19$		$N_t = 39$		$N_t = 79$		$N_t = \infty$
0.2	0.1636	0.9783	0.1645	0.9846	0.1650	0.9882	0.1655	0.9918	0.1660	0.9951	0.1663	0.9974	0.1665	0.9987	0.1667
0.4	0.2770	0.9577	0.2795	0.9700	0.2810	0.9771	0.2825	0.9845	0.2838	0.9906	0.2847	0.9952	0.2852	0.9976	0.2857
0.6	0.3602	0.9384	0.3646	0.9562	0.3670	0.9664	0.3696	0.9772	0.3717	0.9862	0.3733	0.9930	0.3742	0.9965	0.3750
0.8	0.4241	0.9204	0.4300	0.9428	0.4334	0.9562	0.4370	0.9703	0.4399	0.9819	0.4422	0.9909	0.4433	0.9955	0.4444
1.0	0.4747	0.9037	0.4819	0.9300	0.4862	0.9462	0.4907	0.9634	0.4944	0.9777	0.4972	0.9887	0.4986	0.9944	0.5000
1.5	0.5654	0.8672	0.5744	0.8997	0.5805	0.9224	0.5869	0.9470	0.5920	0.9675	0.5960	0.9835	0.5980	0.9916	0.6000
2.0	0.6263	0.8379	0.6356	0.8721	0.6428	0.8998	0.6506	0.9310	0.6570	0.9575	0.6618	0.9784	0.6642	0.9891	0.6667
3.0	0.7046	0.7952	0.7122	0.8248	0.7203	0.8582	0.7298	0.9005	0.7379	0.9382	0.7439	0.9683	0.7470	0.9839	0.7500
4.0	0.7543	0.7673	0.7590	0.7874	0.7668	0.8219	0.7772	0.8719	0.7862	0.9194	0.7931	0.9583	0.7965	0.9787	0.8000
5.0	0.7892	0.7486	0.7913	0.7584	0.7982	0.7910	0.8086	0.8451	0.8184	0.9012	0.8258	0.9484	0.8296	0.9736	0.8333

8.9. Constant of the correlation of Thonon



β	*Re*	C_1	*m*	*Re*	C_2	*P*
75	$50 \leq Re \leq 15000$	0,1000	0,687	≤ 1000	28,21	0,900
				> 1000	0,872	0,392
60	$50 \leq Re \leq 15000$	0,2267	0,631	≤ 550	26,34	0,830
				> 550	0,572	0,217
45	$50 \leq Re \leq 15000$	0,2998	0,645	≤ 200	18,19	0,682
				> 200	0,6857	0,172
30	$50 \leq Re \leq 15000$	0,2946	0,700	≤ 160	45,57	0,670
				> 160	0,370	0,172

8.10. Example of the design of the heat exchanger

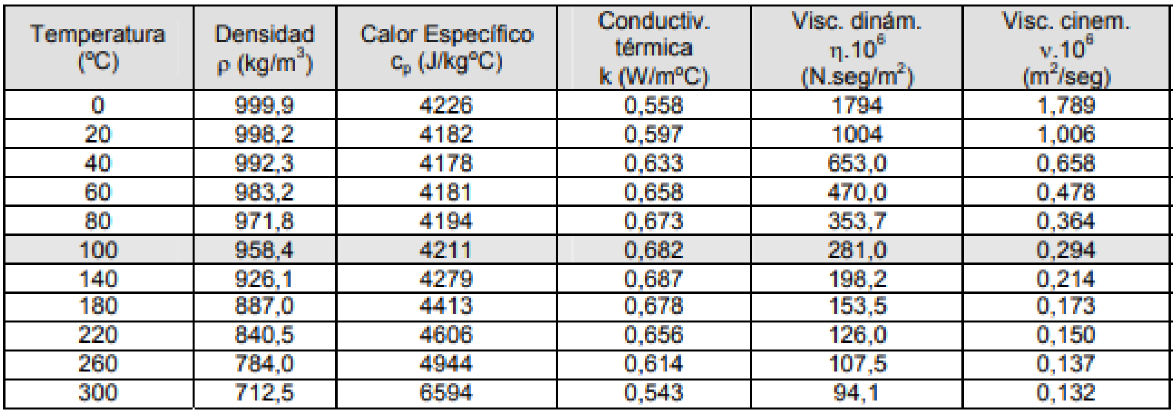
8.10.1. Area obtained by the LTMD method

Parameters	Hot Fluid	Cold Fluid
Q (m^3/h)	16,24	16
M (kg/s)	4,37	4,32
T in (°C)	95	67,73
T out (°C)	73,01	90
Q (kW)	403	
Cp (J/kg°C)	4197,43	4193,26
n	24	
Nc	12	12
Mc (kg/s)	0,36	0,36
m (kg/sm^2)	428,68	423,73
W (mm)	340	
b (mm)	2,5	
Le (m)	1,5	
Ap (m^2)	0,51	
HPCD (mm)	225	
D (mm)	100	
Sc (m^2)	8,50E-04	
De (m)	4,27E-03	
φ	1,17	
μ (Pas)	3,39E-04	3,60E-04
Pr	2,13	2,25
Re	5404,02	5029,98
Nu	55,3	150,49
f	0,084	0,085
h (W/ °Cm^2)	24347,88	23663,33
Rf (W/°Cm^2)	1,75E-05	1,00E-05
ε (mm)	0,4	
k (W/m°C)	15,05	
U (W/ °Cm^2)	7272,86	
A (m^2)	11,61	

8.10.2. Pressure drop obtained of the example

Parameters	Hot Fluid	Cold Fluid
f	0,084	0,085
m (kg/sm^2)	428,68	423,73
Np	1	
Le (m)	1,5	
ρ (kg/m^3)	969,1	972,45
De (m)	4,27E-03	
µ (Pas)	3,39E-04	3,60E-04
µ w (Pas)	3,48E-04	
Tp (ºC)	81,471	
Δp_c (bar)	0,114	0,111
M (kg/s)	4,37	4,32
Sp (m^2)	8,00E-03	
D (mm)	100	
Vp (m/s)	0,574	0,566
ΔP_p (bar)	0,002	0,002
ΔP (bar)	0,116	0,113

8.11. Table of water properties



Temperatura (ºC)	Densidad ρ (kg/m^3)	Calor Específico c_p (J/kgºC)	Conductiv. térmica k (W/mºC)	Visc. dinám. $\eta.10^6$ (N.seg/m^2)	Visc. cinem. $\nu.10^6$ (m^2/seg)
0	999,9	4226	0,558	1794	1,789
20	998,2	4182	0,597	1004	1,006
40	992,3	4178	0,633	653,0	0,658
60	983,2	4181	0,658	470,0	0,478
80	971,8	4194	0,673	353,7	0,364
100	958,4	4211	0,682	281,0	0,294
140	926,1	4279	0,687	198,2	0,214
180	887,0	4413	0,678	153,5	0,173
220	840,5	4606	0,656	126,0	0,150
260	784,0	4944	0,614	107,5	0,137
300	712,5	6594	0,543	94,1	0,132

8.12. API sheet scenario 1

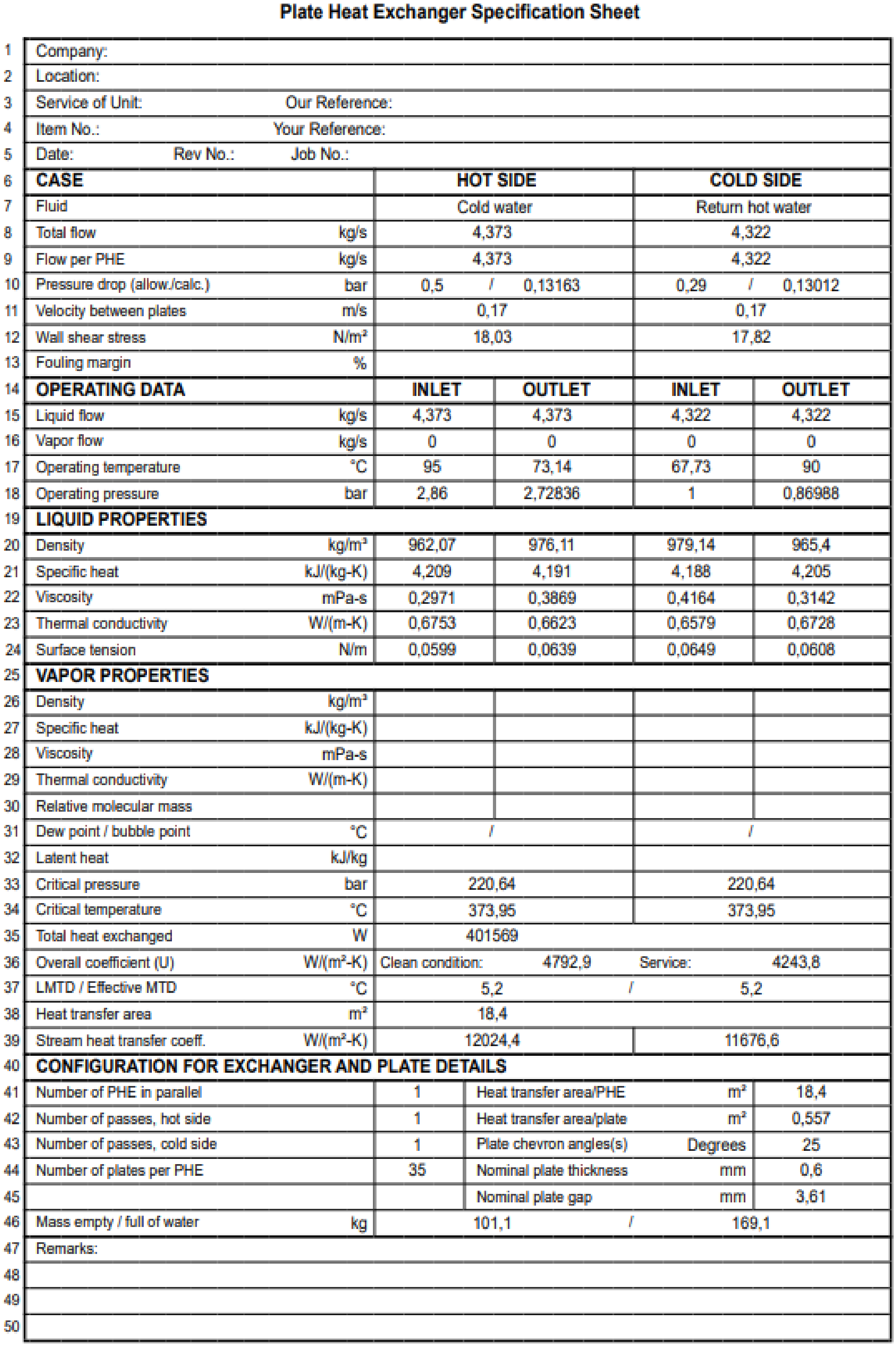


Plate Heat Exchanger Specification Sheet

1	Company:					
2	Location:					
3	Service of Unit:		Our Reference:			
4	Item No.:		Your Reference:			
5	Date: Rev No.:		Job No.:			
6	**CASE**		**HOT SIDE**		**COLD SIDE**	
7	Fluid		Cold water		Return hot water	
8	Total flow	kg/s	4,373		4,322	
9	Flow per PHE	kg/s	4,373		4,322	
10	Pressure drop (allow./calc.)	bar	0,5 / 0,13163		0,29 / 0,13012	
11	Velocity between plates	m/s	0,17		0,17	
12	Wall shear stress	N/m²	18,03		17,82	
13	Fouling margin	%				
14	**OPERATING DATA**		**INLET**	**OUTLET**	**INLET**	**OUTLET**
15	Liquid flow	kg/s	4,373	4,373	4,322	4,322
16	Vapor flow	kg/s	0	0	0	0
17	Operating temperature	°C	95	73,14	67,73	90
18	Operating pressure	bar	2,86	2,72836	1	0,86988
19	**LIQUID PROPERTIES**					
20	Density	kg/m³	962,07	976,11	979,14	965,4
21	Specific heat	kJ/(kg-K)	4,209	4,191	4,188	4,205
22	Viscosity	mPa-s	0,2971	0,3869	0,4164	0,3142
23	Thermal conductivity	W/(m-K)	0,6753	0,6623	0,6579	0,6728
24	Surface tension	N/m	0,0599	0,0639	0,0649	0,0608
25	**VAPOR PROPERTIES**					
26	Density	kg/m³				
27	Specific heat	kJ/(kg-K)				
28	Viscosity	mPa-s				
29	Thermal conductivity	W/(m-K)				
30	Relative molecular mass					
31	Dew point / bubble point	°C	/		/	
32	Latent heat	kJ/kg				
33	Critical pressure	bar	220,64		220,64	
34	Critical temperature	°C	373,95		373,95	
35	Total heat exchanged	W	401569			
36	Overall coefficient (U)	W/(m²-K)	Clean condition: 4792,9		Service: 4243,8	
37	LMTD / Effective MTD	°C	5,2	/	5,2	
38	Heat transfer area	m²	18,4			
39	Stream heat transfer coeff.	W/(m²-K)	12024,4		11676,6	
40	**CONFIGURATION FOR EXCHANGER AND PLATE DETAILS**					
41	Number of PHE in parallel		1	Heat transfer area/PHE	m²	18,4
42	Number of passes, hot side		1	Heat transfer area/plate	m²	0,557
43	Number of passes, cold side		1	Plate chevron angles(s)	Degrees	25
44	Number of plates per PHE		35	Nominal plate thickness	mm	0,6
45				Nominal plate gap	mm	3,61
46	Mass empty / full of water	kg	101,1	/	169,1	
47	Remarks:					
48						
49						
50						

8.13. API sheet scenario 2

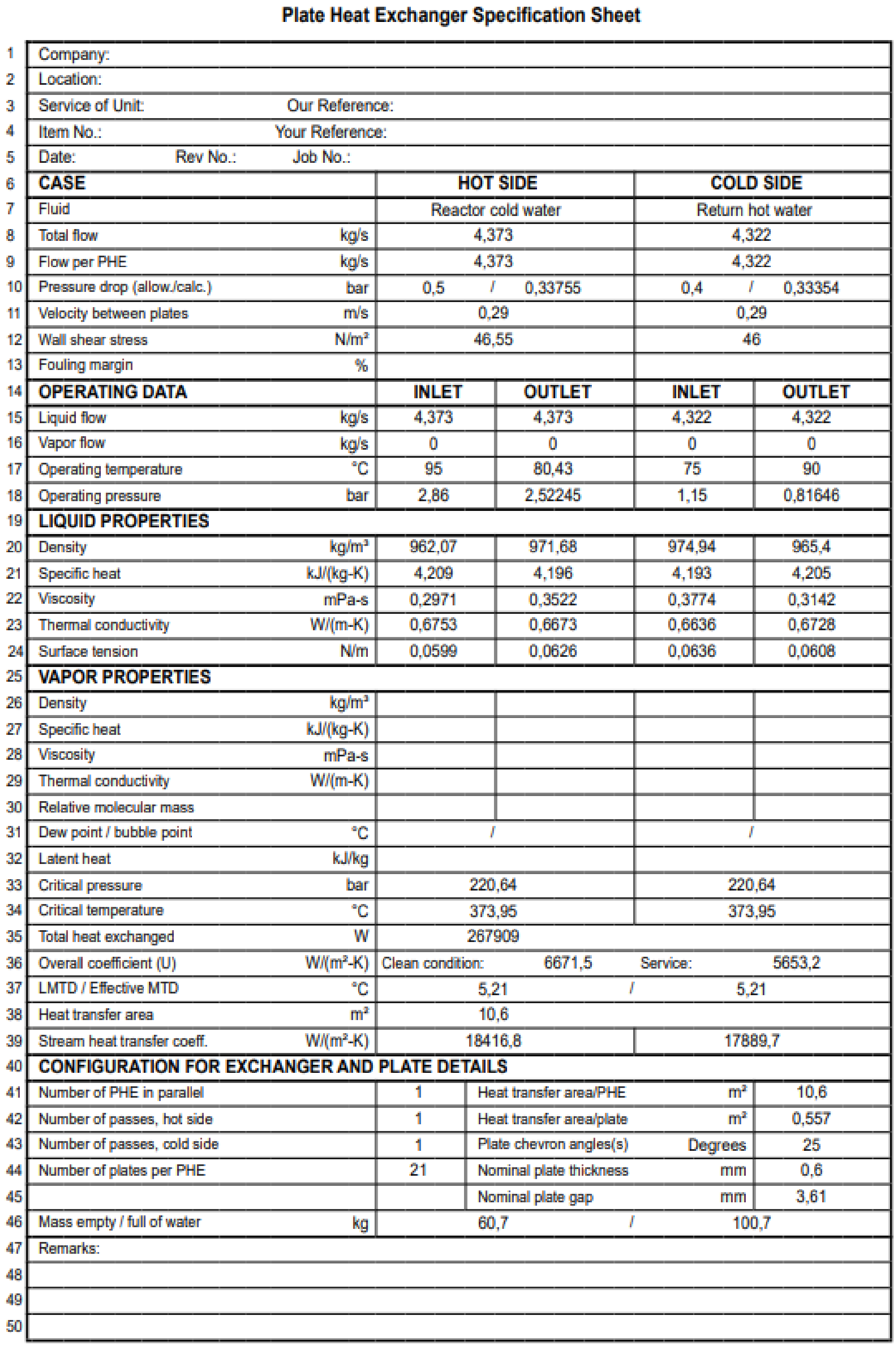


Plate Heat Exchanger Specification Sheet

Company:					
Location:					
Service of Unit:	Our Reference:				
Item No.:	Your Reference:				
Date: Rev No.: Job No.:					
CASE		**HOT SIDE**		**COLD SIDE**	
Fluid		Reactor cold water		Return hot water	
Total flow	kg/s	4,373		4,322	
Flow per PHE	kg/s	4,373		4,322	
Pressure drop (allow./calc.)	bar	0,5 / 0,33755		0,4 / 0,33354	
Velocity between plates	m/s	0,29		0,29	
Wall shear stress	N/m²	46,55		46	
Fouling margin	%				
OPERATING DATA		**INLET**	**OUTLET**	**INLET**	**OUTLET**
Liquid flow	kg/s	4,373	4,373	4,322	4,322
Vapor flow	kg/s	0	0	0	0
Operating temperature	°C	95	80,43	75	90
Operating pressure	bar	2,86	2,52245	1,15	0,81646
LIQUID PROPERTIES					
Density	kg/m³	962,07	971,68	974,94	965,4
Specific heat	kJ/(kg-K)	4,209	4,196	4,193	4,205
Viscosity	mPa-s	0,2971	0,3522	0,3774	0,3142
Thermal conductivity	W/(m-K)	0,6753	0,6673	0,6636	0,6728
Surface tension	N/m	0,0599	0,0626	0,0636	0,0608
VAPOR PROPERTIES					
Density	kg/m³				
Specific heat	kJ/(kg-K)				
Viscosity	mPa-s				
Thermal conductivity	W/(m-K)				
Relative molecular mass					
Dew point / bubble point	°C	/		/	
Latent heat	kJ/kg				
Critical pressure	bar	220,64		220,64	
Critical temperature	°C	373,95		373,95	
Total heat exchanged	W	267909			
Overall coefficient (U)	W/(m²-K)	Clean condition: 6671,5		Service: 5653,2	
LMTD / Effective MTD	°C	5,21	/	5,21	
Heat transfer area	m²	10,6			
Stream heat transfer coeff.	W/(m²-K)	18416,8		17889,7	
CONFIGURATION FOR EXCHANGER AND PLATE DETAILS					
Number of PHE in parallel		1	Heat transfer area/PHE	m²	10,6
Number of passes, hot side		1	Heat transfer area/plate	m²	0,557
Number of passes, cold side		1	Plate chevron angles(s)	Degrees	25
Number of plates per PHE		21	Nominal plate thickness	mm	0,6
			Nominal plate gap	mm	3,61
Mass empty / full of water	kg	60,7	/	100,7	
Remarks:					

8.14. Self-evaluation questionnaire

a) Evaluate the acquired **competences** according to the **tasks** you have carried out.

Degree Competences		**Task in which you have observed the competence**	**Self evaluation [Rank 1 to 10]**	**Aspects to be improved**
SPECIFIC COMPETENCES				
A1.1	Effectively apply knowledge of basic, scientific and technological materials pertaining to engineering.	Field measurements, updating engineering drawings.	8	
A1.2	Design, execute and analyze experiments related to engineering	Field measurements	8	
A1.3	Be able to analyze and synthesize the continuous progress of products, processes, systems and services, whilst applying criteria of safety, economic viability, quality and environmental management. (G6)	Field measurements, development of the master's thesis.	8.5	
A1.4	Know how to establish and develop mathematical models by using the appropriate software in order to provide the scientific and technological basis for the design of new products, processes, systems and services and for the optimization of existing ones. (G5)	Development and evaluation of different plates to be used in the heat exchanger based on the EDR and its correlations. Field measurements.	8	
A2.1	Be able to apply the scientific method and the principles of engineering and economics to formulate and solve complex problems that arise in processes, equipment, installations and services, in which the material undergoes changes to its composition, state or energy content, these changes being characteristic of industrial chemistry and other related sectors such as pharmacology, biotechnology, materials sciences, energy, food and the environment. (G1)	Field measurements, establishment of points to be measured and installation of specific equipment.	8.5	

A2.2	Conceive, project, calculate and design processes, equipment, industrial installations and services in the field of chemical engineering and related industrial sectors in terms of quality, safety, economics, the rational and efficient use of natural resources and the conservation of the environment. (G2)	Field measurements, establishment of points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8.5	
A2.3	Lead and technically and economically manage projects, installations, plants, companies and technological centres in the ambit of chemical engineering and related industrial sectors. (G3)	Field measurements, updating engineering drawings, establishment points to be measured.	8	
A3.1	Apply knowledge of mathematics, physics, chemistry, biology and other natural sciences by means of study, experience, practice and critical reasoning in order to establish economically viable solutions for technical problems (I1).	Field measurements, updating engineering drawings, establishment points to be measured.	8	
A3.2	Design and optimize products, processes, systems and services for the chemical industry on the basis of various areas of chemical engineering, including processes, transport, separation operations, and chemical, nuclear, elctrochemical and biochemical reactions engineering (I2).	Field measurements, updating engineering drawings, establishment points to be measured and communication with other departments.	8	
A3.3	Conceptualize engineering models and apply innovative problems solving methods and appropriate IT applications to the design, simulation, optimization and control of processes and systems (I3).	Field measurements, updating engineering drawings, establishment points to be measured.	8	
A3.4	Be able to solve unfamiliar and ill-defined problems by taking into account all possible solutions and selecting the most innovative. (I4)	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design	8	

		development and required lines.		
A3.5	Lead and supervise all types of installation, process, system and service in the different industrial areas related to chemical engineering (I5).	Field measurements, updating engineering drawings, establishment points to be measured.	7.5	
A3.6	Design, construct and implement methods, processes and installations for the integrated management of waste, solids, liquids and gases, whilst also taking into account the impacts and risks of these products (I6).	Field measurements, updating engineering drawings, establishment points to be measured, installation of the equipment needed.	8	
A4.1	Lead and organize companies and production and service systems by applying knowledge and abilities regarding industrial organization, commercial strategy, planning and logistics, mercantile and labour legislation, and financial and costs accounting (P1).	Field measurements, updating engineering drawings, establishment points to be measured, installation of the equipment needed.	8	
A4.2	Lead and manage the organization of work and human resources by applying criteria regarding industrial safety, quality management, occupation risk prevention, sustainability and environmental management (P2).	Field measurements, updating engineering drawings, establishment points to be measured, installation of the equipment needed.	8	
A4.3	Manage research, development and technological innovation whilst ensuring the transfer of technology and taking into account property and patent rights (P3).	Field measurements, updating engineering drawings, establishment points to be measured, installation of the equipment needed.	8	
A4.4	Adapt to structural changes in society caused by economic, energy or natural factors so as to be able to solve any resulting	Field measurements, updating engineering drawings,	8	

	problems and to contribute technological solutions with a high commitment to sustainability (P4).	establishment points to be measured, installation of the equipment needed.		
A4.5	Lead and monitor the control of installations, processes, products, certification, auditing, verification, testing and reports (P5).	Field measurements, updating engineering drawings, establishment points to be measured, installation of the equipment needed.	8	
A5.1	Carry out, present and defend (once all the curriculum credits have been obtained) an original individually produced piece of work before a university panel. The work will consist of a professional integrated Chemical Engineering project that synthesizes (TFM1)	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8	
TRANSVERSAL COMPETENCES				
B1.1	Communicate and discuss proposals and conclusions in a clear and unambiguous manner in specialized and non-specialized multilingual forums (G9).	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8	Communicate more clearly and precisely.
B1.2	Adapt to changes and be able to apply new and advanced technologies and other important developments with initiative and entrepreneurial spirit. (G10)	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and	8	

		required lines.		
B2.1	Lead and define multidisciplinary teams that are able to make technical changes and address management needs in national and international contexts. (G8)	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8	
B3.1	Work in a team with responsibilities shared among multidisciplinary, multilingual and multicultural teams	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment.	8	
B4.1	Be able to learn autonomously in order to maintain and improve the competences pertaining to chemical engineering that enable continuous professional development. (G11)	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8	
B5.1	Carry out and lead the appropriate research, design and development of engineering solutions in new or little understood areas, whilst applying criteria of creativity, originality, innovation and technology transfer. (G4)	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8	
B5.2	Bring together knowledge, make judgements and take decisions on the basis of incomplete or limited knowledge whilst taking into account the social and	Field measurements, updating engineering drawings,	8	

	ethical responsibilities of professional practice. (G7)	establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.		
NUCLEAR COMPETENCES				
C1.1	Have an intermediate mastery of a foreign language, preferably English	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	7.5	
C1.2	Be advanced users of the information and communication technologies	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8	
C1.3	Be able to manage information and knowledge	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8	
C1.4	Be able to express themselves correctly both orally and in writing in one of the two official languages of the URV	Field measurements, updating engineering drawings, establishment points to be	8	

		measured, installation of specific equipment and heat exchanger design development and required lines.		
C2.1	Be committed to ethics and social responsibility as citizens and professionals	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8.5	
C2.2	Be able to define and develop their academic and professional project	Field measurements, updating engineering drawings, establishment points to be measured, installation of specific equipment and heat exchanger design development and required lines.	8	

b) Evaluate the final master project and suggest improvements.

Key steps	**Evaluation** **[Mark 1 to 10]**	**Improvement proposed**
Selection/assignment of the project (dissemination, communication, assignment requirements...)	9	
Stay (welcome, length, relationship, follow-up made by the company...)	9	
Follow-up made by URV tutor	9	
Other aspects to be considered (which ones...)		